Toward Sustainable Development: Quantifying Environmental Impact via Embodied Energy and CO_2 Emissions for Geotechnical Construction

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ABSTRACT

With rising awareness that future generations may not have access to the resources and quality of life that exist today, sustainable development has become a priority within civil engineering. One important component of sustainable development is environmental stewardship, which concerns both the resources taken from the environment, and the wastes and byproducts emitted to the environment. To facilitate more sustainable development, environmental accounting is necessary within civil and geotechnical engineering design and construction. Historically, geotechnical practice has focused on maximizing design performance while minimizing monetary costs, and well established methods exist for quantifying these factors. Quantitative consideration of environmental consequences has seldom played a large role in geotechnical design and construction, and clear guidelines and a methodology for such an assessment are not available within the geotechnical profession. Therefore, this research has focused on establishing a method for quantitative streamlined environmental Life Cycle Analysis of energy and carbon dioxide (CO_2) emissions for geotechnical ground improvement works, known as the Streamlined Energy and Emissions Assessment Model (SEEAM). The boundaries for the SEEAM extend from raw material extraction through the completion of construction, including the energy and CO_2 emissions associated with construction materials, construction site operations, and the transportation of construction materials and wastes. The methodology relies on energy and CO_2 emissions coefficients, which represent typical industry average values and not necessarily the specific processes contributing to a project. Therefore, there is uncertainty in SEEAM analyses, which is addressed via a Monte Carlo simulation framework that assumes the energy and CO_2 emissions coefficients each follow a lognormal distribution. Data sets of total energy and CO_2 emissions generated by the Monte Carlo simulation framework with the SEEAM may be used to statistically compare the energy and CO_2 emissions of different geotechnical design alternatives. Such comparisons can help facilitate designing for minimum environmental consequences, thus advancing sustainable development within geotechnical engineering. For clarity, the development and application of the SEEAM is illustrated using two different geotechnical case history projects, including rehabilitation of levee LPV 111 in New Orleans, LA, and the construction of foundations for a replacement dormitory on the Virginia Tech campus.

DEDICATION

This work is dedicated first to the Creator of the world, who initially gave humanity the charge of being stewards of the Earth, its creatures and resources. Second, this work is dedicated to my loving wife Jillian, who has selflessly given of herself in support of my doctoral studies.

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PREFACE

Chapters 2 through 7 of this dissertation are each individual paper manuscripts. They consist of three journal manuscripts (Chs. 2, 4 and 6), and three conference paper manuscripts (Chs. 3, 5 and 7). Detailed reference information is provided in this preface for published papers; submission information is provided for papers currently in review or not yet published. Craig M. Shillaber is the first author of all manuscripts; the contributions of all coauthors by chapter/manuscript are delineated in this preface.

Chapter 2: Energy and Carbon Assessment of Ground Improvement Works I: Definitions and Background.

***Reference*:**

Shillaber, C. M., Mitchell, J. K. and Dove, J. E. (2015). "Energy and carbon assessment of ground improvement works. I: definitions and background." *Journal of Geotechnical and Geoenvironmental Engineering*. DOI: 10.1061/(ASCE)GT.1943-5606.0001410.

The contributions of authors to the composition of this manuscript are delineated as follows:

Craig M. Shillaber: Reviewed the literature, composed the first draft manuscript, developed the figures and tables, accounted for the comments and suggestions of coauthors in developing a final draft manuscript, submitted the manuscript for review as the corresponding author and composed the written response to the reviewer comments.

James K. Mitchell: Initiated the idea of studying embodied energy and carbon dioxide emissions for geotechnical ground improvement, provided some background references from prior studies, thoroughly reviewed and edited the manuscript, and provided input in how to respond to reviewer comments.

Joseph E. Dove: Helped refine the discussion of social aspects of sustainability, thoroughly reviewed and edited the manuscript, contributed to the examples included in the manuscript, and provided input for how to respond to reviewer comments.

Chapter 3: Assessing Environmental Impacts in Geotechnical Construction: Insights from the Fuel Cycle.

***Reference*:**

Shillaber, C. M., Mitchell, J. K. and Dove, J. E. (2014). "Assessing environmental impacts in geotechnical construction: insights from the fuel cycle." *Proc., GeoCongress 2014, Geo-Characterization and Modeling for Sustainability*, Geotechnical Special Publication No. 234, ASCE, Reston, VA, 3516-3525. DOI: 10.1061/9780784413272.341.

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Craig M. Shillaber: Performed the literature review and the fuel cycle analysis, described the results of the fuel cycle analysis in the manuscript, developed the tables and figures, performed the calculations for the geotechnical example, accounted for the comments and suggestions of coauthors in developing a final draft manuscript, submitted the manuscript to the conference, and made the conference presentation.

James K. Mitchell: Thoroughly reviewed and edited the manuscript, provided suggestions for making the information presented in the figures clearer, suggested a geotechnical example be included to help connect the fuel cycle analysis to geotechnical engineering for readers.

Joseph E. Dove: Thoroughly reviewed and edited the manuscript, checked the calculations for the geotechnical example.

Chapter 4: Energy and Carbon Assessment of Ground Improvement Works II: Working Model and Example.

***Reference*:**

Shillaber, C. M., Mitchell, J. K. and Dove, J. E. (2015). "Energy and carbon assessment of ground improvement works. II: working model and example." *Journal of Geotechnical and Geoenvironmental Engineering*. DOI: 10.1061/(ASCE)GT.1943-5606.0001411.

The contributions of authors to the composition of this manuscript are delineated as follows:

Craig M. Shillaber: Reviewed background literature, developed the Streamlined Energy and Emissions Assessment Model presented in the manuscript, including the boundaries and equations, performed the analysis for the case history project, drew and/or adapted the figures, created the tables (including locating the energy and emissions coefficients), composed the draft manuscript, accounted for the comments and suggestions of coauthors in developing a final draft manuscript, submitted the manuscript for review as the corresponding author and composed the written response to the reviewer comments.

James K. Mitchell: Provided some background literature for review, made suggestions for including figures for all of the different alternatives in the case history, added the "Comment" column in Table 4.4, thoroughly reviewed and edited the manuscript, and provided input regarding how to respond to reviewer comments.

Joseph E. Dove: Assisted with reaching out to engineering and contracting firms in order to obtain data for the case history example, thoroughly reviewed and edited the manuscript, suggested making a practical/relatable comparison to demonstrate the magnitude of the CO_2 emissions which led to the comparison of pickup truck round trips to the moon.

Chapter 5: Sustainability Considerations in Deep Mixing Applications, with Examples from LPV 111 in New Orleans, LA.

***Reference*:**

Shillaber, C. M., Mitchell, J. K. and Dove, J. E. (2015). "Sustainability considerations in deep mixing applications, with examples from LPV 111 in New Orleans, LA." *Proc., Deep Mixing 2015*, June 2-5, 2015, San Francisco, CA. Deep Foundations Institute, Hawthorne, NJ, 511-520.

The contributions of authors to the composition of this manuscript are delineated as follows:

Craig M. Shillaber: Performed the analysis, generated the figures and tables, composed the draft manuscript, accounted for the comments and suggestions of coauthors in developing a final draft manuscript, and made the presentation at the conference.

James K. Mitchell: Contributed to the description of the case history project with particular emphasis on the embankment fill properties and deep mixing design criteria, helped refine the recommendations, and thoroughly reviewed and edited the manuscript.

Joseph E. Dove: Helped refine the recommendations and draw conclusions, thoroughly reviewed and edited the manuscript, assisted with preparation of the accompanying presentation.

Chapter 6: A Framework to Account for Uncertainty in Energy and Carbon Assessment of Ground Improvement Works.

***Reference*:**

Shillaber, C. M., Mitchell, J. K., Dove, J. E., and Ostrum, Z. A. (In Review). "A framework to account for uncertainty in energy and carbon assessment of ground improvement works." *Journal of Geotechnical and Geoenvironmental Engineering*. In Review.

The contributions of authors to the composition of this manuscript are delineated as follows:

Craig M. Shillaber: Reviewed background literature on uncertainty in geotechnical engineering and in life cycle analysis, performed all embodied energy and CO_2 emissions analyses to compare methods of accounting for variable subsurface conditions, created all tables, created Figures 6.1, 6.3 and 6.4, proposed the steps in the framework of accounting for uncertainty, made the comparison of two LPV 111 alternatives using quantitative and qualitative methods, composed the draft manuscript, accounted for the comments and suggestions of coauthors in developing a final draft manuscript, submitted the manuscript for review as the corresponding author.

James K. Mitchell: Thoroughly reviewed and edited the manuscript, made suggestions for the development of Figure 6.1, suggested the development of Table 6.2, helped refine the framework as presented in Figure 6.3.

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Zachary A. Ostrum: Performed the Kriging for top of rock elevation at the Pearson Hall project site, created Figure 6.2, reviewed and edited the manuscript.

Chapter 7: Uncertainty in Predictions of Embodied Energy and CO_2 Emissions for Ground Improvement: The Influence of Material Haul Distance.

***Reference*:**

Shillaber, C. M., Pearce, A. R., Mitchell, J. K., and Dove, J. E. (Submitted). "Uncertainty in estimates of embodied energy and CO_2 emissions for ground improvement: the influence of material haul distance." *Proc. Geo-Chicago 2016, Sustainability, Energy and the Geoenvironment*. Chicago, IL, August 14-18, 2016.

The contributions of authors to the composition of this manuscript are delineated as follows:

Craig M. Shillaber: Performed the energy and carbon analyses for two case history projects using different material haul distances, generated the tables and figures, conducted a literature review of supplier selection, composed the draft manuscript, accounted for the comments and suggestions of coauthors in developing a final draft manuscript, and submitted the manuscript.

Annie R. Pearce: Initially posed the issue of uncertain haul distance and raised the question about its effect on energy and carbon assessments in a geotechnical context. Clarified the assumptions in the assessment, raised the issue of how suppliers are selected and the role that plays, thoroughly reviewed and commented on the draft manuscript.

James K. Mitchell: Thoroughly reviewed and edited the manuscript and made comments that led to the generation of Figures 7.1 and 7.3 instead of tables.

Joseph E. Dove: Thoroughly reviewed and edited the manuscript and contributed to developing the discussion and conclusions.

Chapter 1: Introduction

1.1 MOTIVATION

The sustainability of human activity is at the forefront in engineering and development. Incorporating sustainable development considerations in geotechnical design and construction is essential to maintaining the viability of Planet Earth for future generations. Population-driven growth places pressure on Earth's resources to meet the demand for energy and materials. At present, fossil fuels are the predominant source of energy for society; producing and combusting these fuels releases carbon dioxide (CO_2), which is a greenhouse gas associated with climate change.

The Intergovernmental Panel on Climate Change (IPCC) (2013) has estimated that cumulative CO_2 emissions from all anthropogenic sources must remain below 1,000 Gt to limit warming to 2 degrees Celsius over the established 1861 to 1880 benchmark. In the IPCC 5th Assessment Report, it is proposed that this amount of cumulative CO_2 emissions be viewed as a carbon budget for limiting human contributions to climate change (IPCC 2013). Therefore, there is a compelling need for methods that account for factors such as energy use, resource consumption and CO_2 emissions associated with human activities, including geotechnical construction.

1.2 CONTRIBUTIONS

In light of the need for reducing resource consumption and quantifying environmental impacts such as energy consumption and CO_2 emissions, this research makes the following contributions to the body of geotechnical engineering knowledge:

1. A concise reference on sustainability and environmental impact assessment via life cycle analysis (LCA) as it relates to geotechnical engineering and ground improvement that provides guidance in how geotechnical practice could make meaningful

advancement toward sustainable development by considering environmental impact in addition to monetary cost and performance criteria when making design decisions;

2. A streamlined LCA methodology for quantifying the energy consumption and CO_2 emissions associated with the construction of geotechnical ground improvement works, known as the Streamlined Energy and Emissions Assessment Model (SEEAM);
3. A framework to account for uncertainty in SEEAM assessments arising from energy and emissions coefficients as well as variable subsurface conditions, including a simple method for comparing the energy and CO_2 emissions associated with different design alternatives;
4. A user friendly engineering tool to facilitate environmental assessments via energy and CO_2 emissions by the geotechnical professional community, called the SEEAM Spreadsheet Calculator.

1.3 DISSERTATION STRUCTURE AND CONTENTS

The chapters of this dissertation consist of a series of paper manuscripts which combine to make the contributions outlined in the previous section. The manuscripts describe various aspects of incorporating streamlined environmental LCA for energy and CO_2 emissions into geotechnical engineering design and construction, focusing on the development and use of the SEEAM for quantifying the embodied energy (defined in Ch. 2) and CO_2 emissions for ground improvement works. Since the chapters of this dissertation are individual paper manuscripts, the last section of each chapter is a stand-alone reference section containing all references cited in that particular chapter. On the title page of each chapter, listed information includes the title and authors of the manuscript, the submission and/or publication information, and a list of relevant accompanying Appendices, which are included at the end of this dissertation. The Appendices contain additional data and analyses that contributed to the development of each chapter (paper manuscript), but could not be included in the manuscript based on submission criteria. Like the dissertation chapters, each Appendix includes its own list of references, as applicable.

The papers that comprise this dissertation may each be read as a stand-alone document; however, they are assembled here in a logical order progressing from review of existing literature and background information (Ch. 2), to basic energy and carbon assessment for construction fuels (Ch. 3), to a presentation of the SEEAM (Ch. 4), and finally to advanced applications of the SEEAM. These include evaluating the influence of different project decisions on total embodied energy and CO_2 emissions for a ground improvement technology (Ch. 5), and accounting for components of uncertainty in the assessment (Chs. 6 – 7). The following paragraphs present an overview of the content of each chapter.

Chapter 2 presents a review of literature focusing on sustainable development, LCA, embodied energy and carbon footprinting in the context of geotechnical ground improvement. The chapter suggests geotechnical engineers can take a leading role for sustainable development by accounting for environmental impacts such as energy consumption and CO_2 emissions along with meeting performance criteria and minimizing monetary cost when making design decisions. The background presented in Ch. 2 lays the groundwork for the SEEAM, which is presented in Ch. 4.

Chapter 3 presents the findings of a fuel cycle analysis (an LCA of fuel) focused on energy and CO_2 emissions for fuels commonly used in geotechnical construction. These include diesel, gasoline, compressed natural gas and grid electricity. By comparing fuels based on a specified quantity of useable energy for construction work, gasoline results in the most CO_2 emissions and grid electricity the least. The chapter contains a geotechnical example where a method for estimating fuel consumption is used with the results from the fuel cycle analysis to estimate the total embodied energy and CO_2 emissions from fuel associated with two deep densification techniques.

Chapter 4 presents the complete SEEAM methodology, which is a streamlined LCA method for quantifying the embodied energy and CO_2 emissions associated with geotechnical ground improvement works. The boundaries for the SEEAM extend from raw material extraction through the completion of construction, including consideration for materials production, materials transportation, site construction operations and waste materials transportation. Chapter 4 also includes a detailed example application of the SEEAM method to a project that involved upgrading levee LPV 111 in New Orleans, LA. Three project alternatives are analyzed deterministically with the SEEAM and compared.

Chapter 5 moves into deeper applications of the SEEAM with the selected design alternative for levee LPV 111, which consisted of supporting an earthen embankment on deep soil mixed elements. This chapter focuses on the deep mixing technology under the assumption that deep mixing has been selected as the most sustainable project alternative. In the context of SEEAM analysis for embodied energy and CO_2 emissions, two pertinent factors in the deep mixing design that can lead to improved sustainability are addressed. These include the selection of binder materials, and the handling of any generated spoils. Discussion also addresses how minimizing environmental impacts such as embodied energy and CO_2 emissions by design can also reap social and economic benefits.

Chapter 6 addresses the fact that the SEEAM methodology presented in Ch. 4 is deterministic; however, in reality the assessment involves uncertainty arising from the embodied energy and CO_2 emissions coefficients, as well as the subsurface conditions. This chapter presents a framework for accounting for uncertainty in SEEAM analyses due to the coefficients and subsurface conditions. The framework was derived by considering rammed aggregate columns extending to bedrock as foundation support for a replacement dormitory on the Virginia Tech campus. The uncertainty framework relies on assumptions regarding the distributions of coefficient values, and utilizes Monte Carlo simulation with the deterministic SEEAM method to generate simulated data sets of possible values of total embodied energy and CO_2 emissions. A simple method for statistically comparing the embodied energy and CO_2 emissions for two geotechnical project alternatives using the Monte Carlo simulated data is also presented. Making statistical comparisons provides useful information for consideration in the overall design decision process, where environmental considerations may be accounted for along with other relevant factors (e.g., cost, final performance, and other site and project-specific constraints). The comparison method is demonstrated using two of the alternatives for levee LPV 111, which are both described in Ch. 4.

Chapter 7 addresses another contributor to uncertainty in the results of SEEAM analyses: haul distances. In this chapter, the SEEAM is used to evaluate the influence of material haul distance on total embodied energy and CO_2 emissions using two case history projects. These include the construction of rammed aggregate columns for foundation support of a replacement dormitory on the Virginia Tech campus, and the installation of deep soil mixing elements to support an earthen embankment for levee LPV 111 in New Orleans, LA. For both projects, the analysis revealed that tripling all as-built material haul distances results in less than a 10% increase in total embodied energy and CO_2 emissions. Recommendations are made for how to handle uncertain material haul distances when conducting an assessment to estimate embodied energy and CO_2 emissions prior to construction, when actual distances are not yet known.

1.4 THE SEEAM SPREADSHEET CALCULATOR

The SEEAM methodology, boundary conditions and considerations for uncertainty in the embodied energy and CO_2 emissions coefficients as described in the chapters of this dissertation were implemented in a user-friendly spreadsheet calculator, called the SEEAM Spreadsheet Calculator. The SEEAM Spreadsheet Calculator enables geotechnical professionals to evaluate the embodied energy and CO_2 emissions for geotechnical project alternatives. By analyzing competing design alternatives, the results may be used to make comparisons of energy and CO_2 emissions performance, or to identify the most significant factors contributing to embodied energy and CO_2 emissions for a given geotechnical alternative. The results from the SEEAM Spreadsheet Calculator may be used by engineers in a comprehensive design decision process that involves the application of appropriate judgement and considers embodied energy, CO_2 emissions, costs, performance and other site and project-specific constraints.

While the underlying SEEAM method has long-term applicability, the energy and CO_2 emissions coefficients used in the calculations are time-dependent and could require future updating. This time dependency results from changes in production processes and technology, as well as the potential for diminishing returns (i.e., as easily accessible raw materials are consumed it takes more energy and resources to obtain needed raw materials). Despite using time-dependent coefficients, the SEEAM Spreadsheet Calculator is a practical and useful tool for geotechnical professionals seeking to quantify the energy and carbon impacts of their designs.

Screen shots from the spreadsheet calculator and a complete user manual are included in the Appendices.

1.5 REFERENCES

IPCC (2013). *Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Chapter 2: Energy and Carbon Assessment of Ground Improvement Works I: Definitions and Background

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Relevant Appendices:

None.

2.1 ABSTRACT

Geotechnical engineers can and should take a leading role in incorporating sustainable development goals into the selection of ground improvement design alternatives and construction methods through quantitative assessment of environmental impacts. Since all valid design alternatives must meet project performance requirements, overall cost and environmental impact become two key factors in the decision process. Although methods of cost estimation are well established within geotechnical engineering, simplified methods for assessing impacts to the environment have remained a largely unfulfilled need. In this paper, life cycle analysis, embodied energy and carbon footprinting are reviewed in the context of geotechnical ground improvement. It is proposed that estimates of life cycle embodied energy and carbon dioxide emissions may be used during the design process by geotechnical engineers to quantify some of the effects of ground improvement on the environment. The life cycle is considered to extend from raw material extraction to the completion of construction. The background presented herein forms the basis for a Streamlined Energy and Emissions Assessment Model (SEEAM), described in a companion paper.

CE Database subject headings: Geotechnical engineering; Sustainable development; Life cycles; Energy; Energy efficiency; Carbon dioxide; Soil stabilization

2.2 INTRODUCTION

Ground improvement is an established and expanding sector of geotechnical engineering, with growth driven by development of sites having challenging subsurface conditions and the need for environmental protection and natural hazard risk mitigation. Currently, geotechnical design decisions are made primarily to minimize monetary cost, while satisfying design and performance criteria (Holt et al. 2010). This approach does not consider both the beneficial and adverse environmental impacts of the construction. Given the increased trend toward using green building methods, formally including environmental considerations has become necessary within the ground improvement and geotechnical engineering design and construction sectors.

Geotechnical work involves large quantities of materials and energy, and therein lie opportunities for meaningful reductions in environmental impact (Abreu et al. 2008; Holt et al. 2010; Jefferis 2008; Simpson and Tatsuoka 2008). According to Fragaszy et al. (2011), geotechnical engineers can and should be actively engaged in developing solutions to reduce energy consumption and degradation of the natural environment. Life Cycle Analysis (LCA) provides the quantitative means through which environmental impacts can be identified and addressed. Unfortunately, potential opportunities are often missed since traditional geotechnical engineering education and practice has been slow to adopt the use of life cycle thinking and quantitative environmental impact assessment methods. Geotechnical engineers must participate in developing sustainable solutions for the future (Mitchell and Kelly 2013).

Essential background information needed for incorporating life cycle thinking and environmental impact assessment into geotechnical ground improvement practice is presented. First, a brief overview is provided of the concepts of sustainability and sustainable development. This paper does not seek to address sustainability in a holistic manner. Rather, it illustrates how for a given set of competing ground improvement alternatives that meet project performance requirements, sustainable development can be advanced by considering environmental impacts in addition to monetary cost in the selection of a final design alternative. Including environmental impact assessment is a practical step that can empower geotechnical engineers with quantitative information for the project planning and decision making process.

The remainder of the discussion focuses on quantifying environmental impacts, with particular emphasis on the means and methods of estimating Embodied Energy (EE) and carbon dioxide (CO_2) emissions through LCA. EE and CO_2 emissions are two measures of global environmental impact that can vary significantly among different means and methods of ground improvement construction in current use. A methodology for quantifying EE and CO_2 emissions for ground improvement works based on the discussion herein is presented in a companion paper (Shillaber et al. 2015).

Since many terms and abbreviations used in this paper may be unfamiliar, a glossary is provided in Table 2.1. Entries are listed in the order in which they appear in the text.

Table 2.1 Glossary of key terms and abbreviations, in order of appearance.

Term (Abbreviation)	Definition
Sustainable/Sustainability	Having the ability to continue indefinitely without depleting resources.
Sustainable Development	The process by which a sustainable state is achieved over time.
Renewable Resources	Resources that can be renewed on a human time scale rather than a geologic time scale.
Non-renewable Resources	Resources that may not be replenished or renewed on a human time scale. They may be renewed over geologic time.
Strong Sustainability	Sustainability model that emphasizes the dependencies among the environmental, social, and economic dimensions of sustainability.
Weak Sustainability	Sustainability model that shows compromise when environment, society, economy are not all considered, but does not show dependencies.
Life Cycle Analysis (LCA)	Method to quantitatively evaluate environmental impacts over the whole life of a product or process.
Life Cycle Carbon Analysis (LCCA)	A LCA that is tailored to consider carbon as the only impact factor.
Life Cycle Energy Analysis (LCEA)	A LCA that is tailored to consider energy as the only impact factor.
Process Analysis	LCA method that traces through the life cycle of a specific product step by step, considering all inputs and outputs.
Input-Output Analysis	LCA method that uses monetary flows between sectors to convert to physical flows.
Hybrid Analysis	LCA method combining the process and input-output approaches to maintain specific product details, but tighten the study boundaries.
Streamlining	Simplifying an LCA by either adjusting the boundary conditions or limiting the impact factors considered.
Embodied Energy (EE)	All energy consumed to bring an item to its current state.
Greenhouse Gas (GHG)	Any gas present in the atmosphere with the ability to absorb infrared radiation from Earth's surface, preventing its escape into outer space.
Carbon Dioxide (CO_2)	A common greenhouse gas in the atmosphere emitted from the combustion of fossil fuels, and the respiration of animals.
Intergovernmental Panel on Climate Change (IPCC)	International body for the assessment of climate change, created in 1988.
Global Warming Potential (GWP)	Numerical value describing the ability of a GHG to absorb infrared radiation relative to CO_2 in a given interval of time.
Carbon Dioxide Equivalents (CO_{2eq})	The amount of GHGs emitted to the atmosphere converted to an equivalent amount of CO_2 via the GWP.
Methane (CH_4)	A common GHG emitted from the decomposition of waste and energy production processes.
Embodied Energy Coefficient (EEC)	Coefficient representing the amount of embodied energy in production of one unit (e.g., kg, L) of a material.
CO_2 Emissions Coefficient (CC)	Coefficient representing the amount of CO_2 emissions in the production of one unit (e.g., kg, L) of a material.
Carbon Critical Design	Design that considers carbon as a key parameter, and a proxy for sustainable development.

2.3 SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

Sustainability and sustainable development are broad concepts that have far reaching implications both for society in general and for geotechnical engineering. By definition, a process or practice is sustainable if it can continue indefinitely without depleting resources or damaging ecosystems (Parkin 2000; Pearce et al. 2012). Sustainability is the ultimate goal, and sustainable development is the process by which sustainability is achieved over time (Parkin 2000). Based on the United Nations World Commission on Environment and Development (WCED), sustainable development is often described as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). To that effect, Pearce et al. (2012) assigned two main goals to sustainable development: 1) enable people to meet essential needs and improve their standard of living; and, 2) ensure that the natural resources and systems on which people depend are maintained and advanced for both current and future use.

The preceding definitions imply that a truly sustainable system operates in an equilibrium state between inputs and outputs, where consumed resources are continually replaced or recreated from renewable inputs. Although almost all resources can be renewed over geologic time, including fossil fuels, the authors define renewable resources as those that are regenerated on a human time scale rather than a geologic time scale, such as timber. According to Odum (1996), the fundamental renewable energy inputs to the Earth are solar energy, deep earth heat energy, and tidal energy. Practically all geotechnical construction processes rely on non-renewable energy and material resources such as petroleum fuels, cement, steel, plastics and other chemicals. By definition these systems are not sustainable, and thus traditional geotechnical construction practices cannot continue indefinitely into the future without depleting resources. Since it typically takes years for new technologies to become established in the civil engineering profession, there should be a sense of urgency to foster improvements in resource use and practice sustainable development.

2.3.1 The Environment and Sustainable Development

A misconception regarding sustainable development is that it is focused purely on conserving the natural environment. In reality, achieving the goal of sustainability requires a balance between three interlinked dimensions: environment, society, and economy (Parkin 2000; Parkin et al. 2003). Emphasizing any one of these dimensions (such as economy via monetary savings) without consideration for the others can lead to unsustainable designs.

Parkin et al. (2003) define two sources of wealth in the world: the natural environment, and the work of human minds and hands. While these are separate sources of wealth, the work of humans cannot happen outside of, or without, the natural environment. This fact agrees with sustainable economic development principles that define the world and its environmental resources as finite, creating a limit to societal and economic growth (Daly 1990; Daly 2005). This concept of dependency on the environment creating a limit to societal and economic growth is known as strong sustainability, which is depicted by the concentric ellipses of Figure 2.1a. In contrast, weak sustainability implies that the three dimensions can exist independently. The pictorial model of weak sustainability (Figure 2.1b) is very useful for clearly illustrating that considering any one or two of the three dimensions (environment/society/economy) alone is a state of compromise rather than sustainability.

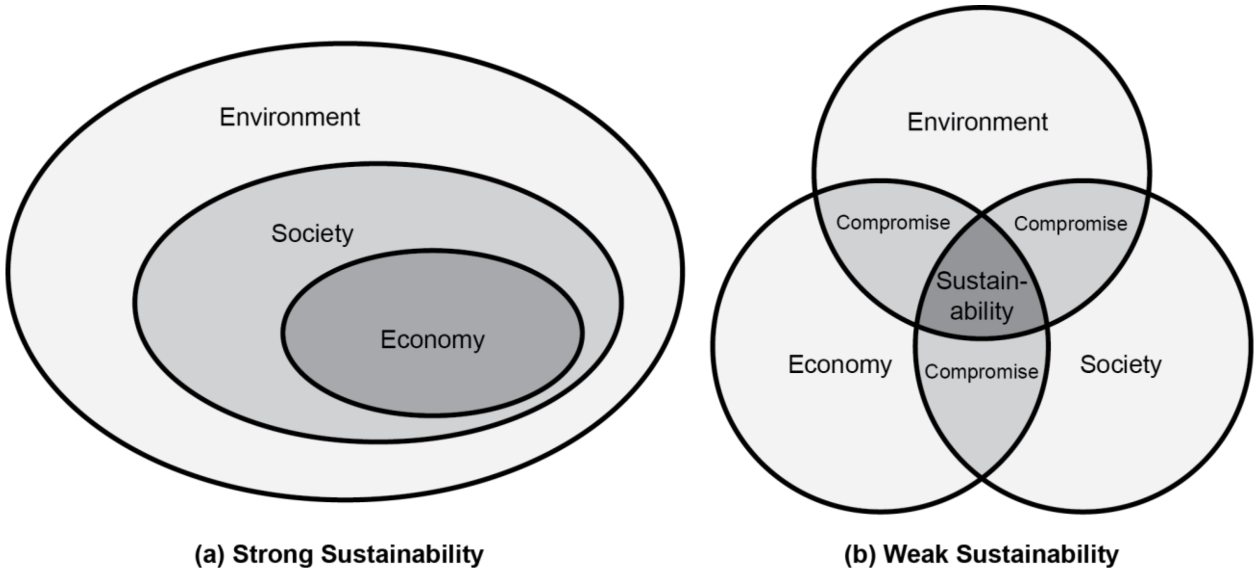

Figure 2.1 Definitions of Sustainability: (a) Strong form, (b) Weak form. Strong sustainability emphasizes that society and economy depend on the environment and their growth is limited by environmental carrying capacity. Weak sustainability places the three dimensions (environment, society, economy) in separate, overlapping realms; compromise exists when two or fewer dimensions are considered.

As a practical analogy of the difference between the weak and strong sustainability models, consider a 100 hectare farm without access to external resources. If the farmer only considered the weak sustainability model, he could envision working the 100 hectares of land in a socially and environmentally responsible manner and producing ever increasing crops and wealth through advances in farming techniques (i.e., with the three dimensions separate as in the weak model, the farmer can envision infinite expansion of the economic dimension and still be sustainable). The reality is that 100 hectares of land has a certain finite crop carrying capacity, which limits the total crop output and wealth the farmer can expect to achieve. Crop production is dependent on the land (the environment), and since the carrying capacity of the land is finite, the amount of land available creates a limit to the amount of wealth that may be generated from harvests (economic growth). This limitation is depicted in the strong sustainability model.

The interlinked and dependent nature of the three dimensions of sustainability means that factors relevant to one dimension can also be important for another. For example, dust control is an important environmental consideration during construction operations that can also benefit both society by reducing dust induced respiratory issues, and economy by reducing clean-up costs or the amount of additional maintenance costs incurred by adjacent facilities due to premature clogging of HVAC filters. In addition, the interlinking between dimensions means that some concerns for global society, such as the consequences of environmental damage due to climate change on the poor, may be accounted for through addressing the related environmental impacts (Murphy 2012). Since there are many social and economic benefits (both present and future) associated with good environmental practices, addressing environmental issues is a very important aspect of sustainable development.

2.3.2 Consideration of Cost, Environmental Impact and Society

Ground improvement design selection is typically based on performance assessment and the associated monetary cost, with much less regard given to environmental impacts or other social concerns (Holt et al. 2010). Final performance requirements established for the project must be met by any relevant design alternative. Therefore, once ground improvement alternatives are identified that will meet the project performance requirements, monetary cost and environmental impacts together remain as key considerations for the geotechnical aspects of sustainable development.

From the previous discussion of sustainability, it might seem that the societal dimension is absent from consideration if geotechnical engineers account for performance, cost and environmental impacts when making final ground improvement design selections. However, aside from the social benefits derived from addressing economic and environmental issues due to the interlinking between the dimensions of sustainability, several social aspects of projects are accounted for in the final performance requirements for the design and construction. These may include aesthetics, user/occupant comfort, community impact, accessibility and site stewardship. These requirements are established in the overall project master plan, and are implemented through the contract documents. Ideally, the planning process should include input from owners, developers, architects, civil engineers (land development, environmental, structural, and geotechnical), project stakeholders and the general public in the development of the final project design and criteria. The public should be involved early in the planning process so that through their participation, social wants, needs and desires may be accounted for in the project design and specifications (Pantelidou et al. 2012).

During project planning, some societal (and environmental) impacts falling under the site stewardship category that should be addressed in project specifications include noise, wastewater emissions, traffic interruption (vehicular and pedestrian), dust control, and potential spoil migration onto roads and pedestrian walkways that would require removal by the contractor or local municipality. In addition, specifications regarding site conditions and stewardship should emphasize protecting the health and safety of workers. All of these factors are important for social sustainability and relevant to geotechnical construction activities. Therefore, even if they are not included in project specifications and criteria generated during project planning, conscientious action on the part of geotechnical designers and contractors in addressing these site stewardship factors is one way geotechnical design and construction can immediately contribute to social sustainability.

The preceding discussion is not an exhaustive consideration of the social dimension of sustainability, as there are many other important and complex issues (such as equity and social justice). However, it does illustrate that some aspects of the social component of sustainability are addressed when the geotechnical design and construction meets or exceeds the final performance and site stewardship criteria of the project, particularly for well planned projects. Many of the listed social factors related to site stewardship are also a measure of local environmental impacts because of the interlinking between the environmental, social and economic dimensions of sustainability. Contractors are often working hard to address these issues as part of their best practices. Therefore, since methods of achieving performance requirements and estimating monetary cost are already well established and utilized in geotechnical engineering, global environmental impacts (e.g., resource consumption and potential climate change impact) remain a key component of sustainability that is not currently well addressed or considered in the geotechnical decision making process. The following sections explain how LCA may be used to quantify environmental impacts, and how LCA may be streamlined for quantifying the EE and CO_2 emissions attributable to ground improvement projects.

2.4 LIFE CYCLE ANALYSIS

LCA is a quantitative method to evaluate the environmental impacts of a product or process over its whole life, from cradle to grave (EPA 2006; Hammond and Jones 2008a) by considering factors such as raw material extraction, processing, use, recycling, reuse, and ultimately final disposal (Menzies et al. 2007). For example, the whole life of a plastic bottle includes extraction and processing of the petroleum products to make the plastic resin, manufacturing the bottle from resin, filling it and using it to carry a liquid product, and then at the conclusion of its useful life either recycling the bottle into another plastic product or disposing it via landfilling or incineration.

A conventional LCA considers all types of environmental impacts, but the analysis may be simplified by tailoring it to examine specific impact factors alone. For example, a life cycle energy analysis (LCEA) considers energy use as the only environmental impact factor, and a life cycle carbon analysis (LCCA) considers carbon as the only environmental impact factor (Menzies et al.

2007). These types of LCA simplifications are often called LCA streamlining (Todd and Curran 1999).

Published international standards for the phases of a LCA and the presentation of the results include ISO 14040 – 14044, produced between 1997 and 2006 (Hammond and Jones 2008a). Based on the ISO 14040 and 14044 standards (ISO 2006a; ISO 2006b) and a U.S. Environmental Protection Agency (2006) report, a LCA involves four major components or phases: 1) goal definition and scoping; 2) inventory analysis; 3) impact assessment; and 4) interpretation.

Goal definition and scoping shapes all remaining phases, as it involves defining the subject product or process and determining the study boundaries. Study boundaries must be carefully selected since they have a significant impact on the outcome. For example, a LCA of timber piles that ignored the production of the fuel used by the saws and logging equipment to harvest the timber for the pile may have noticeably different results from a LCA where these upstream fuel impacts are included. For instance, assuming CO_2 emissions as an environmental impact factor of concern in the LCA, producing 1 L of diesel fuel for use by the logging equipment results in 0.55 kg of CO_2 emissions (Shillaber et al. 2014). These upstream emissions are about 17% of total CO_2 emissions from production and combustion of the diesel fuel (Shillaber et al. 2014). Therefore, LCA boundaries for the timber pile that ignore fuel production can lead to significantly different results for this impact factor.

The primary work of the LCA is conducted in the inventory analysis phase, where the material, energy, water use, and environmental releases are identified and quantified. The impact assessment involves determining the human and ecological impacts of the material, energy, water use, and environmental releases as determined by the inventory analysis. The interpretation phase involves evaluating the assembled information, and then using it to select preferred methods, products, processes or designs. Interpretation can also reveal parts of the life cycle where there is room for improvement to bring about reduced impact (EPA 2006; ISO 2006a; ISO 2006b).

LCAs may be conducted following one of three major analysis approaches: process, input/output, or hybrid. Process analysis is specific and detailed, beginning with the final product and tracing back through its life cycle to raw material extraction, considering all impacts in each step (Menzies et al. 2007; Williams et al. 2012). Process LCA is like creating a 'genealogy' of the product of interest, tracing back through every step that has contributed to its existence. Input/output analysis is much less specific, using monetary flows between sectors to convert to physical flows (Carnegie Mellon University Green Design Institute 2008; Menzies et al. 2007). This approach works better for comparing sectors (such as steel manufacturing) rather than individual products (such as steel pipe piles). The Carnegie Mellon University Green Design Institute (2008) has developed an online tool for conducting input/output LCAs, which allows for quick determination of the environmental impacts associated with a level of economic activity in a sector. Compared to process analysis, input/output analysis requires less time to conduct, but loses specificity (Williams et al. 2012).

Hybrid analysis seeks to combine the specific product information from the process analysis with the interactions between sectors and tight boundary conditions of the input/output analysis (Menzies et al. 2007). Most streamlined LCAs focusing on specific impact factors use some kind of hybrid approach in order to utilize the benefits from both the process and input/output methods. A hybrid analysis can be particularly helpful by using the input/output method to account for upstream impacts where specific process details are not necessarily known (Williams et al. 2012), while using process analysis to account for all steps in the production of the product under consideration. When using the hybrid approach, care must be taken to ensure the same inputs are not accounted for in both the process and input/output portions of the analysis. This double counting would result in an erroneous assessment.

The benefits of performing a LCA are that it allows for selection of environmentally benign products or processes and avoids shifting environmental problems from one place to another by considering the whole life cycle instead of only one part of it (EPA 2006). However, LCA does not determine what product or process actually works best or is most cost effective (EPA 2006). Moreover, even for relatively simple processes, a thorough process based LCA can be complex and the time required to complete it can be substantial.

While modern databases and LCA software can reduce the time and effort required to conduct a LCA (Inui et al. 2011), it can still take experienced LCA practitioners 6 to 10 days to complete a simple screening LCA for manufactured products using existing database information, and 75 to 180 days or more to complete an LCA for external publication according to the ISO standards (PRe Consultants 2010). While it may be justified to take the time to complete full process based LCAs for manufacturing processes or manufactured products, this level of time and resource commitment is not practical for geotechnical engineers seeking to determine the environmental impacts associated with their designs.

Therefore, it makes sense for geotechnical engineers to utilize LCA streamlining when conducting environmental impact assessments of their designs, which can be accomplished through simplifying the analysis by considering specific environmental impact factors, as previously mentioned. The following section discusses energy and CO_2 emissions, which are demonstrated to be useful impact factors to consider in streamlined LCAs of geotechnical works.

2.5 ENERGY AND CO_2 EMISSIONS

Developing and implementing new energy technologies for supply and end use is a key challenge for the next three decades (National Academies 2009). Simpson and Tatsuoka (2008) also emphasize the emerging importance of energy conservation and its significance to geotechnical engineering; geotechnical construction must become more energy efficient in material manufacturing and use, transportation and site work. Most energy production in the U.S. involves consumption of fossil fuels and other non-renewable raw materials from the environment, and also releases CO_2 and other pollutants into the environment. In the strong sustainability model (Figure 2.1a), society and the economy cannot exist outside of the environment. Since the predominant current methods of energy production cause significant adverse environmental impacts through non-renewable resource extraction, fuel combustion and emissions, energy consumption is an important indicator of overall sustainability. Since all geotechnical construction processes consume energy, minimizing the energy use and associated emissions is an excellent approach in the near term to reduce non-renewable resource consumption and advance the goals of sustainable development in geotechnical engineering. To implement this approach, the impacts of energy consumption throughout the life cycle of geotechnical works must be determined through a streamlined LCA.

Major categories of energy involved in the life cycle stages of civil infrastructure projects include (Cole and Kernan 1996; Dixit et al. 2010):

- Initial Energy - Energy associated with materials acquisition and initial construction.
- Operational Energy - Energy associated with operating the building or civil infrastructure, including heating, cooling, and lighting.

- Recurring Energy - Energy associated with materials and construction for refurbishment and ongoing maintenance.
- Demolition Energy - Energy consumed to demolish and dispose of the structure at the end of its useful life.

Not all of these energy categories are relevant for analyses of geotechnical works. Inui et al. (2011) describe the life cycle energy consumption of a foundation as having four stages: 1) extraction of raw materials; 2) processing and manufacture of composite items and building materials; 3) transportation between and within sites and processes; and, 4) construction. These four stages are all part of the initial energy category in the life cycle of infrastructure. Therefore, establishing a boundary at the completion of construction for a streamlined LCA of geotechnical works makes sense because most often foundations and ground improvement do not require energy to operate and do not need refurbishment or remediation during the lifetime of the structure.

Quantifying energy and CO_2 emissions is a skill in which Simpson and Tatsuoka (2008) predict geotechnical engineers will need to be proficient as sustainability considerations mature. The following subsections discuss definitions and current methods for quantifying energy and CO_2 emissions due to construction, laying groundwork for the methodology presented in a companion paper (Shillaber et al. 2015).

2.5.1 Embodied Energy

EE is the energy associated with the non-operational stages of the life cycle of a building or civil infrastructure. There are varying definitions of EE, which differ primarily based on the boundary conditions placed on the analysis for a given project. Hammond and Jones (2008a) define EE as the energy required to produce and supply materials to the construction site. Dixit et al. (2012) describe EE in terms of the life cycle of a building, accounting for production, use, and demolition. Rennie (2011) refers to EE as the total primary energy (defined later) consumed during the lifetime of a product.

In simplest terms, EE is the total energy required to bring an item to its present state (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011). This definition implies that the EE in a product is the sum of the energy consumed to produce required inputs and the energy consumed by the production process. In terms of the four major categories of life cycle energy for civil infrastructure described previously, this definition of EE includes initial energy and recurring energy. These energy categories are associated with bringing the building or civil infrastructure to a new or updated present state. The authors believe this definition is most useful because it can be applied at almost any scale, whether considering a single item such as a steel beam, a building, or a major civil infrastructure project.

2.5.2 CO_2 Emissions and Carbon Footprint

Much of the climate change discussion has centered on emissions of Greenhouse Gases (GHGs) such as CO_2, which are partial contributors. GHGs are those gases present in the atmosphere with the ability to absorb infrared radiation from the earth's surface (EPA 2012), preventing its escape into outer space. The Intergovernmental Panel on Climate Change (IPCC) (2013) has assigned GHGs a Global Warming Potential (GWP) value based on their ability to absorb heat in an interval of time, relative to the ability of CO_2; the most commonly considered time interval for GWP values is 100 years. GWP values are updated in Assessment Reports issued periodically by the IPCC. Emissions of GHGs may be presented in the form of an equivalent quantity of carbon dioxide (CO_{2eq}) by multiplying the quantity of a GHG emitted by its GWP (IPCC 2013). Therefore, the total quantity of CO_{2eq} from a GHG emissions assessment will always be greater than the quantity of CO_2 from a CO_2 emissions assessment of the same product or process.

It is common to encounter the term 'carbon footprint,' as a descriptor relating to a set quantity of carbon emissions, but a specific definition of its meaning is elusive. There are numerous definitions in both peer reviewed and non-peer reviewed literature (Wright et al. 2011). In light of this, Wright et al. (2011) compiled a specific definition of 'carbon footprint,' defining it as all CO_2 and methane (CH_4) emissions from the subject of interest, presented in the form of CO_{2eq} by means of the GWP. They explain that limiting the scope to these two common (and easily measurable) GHGs helps ease the burden of analysis without sacrificing much accuracy.

However, the authors believe geotechnical engineers should consider emissions of CO_2 alone in carbon footprint analyses instead of CO_{2eq}. This removes the complications caused by changes in GWP values over time, the ambiguity regarding the quantity of non-CO_2 GHGs contributing to the CO_{2eq} value, and the uncertainty in the computed CO_{2eq} from the GWP. For example, the 100 year GWP of CH_4 is listed as 28 with an uncertainty of +/-40% in the IPCC Fifth Assessment Report (2013). In the IPCC Fourth Assessment Report, the 100 year GWP of CH_4 is listed as 25 (IPCC 2007). Therefore, depending on the date of the assessment and the GWP value used, a carbon footprint assessment that included CH_4 and presented the results in the form of CO_{2eq} will have different results for the same amount of emissions. The same is true of other GHGs. Therefore, unless analyses use the same GWP values and consider the same GHGs, the CO_{2eq} values cannot be compared. In addition, based on a CO_{2eq} value alone, there is no way to discern which GHGs it represents, or how significantly they contribute to the total. Finally, the uncertainty associated with the GWP values implies there is significant uncertainty in the determination of CO_{2eq}, even when comparing analyses using the same GWP values and GHGs. Therefore, limiting the scope of carbon footprint assessments in geotechnical engineering to CO_2 alone both simplifies the analysis and greatly increases its transparency by eliminating the issues with GWP and conversions to CO_{2eq}.

2.5.3 Classification of Energy and CO_2 Emissions

In terms of building and civil infrastructure construction, EE and CO_2 emissions may be classified as either indirect or direct. EE may further be classified as either primary or delivered. Since these terms are widely used, they are defined in Table 2.2. Their relationships for energy are also illustrated in Figure 2.2. In this discussion, total EE is the sum of direct and indirect energy. Likewise, total CO_2 emissions are the sum of direct and indirect CO_2 emissions.

Table 2.2 Summary of energy and carbon categories and definitions used in embodied energy and carbon assessment of construction projects.

Energy & Carbon Component	Definition	References
Indirect Energy & CO_2	Energy consumed and CO_2 emissions generated outside the production process to create necessary inputs (materials, fuel, and electricity).	(Dixit et al. 2010; Dixit et al. 2012; Williams et al. 2012)
Direct Energy & CO_2	Energy consumed and CO_2 emissions generated during the production process on-site.	(Dixit et al. 2010; Dixit et al. 2012; Williams et al. 2012)
Primary Energy	All energy derived from nature, including losses in production.	(Dixit et al. 2010; Yohanis and Norton 2002)
Delivered Energy	Energy embodied in materials delivered to the site alone, ignoring losses in production of the delivered materials.	(Dixit et al. 2010; Yohanis and Norton 2002)
Total Embodied Energy	The sum of the direct energy and indirect energy.	----
Total CO_2 Emissions	The sum of the direct and indirect CO_2 emissions	----

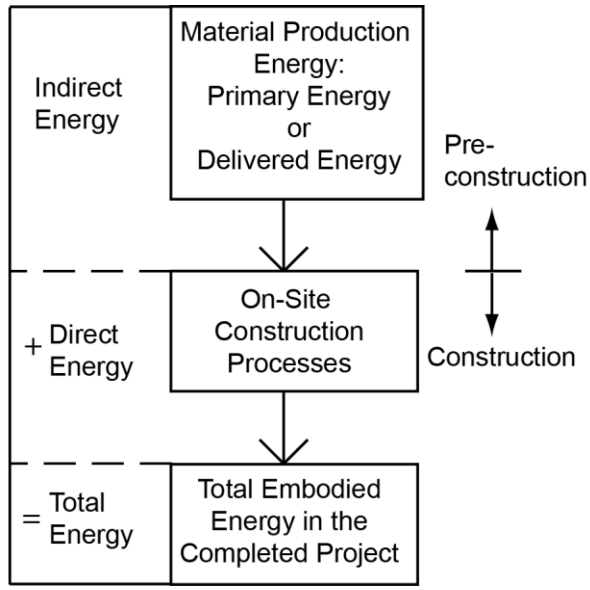

Figure 2.2 Components of embodied energy for construction projects.

2.5.4 Determining Embodied Energy and CO_2 Emissions of Construction

2.5.4.1 Embodied Energy

EE is determined by conducting a LCEA for the product of interest. In the case of construction, the finished product is often complex, involving many input materials from different upstream sources. For such cases, the LCEA can be simplified by utilizing an Embodied Energy Coefficient (EEC) for each individual material. The EEC represents the amount of EE in the production of a material from cradle to factory gate, on a unit basis, such as MJ/kg or MJ/L (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011).

EECs can be used to determine the total EE of the materials in a completed civil infrastructure project by Eq. 1 (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011):

$$EE = \sum_{i=1}^{n} Q_i * EEC_i, \quad (1)$$

where: n = number of materials, Q_i = quantity of the i^{th} material used, in mass or volume units, and EEC_i = the EEC for the i^{th} material.

It should be noted that when performing an analysis using an EEC, the specific details of the exact material source and production process are lost in favor of a typical or representative average value. This provides significant savings of time and resources for conducting the analysis, but it does not constitute a full process LCEA. For more exact results, a complete process LCEA of the product, accounting for the specific material source(s) and manufacturing process(es) would need to be conducted. However, from a practical standpoint, it would be very difficult to perform a complete process LCEA for each input material or component because manufacturers are reluctant to divulge potentially proprietary information.

2.5.4.2 CO_2 Emissions

Due to its significance as a GHG, there are many published specifications and criteria for conducting assessments of CO_2 and other GHG emissions. Relevant standards for products include the GHG Protocol Product Standard (2012), and ISO 14067 (2013). While the standards do not require the inclusion of all indirect emissions in the assessment, Williams et al. (2012) suggest that all direct and indirect emissions should be included in carbon footprint analyses for accuracy. Although ISO 14067 (2013) largely mirrors the requirements of the GHG Protocol Product Standard (2012), the GHG Protocol provides greater detail and guidance in how to conduct assessments of GHG emissions.

For complex products such as civil infrastructure and geotechnical works, the standards permit the use of emissions coefficients for GHGs, utilized in the same way as the EECs. For CO_2, the CO_2 Coefficients (CCs) are obtained from a cradle to gate LCCA of a material, and are subject to the same advantages and limitations of EECs discussed previously.

2.5.4.3 Sources of EECs and CCs, their Uncertainty, and the Relationship between Embodied Energy and CO_2 Emissions

EECs and CCs can be obtained from life cycle energy and CO_2 analyses published in peer reviewed articles, lab and field measurements, or published databases (Menzies et al. 2007). One of the largest databases available for construction materials is the Inventory of Carbon and Energy (ICE) version 2.0, developed by Hammond and Jones (2011b) for construction materials in the U.K.

The ICE version 2.0 database (Hammond and Jones 2011b) presents EECs based on as many available studies for each material as possible. The database includes minimum, maximum, average, and standard deviation of EECs for each material, giving an indication of the spread in the available data from published sources. As an example, the minimum, maximum and average EECs from the ICE version 2.0 database (Hammond and Jones 2011b) for general steel, general cement and general aggregate are shown in Figure 2.3. The plot in Figure 2.3 illustrates that there are significant differences in the EE of different construction materials, and that EECs for a given material from different studies vary significantly, as indicated by the spread between the minimum and maximum values for each.

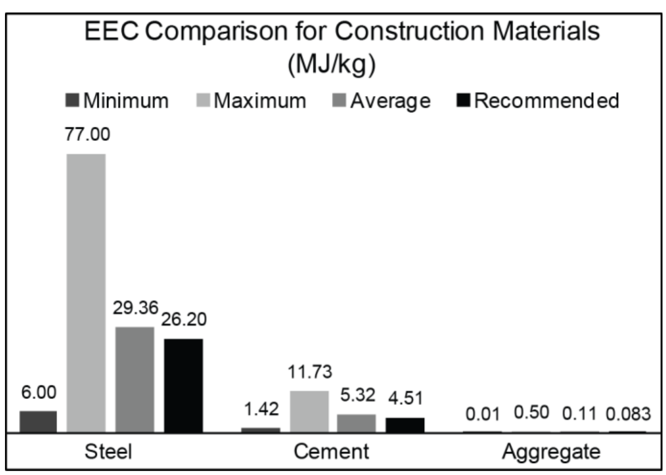

Figure 2.3 Variation in embodied energy for materials among studies included in the ICE Version 2 database (data from Hammond and Jones 2011b).

The ICE database also includes a recommended EEC for each material in the U.K. based on the available data and information. These recommended EECs may not agree with the average from the input data, because additional factors make some input data more relevant (Hammond and Jones 2011a). For example, the general average EE for cement does not account for differences in cement type (I, II, etc.), or replacement additives such as coal fly ash. The ICE database breaks down recommended EECs based on some of these more specific factors. The recommended EECs from the ICE database for general steel (based on world average recycled content), general cement and general aggregate are shown in Figure 2.3, and are lower than the statistical average EEC for the materials.

Another factor contributing to the range in EE observed in the ICE database for a product or material is that the published EE varies between source studies, sometimes significantly. Dixit et al. (2010) discuss ten reasons for these variations. Of these, the authors believe the biggest three factors are: 1) boundary conditions placed on the study, 2) varying process efficiency, and 3) the type of energy considered (primary versus delivered).

Defining the boundaries can have a significant impact on the resulting EE values by eliminating some upstream processes from consideration (Dixit et al. 2010). Therefore, it is important when comparing studies and EECs for a product or material to ensure that the same boundary conditions are used. Otherwise, the comparison is not “apples to apples,” and it loses relevance.

Different process efficiencies and methods can also have a significant impact on EE values for the same material in different studies (Buchanan and Honey 1993). This influence is closely linked to the age of the EE data, as processes and production using more modern and state-of-the-art technologies are often more efficient than older techniques to produce the same products and materials. For example, increases in vehicular fuel economy due to technological advances over the last 20 years mean that moving the same materials or people the same distance results in less fuel consumption and therefore less EE (and CO_2 emissions) today than it did 20 years ago. Another significant contributor to differences in EE is whether the study considered primary energy or delivered energy (Yohanis and Norton 2002). By definition, delivered energy establishes a boundary condition that eliminates upstream losses from consideration, and will result in lower EE than a primary energy assessment.

Energy is often at the foundation of CO_2 emissions assessments. CO_2 emissions are approximately proportional to EE, particularly when energy is supplied from the combustion of fossil fuels, where CO_2 emissions are generated as a product of the combustion reaction. As such, carbon analyses often rely on the predominant source of energy (e.g., coal, oil, gas, nuclear), converting energy units into a mass of CO_2 emissions (Menzies et al. 2007). Such an approach was used by Hammond and Jones (2008b; 2011a) to develop the CCs incorporated into the ICE database; the typical fuel mixes from the industries of interest were converted to CO_2 emissions. This method does not necessarily provide exact values of CO_2 generation for the production of a material by a specific method or plant, but it does provide information regarding industry average emissions where a certain fuel source is utilized. Some discrepancy in the relationship between EE and CO_2 emissions arises when the production process chemically releases CO_2 in addition to the emissions due to energy production and consumption, such as for materials like cement (Inui et al. 2011).

Hammond and Jones (2011a) indicate that for international use, the EE values in the ICE database are more reliable than the CO_2 emission values. This is because the amount of primary energy required to produce a material from cradle to gate is largely fixed by the physics of the production process. In contrast, the fuel and electricity sources providing the energy can be very different from nation to nation than they are in the U.K., which forms the basis for the ICE database. The difference in fuel and energy sources can result in significant variation in CO_2 emissions between regions. For example, a steel mill in the Midwestern U.S. may consume electricity generated by a coal fired power plant, whereas a mill using the same production process in upstate New York may consume electricity generated by a hydroelectric power plant. Based on the differing sources of electricity, there will be fewer CO_2 emissions associated with steel produced at the New York mill, but it will have the same amount of EE. This emphasizes the importance of having relevant local data informing the selection of EECs and CCs whenever possible, in order to ensure the accuracy of energy and CO_2 emissions analyses when such coefficients are used.

2.5.5 Carbon Critical Design

The term Carbon Critical Design is used when carbon is used as a design parameter and is considered a proxy for sustainable development (Clarke 2010). It has the advantage of narrowing the focus to one impact factor, which is a general indicator of the consumption of non-renewable fuels and materials in addition to the potential for climate change. However, a major drawback to using carbon as a proxy for sustainable development is that a single impact factor, taken alone, does not account directly for other potential societal, economic or environmental impacts (Jefferson et al. 2010), which could be of greater significance. Therefore, while carbon may be an important factor to consider in design, decisions should not be made at the exclusion of other important considerations for sustainable development, such as cost and performance. Additionally, continued growth of renewable energy technologies (wind, solar, tidal, geothermal, hydroelectric) can lead to reduced CO_2 emissions, but energy consumption could remain high.

Based on the preceding facts regarding EE and CO_2 emissions, the authors believe it makes sense to use both EE and CO_2 emissions as global impact factors in life cycle environmental impact assessments for ground improvement practice.

2.6 IMPLICATIONS FOR GROUND IMPROVEMENT PRACTICE

Since a full LCEA of civil infrastructure considers its whole life, initial, operational, recurring and demolition energy are all included. As the operational efficiency improves, the initial EE becomes a more significant component of total life cycle energy use (Vukotic et al. 2010). This fact underscores the importance of determining the initial EE of the project, and the geotechnical engineering input necessary for a more complete accounting.

The authors agree with Spaulding et al. (2008) and Egan and Slocombe (2010) that ground improvement techniques can be a more sustainable geotechnical construction alternative relative to some more traditional foundation systems because they have the potential to reduce construction time, material use, fuel consumption, and labor. These four factors are directly related to the environmental impact and/or the cost of the geotechnical design and construction.

For example, a case study by Egan and Slocombe (2010) compared deep dynamic compaction and vibro stone columns as alternatives to conventional piling. For the project requirements and subsurface conditions, they showed that the ground improvement techniques produce less GHG emissions than piling. Egan and Slocombe (2010) concluded that one of the primary ways to lower GHG emissions for ground improvement is to reduce, or eliminate the use of concrete and steel. This finding agrees with other studies that show building materials are the largest contributor to the EE in civil construction projects (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011; Vukotic et al. 2010). The sizeable amount of EE in cement and steel is also illustrated by the relatively large EECs for these materials in the ICE database as compared to aggregate (Figure 2.3). Therefore, material selection and use is an important consideration that should be accounted for at the design stage when seeking to balance performance and constructability with other sustainability criteria.

Specifications can also have an impact on whether ground improvement techniques can be utilized, and what energy and emissions reduction benefits can be realized from them. For example, Jefferson et al. (2010) point out that with regard to vibro stone columns, the aggregate source and transport distance can make a significant difference in the energy and emissions of the project. Performance based specifications are better than prescriptive specifications because they provide the flexibility to use local materials and better select for overall energy efficiency (Jefferson et al. 2010).

For example, for a site neighboring a quarry, it may be more energy, emissions and resource intensive to use a specified recycled aggregate if it can only be sourced from a comparatively long distance away and must be transported to the site. In such instances, a prescriptive specification calling for recycled aggregate could result in more energy use and emissions than a performance based specification calling for a certain aggregate quality, and a demonstration that the material and/or ground improvement technique utilized minimizes energy use and other environmental impacts.

2.7 SUMMARY AND CONCLUSION

There is a recognized need for improving geotechnical construction materials and practices as a means to minimize energy consumption and carbon dioxide (CO_2) emissions, thereby improving the sustainability of the natural systems on which society depends. The traditional definition of sustainable development involves an equitable balance of environmental, societal and economic considerations.

For geotechnical ground improvement projects, considering both the economic cost and environmental impacts when deciding between design alternatives that meet performance criteria can lead to more sustainable projects. To that end, the authors propose that life cycle embodied energy (EE) and CO_2 emissions are two relevant factors for quantifying the global environmental impact of ground improvement in a simple and transparent manner. The life cycle can be considered to extend from raw material extraction to the completion of construction.

Making ground improvement and other geotechnical design decisions that take into account the life cycle environmental impacts of EE and CO_2 emissions in addition to monetary cost and final performance requirements can advance the geotechnical profession in achieving the goals of sustainable development. In a companion paper (Shillaber et al. 2015), a Streamlined Energy and Emissions Assessment Model (SEEAM) is presented for quantifying the EE and CO_2 emissions associated with ground improvement projects, and its application is illustrated by an example.

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Chapter 3: Assessing Environmental Impacts in Geotechnical Construction: Insights from the Fuel Cycle

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Relevant Appendices:

Appendix C: Fuel Cycle Analysis using GREET 1, Version 2012 rev.2

Appendix D: Fuel Cycle Supporting Calculations

3.1 ABSTRACT

Historically, geotechnical practice has focused on maximizing design performance while minimizing monetary costs. This approach does not always include consideration of potential adverse environmental impacts. Concern within developed nations regarding the sustainability of human activities in the long term has given rise to the need to assess and reduce the environmental impacts associated with geotechnical construction. Current methods of construction involve consumption of a large amount of energy, often obtained from fossil fuels or electricity. Energy from these sources is directly associated with environmental impacts through both the extraction and supply of the fuels, and the emissions generated when they are burned to produce energy. For a complete representation of the environmental impact due to energy consumption in geotechnical construction, it is necessary to consider the life cycle of the fuel consumed and not simply the emissions generated on-site. This paper presents the findings of a fuel cycle analysis for fuels commonly used in geotechnical construction, demonstrating the impacts of fuel life cycle energy and emissions. The results are applied in an example comparing two deep densification alternatives to illustrate the impact of equipment fuel consumed to densify 25,000 m^3 of loose sand.

3.2 INTRODUCTION

A key component of geotechnical construction is the operation of vehicles and equipment to perform required earthworks. At present, all vehicles and equipment derive the energy needed to do work either wholly or predominantly from a fossil fuel source, which has accompanying environmental effects. In order to understand the overall environmental impacts of construction operations, it is necessary to quantify the impacts associated with the fuel consumed to do the work. The goals of this paper are to quantify the environmental impacts of fuel consumption in geotechnical construction and to illustrate by example how they could become factors in the selection of a ground improvement technology.

One established method for examining environmental impact is through a Life Cycle Analysis (LCA) of the product or process of interest (EPA 2006). A conventional LCA investigates all environmental impacts, making it highly detailed and cumbersome to perform. As such, a process called "streamlining" may be used to simplify the LCA to consider specific impact factors (Todd and Curran 1999). Key environmental impact factors relevant for a streamlined LCA of geotechnical works include: 1) greenhouse gas emissions, and 2) embodied energy.

Greenhouse gases (GHGs) are those gases present in the atmosphere having the ability to absorb infrared radiation, thus trapping heat, which is believed to contribute to climate change (EPA 2012). Carbon dioxide (CO_2) is the primary human generated GHG. It is generated from fossil fuel combustion (such as in mechanical engines and electric power plants), land use changes, and many industrial and agricultural processes (EPA 2012). Due to its prevalence as a combustion product, CO_2 is the reference GHG and is assigned a Global Warming Potential (GWP) of unity. The GWP is dimensionless and compares the ability of different GHGs to absorb infrared radiation over 100 years (EPA 2012). All GHGs are typically related back to a quantity of CO_2 in the form of a carbon dioxide equivalent (CO_{2eq}) value, determined by multiplying the GWP for a GHG by the quantity emitted (EPA 2012).

Emissions from the production and combustion of fuels for equipment and vehicle engines include CO_2 and other GHGs such as nitrous oxide (N_2O) and methane (CH_4). Generation of N_2O and CH_4 from combustion is dependent upon the catalytic engine exhaust technology used, making it difficult to quantify. In addition, based on generic emissions coefficients for construction equipment (EPA 2013a) and the GWP for these gases (EPA 2013b), on-site combustion emissions of CO_{2eq} from N_2O and CH_4 are only about 0.9% of the total CO_2 emitted. Therefore, this analysis considers only direct CO_2 emissions rather than total GHG emissions in the form of CO_{2eq}.

Embodied energy (EE) is defined as the amount of energy required to bring an item to its present state, which is typically determined through an LCA method (Chau et al. 2012). EE coefficients define the amount of EE per unit mass or volume of a material. They can be used to compute the total EE in a geotechnical construction project by multiplying each material's EE coefficient by the quantity of material used, and summing the resulting EE for all materials (Chau et al. 2012; Inui et al. 2011).

The EE of fuel is determined by:

$$Fuel\ EE = (Q_F)(C_{EE}), \tag{3.1}$$

where Q_F is the quantity of fuel and C_{EE} is the EE coefficient. Likewise, the total CO_2 emissions for fuel are given by:

$$Fuel\ CO_2 = (Q_F)\left(C_{CO_2}\right), \tag{3.2}$$

where C_{CO2} is the total CO_2 emissions coefficient. These equations are applied in this paper in a geotechnical densification example to illustrate the EE and CO_2 impact associated with fuel consumption.

3.3 FUEL CYCLE AND FUEL CYCLE ANALYSIS

Fuel is consumed in construction to provide the energy needed for equipment operations and vehicular transport of materials and wastes. It is important to consider that while fuel is an energy source for machines performing construction work, it is also an input material to site operations that requires energy and CO_2 emissions to produce. A fuel cycle analysis is a LCA of the fuel, including its impacts from raw material extraction, transportation and storage, fuel production (refining), storage and distribution, and combustion for machine or vehicle operations (Wang and Huang 1999). As an LCA, a full fuel cycle analysis considers all environmental impacts. However, the analysis presented in this paper is streamlined to consider only energy and CO_2.

The fuel cycle relevant to geotechnical construction has two major stages: upstream impacts (from fuel production) and on-site impacts from combustion. It should be noted that the environmental impacts from energy and emissions associated with the fuel cycle do not encompass all environmental impacts due to construction operations.

3.4 IMPACTS OF FUEL CONSUMPTION

3.4.1 Upstream Fuel Impacts

Determining the upstream energy and CO_2 impacts of the fuel requires a cradle to gate LCA, which may be accomplished with methods such as the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model, developed by Argonne National Laboratory (2012). The GREET Model was developed to perform fuel cycle analyses for U.S. transportation fuels such as diesel and gasoline, which are also common construction equipment fuels. The model includes many built-in assumptions and standard values for production methods, and uses 2010 as the base year for analysis. Analyses may be carried out to make projections for future and past dates. The analysis of fuel production presented in this paper was conducted using GREET 1, Version 2012 rev. 2 software (Argonne National Laboratory 2012).

The GREET model was run for the base year of 2010 only, using all standard and default assumptions and values for the input. The fuels considered include diesel, gasoline, compressed natural gas (CNG), and electricity. GREET has the ability to consider different impacts from electricity based on the mix of electrical generation methods; e.g., fossil fuel, nuclear, hydro. In this analysis, the U.S. average generation mix was used. However, electricity generation methods vary regionally, and this can result in significantly different EE and CO_2 emissions. Accordingly, it is important that the appropriate mix be selected from among those available in the GREET model.

Results of the GREET analysis for the energy consumed to produce a unit of each fuel are included in the first line of Table 3.1. The amount of CO_2 emitted to produce a unit of each fuel is shown on the first line in Table 3.2.

3.4.2 On-Site Fuel Combustion Impacts

The amount of emissions associated with the on-site combustion of fuel may be determined by multiplying published CO_2 emission coefficients for combustion by the quantity of fuel consumed. CO_2 emissions coefficients describe the amount of emissions per unit of fuel combusted and are available from the U.S. Energy Information Administration (2013) for various fuel types. Relevant combustion CO_2 emissions coefficients are shown in Table 3.2.

Table 3.1 Embodied energy and energy content of fuel by fuel type.

	Diesel (MJ/L)	Gasoline (MJ/L)	CNG (MJ/kg)	Electricity (MJ/kWh)
Embodied Energy[a]	7.166	7.302	8.319	5.136
Energy Content[b]	35.801	32.356	47.143	3.600
Engine Efficiency[c, d]	30% - 43%	20% - 30%	20% - 30%	85% - 95%
Useable Energy[e]	13.067	8.089	11.786	3.240

a. Values from GREET 1 version 2012 rev. 2 (Argonne National Laboratory 2012).
b. Lower Heating Value (LHV) for combustion fuels, from Alternative Fuels Data Center (2013), converted to appropriate units.
c. Efficiency values from Heywood (1988) for diesel and gasoline; Burt et al. (2006) for electricity.
d. CNG Efficiency assumed equal to gasoline for spark ignition (EPA 2010).
e. Useable energy = (Energy Content)x(Engine Efficiency), where typical engine efficiency is assumed at the middle of the given range.

Table 3.2 Total CO_2 emissions by fuel type.

	Diesel (kg/L)	Gasoline (kg/L)	CNG (kg/kg)	Electricity (kg/kWh)
Fuel Production[a]	0.553	0.475	0.497	0.627
On-Site Combustion[b]	2.695	2.351	2.373	0.000
Total CO_2 Emissions	3.248	2.826	2.870	0.627

a. Values from GREET 1 version 2012 rev. 2 (Argonne National Laboratory 2012).
b. Combustion CO_2 emissions coefficients from U.S. EIA (2013), converted to appropriate units.

3.4.3 Total Impacts

3.4.3.1 Energy

The energy impact of fuel consumption is primarily from the energy required to produce the fuel, which is its EE. The energy benefit can be realized by comparing the EE to the useable energy that may be obtained from the fuel. The lower heating value (LHV) is the maximum energy that may be harnessed from a fuel in a mechanical engine (Heywood 1998). LHVs for fuels are available from the U.S. Department of Energy Alternative Fuels Data Center (AFDC 2013). Values for the construction fuels considered in this paper are presented in Table 3.1.

In reality, the amount of useful energy obtained from the fuel is never equal to the LHV because mechanical engines are not 100% efficient. The Fuel Conversion Efficiency (FCE) of a combustion engine is defined as the ratio of the brake power to the rate of energy supplied to the engine by the fuel, where the brake power is the useful power measured at the output shaft (Heywood 1988). The rate of energy supplied to the engine is equal to the product of the Brake Specific Fuel Consumption (BSFC) and the LHV of the fuel, where BSFC is the ratio of the fuel consumption rate to the brake power (Heywood 1988). The resulting relationship from Heywood (1988) between FCE, BSFC and LHV for combustion engines is shown in Eq. 3.3.

$$FCE = \frac{1}{(BSFC)(LHV)} \tag{3.3}$$

Typical engine FCE ranges from 30% to 43% for representative compression ignition (diesel) engines and from 20% to 30% for representative spark ignition (gasoline) engines (Heywood 1988). This agrees with recent data from Isuzu (2013). By contrast, electric motors are typically 85% to 95% efficient over a range of operating conditions (Burt et al. 2006). By using the LHVs of combustion fuels from Table 3.1, and assuming typical engine efficiencies to be at the middle of the above ranges, Eq. 3.3 can be rearranged to determine the BSFC by fuel type. Results obtained from using this procedure indicate that diesel engines consume about 0.275 L/kW-hr (0.098 gal/hp-hr) and gasoline engines consume about 0.445 L/kW-hr (0.158 gal/hp-hr). BSFC will vary with engine efficiency, engine load and crankshaft speed, but these values are reasonable for estimating fuel consumption by construction equipment.

The useable energy that can be obtained from a unit of fuel is determined by multiplying the engine efficiency by the fuel energy content. Figure 3.1 compares fuels in terms of the useable energy to embodied energy ratio. The error bars represent the range in values due to engine efficiency.

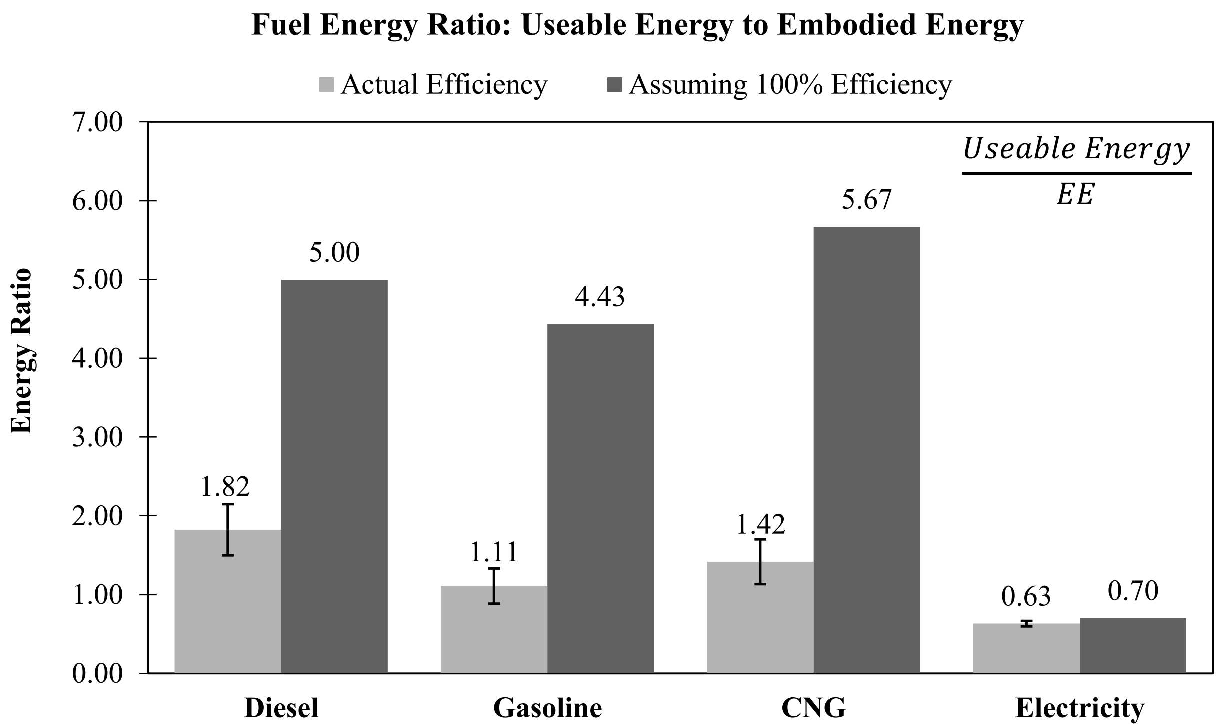

Figure 3.1 Ratio of useable energy to embodied energy per unit of fuel.

A significant amount of energy is lost for combustion fuels, as indicated by the difference in the energy ratio for 100% efficiency as compared to the actual efficiency. This is not the case for electric motors, where efficiencies are high. Of note, the energy ratio for electricity is less than 1.0, indicating that it requires more energy to produce electricity than can be obtained from it. This is because electricity is a form of energy that was generated from fuels in a process that is less than 100% efficient.

3.4.3.2 Carbon Dioxide

The total CO_2 emitted per unit of fuel is equal to the sum of the fuel production emissions and the on-site combustion emissions (Table 3.2). The total impacts from fuels must be compared on the basis of a quantity of useable energy (i.e., energy at an engine crankshaft able to perform work) since they do not have equal energy contents and engine efficiencies. Therefore, the amount of useable energy selected for comparing CO_2 emissions is 100 MJ (27.78 kW-hr or 37.25 hp-hr).

A graphical comparison of the total CO_2 emissions from different fuels to produce 100 MJ of useable energy is shown in Figure 3.2.

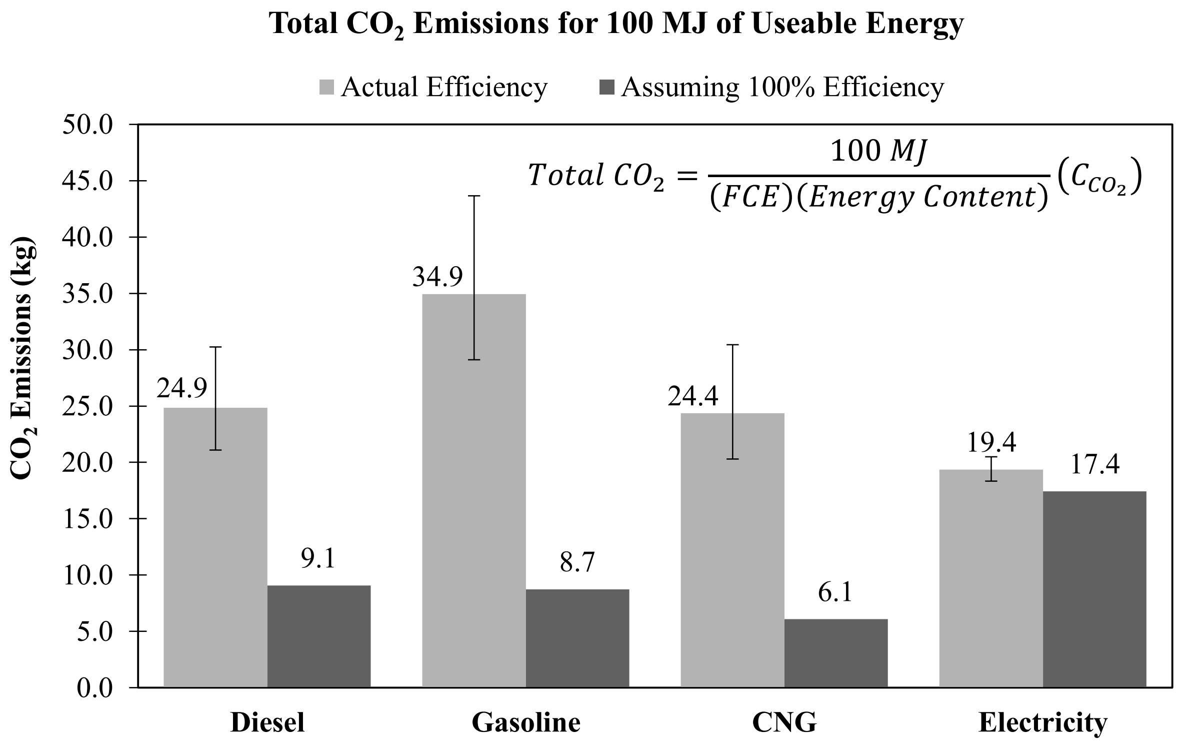

Figure 3.2 Total CO_2 emissions to produce 100 MJ of useable energy based on engine efficiency. Error bars represent the range in actual efficiency.

As a result of the high efficiency of electric motors, electricity actually produces the least CO_2 emissions from the production of 100 MJ of useable energy for the average U.S. electricity generation mix. In contrast, gasoline is responsible for the most CO_2 emissions at both the fuel production and on-site combustion stages. This is largely because gasoline has lower energy content than the other combustion fuels, and gasoline engines also have a lower efficiency.

Combustion engines involve CO_2 emissions at both the fuel production and on-site consumption stages of the fuel cycle, whereas grid electricity only involves energy and emissions in the production process. Based on this emission breakdown, about 17% of the total CO_2 emissions associated with a unit of combustible fuel occur prior to on-site consumption. For grid electricity, 100% of the emissions occur during the production stage, prior to on-site consumption.

This is illustrated graphically in Figure 3.3, which shows the contributions of fuel production and on-site combustion to total CO_2 emissions for 100 MJ of useable energy. Given the significant contribution of fuel production to total CO_2 emissions, it is important to include it in an assessment of the environmental impacts of construction.

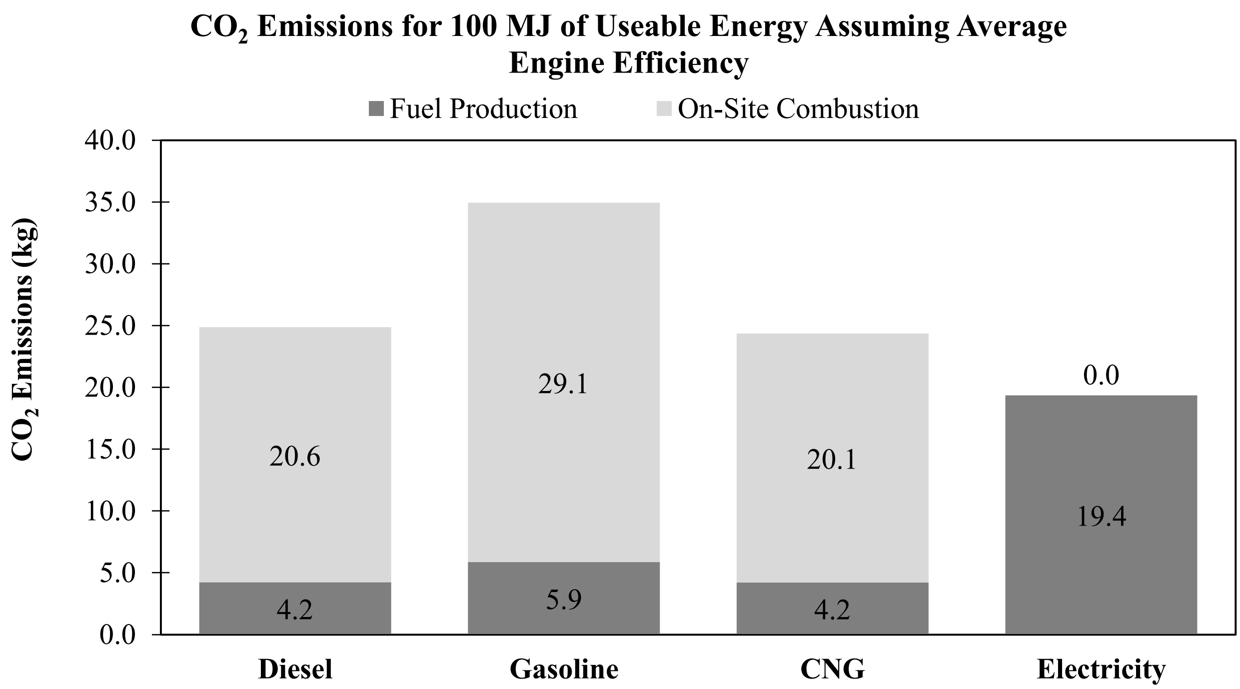

Figure 3.3 Breakdown of total CO_2 emissions for 100 MJ of useable energy, showing the fuel production and on-site combustion contributions.

3.5 APPLICATION

Based on the results of this streamlined fuel cycle analysis of construction fuels, recommended values of EE and total CO_2 emissions coefficients for assessing the environmental impacts from construction equipment operations are shown in Table 3.3. The recommended CO_2 emissions coefficients include emissions generated during fuel production and on-site combustion.

Table 3.3 Recommended embodied energy and total CO_2 emissions coefficients.

Fuel	Embodied Energy Coefficient	CO_2 Emissions Coefficient
Diesel	7.17 MJ/L	3.25 kg/L
Gasoline	7.30 MJ/L	2.83 kg/L
CNG	8.32 MJ/kg	2.87 kg/kg
Electricity	5.14 MJ/kWh	0.63 kg/kWh

These coefficients can be used to estimate the fuel impacts for a geotechnical construction project. To do this, the amount of fuel that will be consumed by the equipment is first estimated based on Runge (1998):

$$Q_F = (P)(LF)(BSFC)(T), \tag{3.4}$$

where *P* is the maximum rated engine power, *BSFC* is the brake specific fuel consumption, *LF* is the engine load factor, and *T* the total time of operation. The engine load factor represents the fraction of maximum available engine power required to do the work, and is related to the conditions and duty cycle of the task (EPA 2010). Total energy and CO_2 can then be estimated by using Eq. 3.1 and Eq. 3.2.

3.5.1 Geotechnical Example

As an example application to determine the embodied energy and CO_2 emissions associated with fuel consumed in ground improvement construction, assume a site with loose sands (D_r = 30%) extending from the surface to a depth of 10 m. This sand needs to be densified to D_r = 70% to provide adequate bearing capacity and mitigate liquefaction risk over a 50 m by 50 m area, for a total treated volume of 25,000 m^3. This improvement could be accomplished with either deep dynamic compaction or vibrocompaction.

Following the design procedures in Lukas (1995) for deep dynamic compaction, the drop locations could be spaced at 4 m in a square grid. To apply appropriate energy to the ground requires 10 drops of a 15 Mg weight falling from a height of 27 m per location. This corresponds to a total of 1,690 drops. Assuming a crane completes an average of 60 drops per hour, this improvement requires 29 hours of crane operation. In that time, a 450 kW (603 hp) diesel crane will consume 1,543 L of fuel with an engine load factor of 0.43, selected based on the EPA (2010). Applying Eq. 3.1 and Eq. 3.2 yields a total embodied energy in the fuel of 11,100 MJ, and generation of 5,000 kg of CO_2 emissions to densify the 25,000 m^3 of soil.

For the vibrocompaction alternative, following guidelines in Elias et al. (2006) the compaction locations can be spaced at 2 m in a triangular array. This results in a total of 780 probe locations to improve the 50 m by 50 m area. Assuming it takes 0.5 hours to conduct the vibrocompaction at each location, it will take a total of 390 machine hours to complete the densification. In this case, the equipment includes a 450 kW (603 hp) diesel crane and 213 kW (286 hp) diesel generator to power an electric vibroflot and water pump. The total fuel consumption for both machines is 30,576 L for the specified improvement. This corresponds to a crane engine load factor of 0.43 and a generator engine load factor of 0.43, selected based on the EPA (2010). Applying Eq. 3.1 and Eq. 3.2 yields a total embodied energy in the fuel of 220,500 MJ, and generation of 100,000 kg of CO_2 emissions to treat the 25,000 m^3 of soil.

Based on this simplistic example, these two densification alternatives are significantly different in their environmental impacts associated with fuel consumption. However, while this comparison is valid for these two simple densification methods, fuel consumption may not be indicative of the total environmental impacts of all other potentially applicable methods for ground improvement at this site. These techniques are also not equally applicable to all densification situations. Nonetheless, the example illustrates that quantifying the energy and CO_2 emissions associated with the fuel cycle is one step in assessing the total impact of geotechnical works.

3.5.2 Innovations to Reduce Environmental Impact

The preceding analysis provides a basis for comparing innovations in the means and methods of construction and equipment function that are developed with the goal of reducing environmental impact. Possible innovations to reduce CO_2 emissions could include using different fuels to power machinery for construction operations whenever practical. CNG, electricity and biofuels are viable alternatives. However, before adopting a new alternative fuel, a fuel cycle analysis should be performed to ensure the energy ratio and total life cycle emissions are advantageous over conventional fossil fuels. Reductions in emissions could also be realized by improvement in the fuel conversion efficiency of the internal combustion engines used to power construction equipment, or by reductions in the power requirement for geotechnical tasks.

3.6 CONCLUSIONS

In conclusion, the fuel cycle analysis presented in this paper demonstrates that fuel production contributes significantly to the total life cycle energy and emissions associated with fuel consumed by construction machinery. As such, energy and emissions assessments of geotechnical construction should include the upstream energy and emissions from fuel production. Total EE and CO_2 emission coefficients for U.S. construction fuels including both upstream and on-site contributions are presented. The fuel cycle analysis also shows that for producing the same amount of useable energy with current technology, gasoline generates the most CO_2 emissions and grid electricity the least. Future innovations in fuel types and engine efficiency could reduce the environmental impacts of construction. Further research into the engine load factors for construction machinery in geotechnical applications could lead to improved accuracy of the energy and emissions assessment. Quantifying the EE and CO_2 associated with construction fuel consumption provides information about environmental impacts that could lead to developing and applying more sustainable designs and construction practices for ground improvement and other geoconstruction projects.

3.7 ADDITIONAL CLARIFICATIONS

The material contained in this section was not included in the original conference paper as published by ASCE, and serves to clarify information presented in section 3.5 of this manuscript.

The recommended embodied energy coefficients shown in Table 3.3 for fuels represent the amount of energy required to produce the fuels only, while the CO_2 emissions coefficients represent the CO_2 emissions from fuel production and combustion. When the fuels are used for construction, the embodied energy in the completed construction includes both the energy required to produce the fuel, and the energy released when it is combusted by construction machinery. Table 3.4 contains embodied energy and CO_2 emissions coefficients for fuels that represent the total energy and CO_2 emissions from fuel in completed construction.

Table 3.4 Recommended unit coefficients of total embodied energy and CO_2 emissions in completed construction from consumed fuels.

Fuel	Embodied Energy Coefficient	CO_2 Emissions Coefficient
Diesel	43.0 MJ/L	3.25 kg/L
Gasoline	39.7 MJ/L	2.83 kg/L
CNG	55.5 MJ/kg	2.87 kg/kg
Electricity	8.74 MJ/kWh	0.63 kg/kWh

In the geotechnical example (section 3.5.1), the computed embodied energies represent the energy consumed to produce the diesel fuel alone, while the computed CO_2 emissions represent the total CO_2 emissions due to fuel used for densifying the sand. The total embodied energy in the densified sand would actually be much higher than the values stated in section 3.5.1, as shown in Table 3.5.

Table 3.5 Total embodied energy from fuel for densification alternatives.

Densification Alternative	Embodied Energy in Fuel from Section 3.5.1 (MJ)	Embodied Energy in Densified Sand (MJ)
Deep Dynamic Compaction	11,100	66,300
Vibrocompaction	220,500	1,322,500

3.8 ACKNOWLEDGEMENTS

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Chapter 4: Energy and Carbon Assessment of Ground Improvement Works II: Working Model and Example

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Relevant Appendices:

Appendix A: SEEAM Spreadsheet Calculator Screen Shots

Appendix B: SEEAM Spreadsheet Calculator User Manual

Appendix E: SEEAM Results for Analyses of LPV 111 Design Alternatives

Appendix F: LPV 111 SEEAM Analysis – Supporting Calculations

Appendix G: Development of the Embodied Energy and CO_2 Emissions Coefficients of Bentonite

Appendix H: Development of Rail and Water Freight Coefficients

Appendix I: EFFC-DFI Geotechnical Carbon Calculator Analysis of Deep Mixing at LPV 111

4.1 ABSTRACT

A Streamlined Energy and Emissions Assessment Model (SEEAM) is presented that is based on Life Cycle Analysis (LCA) methods. The SEEAM provides geotechnical engineers with the means to quantify the embodied energy (EE) and carbon dioxide (CO_2) emissions associated with ground improvement projects. A companion paper (Shillaber et al. 2015) provides detailed background for sustainable development and environmental impact assessment, which are at the foundation of the SEEAM. The boundary conditions and methodology for this model are presented herein. Construction of levee LPV 111 in New Orleans, LA is used as a case history example to illustrate the use of the model. This project involved supporting an earthen embankment by Deep Soil Mixing (DSM) elements. Results of a SEEAM analysis of the DSM supported embankment indicate that constructing the levee involved 1,174,000 GJ of EE and 147,000 tonnes of CO_2 emissions. For comparison, the SEEAM was also used to estimate the EE and CO_2 emissions associated with two other LPV 111 design alternatives; one utilizing prefabricated vertical drains (PVDs) to increase the rate of primary consolidation in the foundation soils, and the other a pile supported reinforced concrete T-wall. The results show that the PVD design has the lowest EE and CO_2 emissions at 809,000 GJ and 64,000 tonnes, respectively. The concrete T-wall has the greatest EE and CO_2 emissions, at 2,755,000 GJ and 211,000 tonnes, respectively (for the materials alone). Despite having the lowest EE, CO_2 emissions and cost, the PVD design was not a viable solution because it could not meet a 20 month time constraint placed on the construction to achieve the needed flood protection. When performance criteria are met, quantitative information about environmental impacts, such as EE and CO_2 emissions, is useful for making geotechnical decisions for sustainable development.

CE Database subject headings: Soil stabilization; Geotechnical engineering; Life cycles; Energy consumption; Energy efficiency; Carbon dioxide; Sustainable development

4.2 INTRODUCTION

Sustainable development has been an important goal of civil engineering design and construction for many years and the concept has been part of the first canon of the ASCE code of ethics since 1996 (ASCE 2008). However, discussion of sustainable development as it pertains to ground improvement design and construction is recent, and there are few related studies. An emerging challenge in geotechnical engineering is to develop a framework for assessing whether or not construction processes and methods comply with the principles of sustainable development (Mitchell and Kelly 2013).

A companion paper (Shillaber et al. 2015) describes how including environmental impact assessment along with final performance requirements and monetary costs in the design decision process can contribute to the development of more sustainable ground improvement projects.

Quantitative methods for estimating final performance and monetary costs are well established in ground improvement practice, but the geotechnical profession does not typically quantify environmental impacts. Furthermore, no generally accepted methodology presently exists within the geotechnical community for how to conduct such an analysis. This paper presents a Streamlined Energy and Emissions Assessment Model (SEEAM) for quantifying energy consumption and carbon dioxide (CO_2) emissions, which are two specific environmental impact factors with global implications (Shillaber et al. 2015).

The SEEAM compiles existing environmental impact assessment principles and methods into a methodology that can be readily used by geotechnical engineers to incorporate sustainable development principles into the ground improvement planning and design decision making process. Such assessments are becoming a necessary and important part of geotechnical practice, in order to reduce environmental consequences by design rather than relying on end of pipe methods during construction.

4.2.1 Background

Life Cycle Analysis (LCA) is a method of assessing the environmental impacts of a product or process over its whole lifetime (EPA 2006; Hammond and Jones 2008). As discussed in greater detail by Shillaber et al. (2015), a full process-based LCA seeks to determine all environmental impacts and can be very laborious. However, the analysis may be simplified, or "streamlined" by limiting it to specific impact factors (Todd and Curran 1999), such as energy consumption and/or carbon emissions (Menzies et al. 2007). The simplified LCA methodology presented herein focuses on Embodied Energy (EE) and the accompanying CO_2 emissions. EE is defined as the energy required to bring an item to its present state (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011). The item may be simple, such as a section of steel pipe, or complex, such as the constructed foundation system of a building. CO_2 is a Greenhouse Gas (GHG) associated with climate change. Accounting for CO_2 alone instead of additional GHG emissions presented as an equivalent quantity of CO_2 removes layers of complexity in the analysis, reducing its uncertainty and increasing its transparency. Additional rationale behind the selection of EE and CO_2 as impact factors of interest is explained by Shillaber et al. (2015).

EE and CO_2 emissions assessments involve first determining the relevant life cycle stages for the subject of interest and defining boundaries regarding what is included in the analysis. According to Inui et al. (2011), the life cycle energy use for foundations has the following stages: 1) extraction of raw materials; 2) processing and manufacture of composite items and building materials; 3) transportation between and within sites and processes; and, 4) construction. These stages can be applied in a streamlined LCA of ground improvement works. Neither operations and maintenance, nor demolition and end of life disposal are included in the life cycle for most ground improvement applications and foundation types, even though they are important in the lifetime energy consumption of buildings and other civil infrastructure (Cole and Kernan 1996; Dixit et al. 2010).

Pinske (2011) used similar life cycle stages for a LCA of ground improvement techniques proposed for redevelopment of Treasure Island in San Francisco Bay, California. Considering improved ground to have no operational energy means that the life cycle energy consumption may be attributed to material manufacturing and transportation, along with site construction operations. Since the energy consumption essentially ends at the completion of construction, an effective way to lessen the impacts associated with ground improvement is to select construction materials and techniques that minimize EE and CO_2 emissions, while still meeting all end-use requirements. The SEEAM can assist in this process by quantifying both the EE and CO_2 emissions associated with ground improvement designs that meet project-specific performance requirements.

4.3 THE SEEAM FOR GROUND IMPROVEMENT

The SEEAM accounts for relevant upstream primary energy (i.e., all energy derived from nature, including losses in production (Dixit et al. 2010; Yohanis and Norton 2002)) and CO_2 emissions in addition to those directly associated with construction operations. As part of the streamlining, the SEEAM relies on Embodied Energy Coefficients (EECs) and CO_2 emissions Coefficients (CCs) for relevant ground improvement construction inputs. Table 4.1 presents EECs and CCs for selected common ground improvement construction materials. Detailed definitions of EECs and CCs may be found in the companion paper (Shillaber et al. 2015).

Table 4.1 Selected embodied energy and CO_2 emissions coefficients.

Material Category	Material	Unit	EEC (MJ/Unit)	CC (kg CO_2/Unit)	Reference
Steel	General Steel, Virgin	kg	35.4	2.71	Hammond and Jones (2011b)
	General Steel, World Avg. Recycled Content	kg	25.3	1.82	Hammond and Jones (2011b)
	Steel Bar and Rod, Virgin	kg	29.2	2.59	Hammond and Jones (2011b)
	Steel Bar and Rod, World Avg. Recycled Content	kg	21.6	1.74	Hammond and Jones (2011b)
	Engineered Sections, Virgin	kg	38.0	2.82	Hammond and Jones (2011b)
	Engineered Sections, World Avg. Recycled Content	kg	27.1	1.89	Hammond and Jones (2011b)
Cementitious Materials	Portland Cement (U.S.)	kg	4.8	0.927	Marceau et al. (2006)
	Lime	kg	5.3	0.78	Hammond and Jones (2011b)
	Slag (U.S.)	kg	0.721	0.021	Slag Cement Association (2014)
	Fly Ash	kg	0.1	0.008	Hammond and Jones (2011b)
Concrete	35MPa Concrete (Portland Cement Only)	m^3	1,630	313	Marceau et al. (2007)
	25MPa Concrete (Portland Cement Only)	m^3	1,390	262	Marceau et al. (2007)
	20MPa Concrete (Portland Cement Only)	m^3	1,140	211	Marceau et al. (2007)
	20MPa Concrete (20% Fly Ash by Weight)	m^3	944	171	Marceau et al. (2007)
Earth Materials	Aggregate: Sand and Gravel or Crushed Rock	kg	0.083	0.0048	Hammond and Jones (2011b)
	Bentonite	kg	1.65	0.101	Jiang et al. (2011); Carnegie Mellon University (2008)
Plastics	General Plastics (Average)	kg	80.5	2.73	Hammond and Jones (2011b)
	Polyethylene (General)	kg	83.1	2.04	Hammond and Jones (2011b)
	Polypropylene (Injection Molding)	kg	115.1	3.93	Hammond and Jones (2011b)
	Polypropylene (Oriented Film)	kg	99.2	2.97	Hammond and Jones (2011b)
Water	Water	L	0.01	0.001	Hammond and Jones (2011b)
Fuel	Diesel	L	43.0	3.25	Shillaber et al. (2014)
	Gasoline	L	39.7	2.83	Shillaber et al. (2014)
	Compressed Natural Gas (CNG)	kg	55.5	2.87	Shillaber et al. (2014)
	Electricity (U.S. Avg. Generation Mix)	kW-hr	8.74	0.63	Shillaber et al. (2014)

The EECs and CCs used in the SEEAM were obtained from published sources, where they were determined through an LCA of the material or activity that they represent. The exception to this is bentonite, where the coefficients were determined through Economic Input-Output LCA (Carnegie Mellon University Green Design Institute 2008) using the same input assumptions as Jiang et al. (2011) in their assessment for bentonite drilling mud. The coefficients used in the SEEAM assessment have been selected to be as relevant as possible for processes and production in the U.S. The number of significant digits for the coefficients in Table 4.1 varies based on the values given in their respective sources. It is not known in all cases if the number of significant digits is justified by the amount of input data; however, in all cases the coefficients can be improved upon with additional data to reduce uncertainty.

By using EECs and CCs as part of the streamlining, the SEEAM adds a degree of uncertainty when compared to performing a full LCA for energy and CO_2. This uncertainty arises because the coefficients represent industry average energy consumption and CO_2 emissions for material production. These coefficients do not account for the specific manufacturing processes or energy sources responsible for supplying a particular construction site. An example of the range in selected coefficient values from the Inventory of Carbon and Energy (Hammond and Jones 2011b) is shown in Shillaber et al. (2015). Despite this tradeoff of greater uncertainty for usability, the SEEAM provides a consistent framework for assessing the life cycle energy consumption and CO_2 emissions associated with ground improvement construction and can permit comparisons between design alternatives. An additional benefit is that the SEEAM methodology saves substantial time as compared to a full LCA, and requires less specialized software, knowledge and training to implement. These factors combine to make it a practical method for geotechnical engineers to use on a regular basis.

Using the SEEAM to determine the EE and CO_2 emissions of ground improvement design alternatives allows geotechnical engineers to optimize their design selection based on final performance, environmental impact, and cost. Weighting these potentially competing factors can be difficult and subjective, plus special project and site conditions may impose additional constraints in making a final design selection. However, because all valid design alternatives must meet the performance requirements of the project, EE and CO_2 emissions (environmental impact) and monetary cost are the primary competing factors for decision making for many projects.

4.3.1 SEEAM Boundary Conditions

4.3.1.1 General

The boundary conditions for the SEEAM extend from the extraction of raw materials to the completion of construction, including the energy and CO_2 emissions associated with transportation of materials and wastes, as well as construction operations (Chau et al. 2012; Inui et al. 2011; Pinske 2011). The material EECs and CCs used in the assessment account for the EE and CO_2 emissions from the extraction of raw materials and the other aspects of material production upstream of the construction site. Transportation and site operations are included by determining the amount of energy and emissions associated with the input fuel required for performing the work.

4.3.1.2 Equipment Manufacture

The SEEAM boundary conditions exclude the EE and CO_2 emissions from the manufacture of equipment and vehicles used to complete the construction unless they become permanent to the site. This exclusion is made because equipment and vehicles are typically used for completing many projects; when divided over all the projects completed within the lifetime of a machine, the EE and CO_2 emissions from machine manufacturing associated with each project become small compared to the total EE and CO_2 emissions from other sources. The validity of this boundary will be demonstrated in a later example.

4.3.1.3 Wastes

Construction wastes result from site operations and the use of input materials. Such wastes are included in the SEEAM because the EE and CO_2 emissions from all input materials are included in the SEEAM output, including the energy consumed and emissions generated from the production of input materials that ultimately leave the site as waste. The EE and CO_2 emissions in waste are not subtracted from the total because the analysis considers all primary energy and emissions in the project.

The only additional energy and CO_2 emissions associated with waste disposal that are included in the analysis are those associated with waste transportation. The impacts due to waste disposal methods (e.g., landfilling, incineration) are not accounted for in the SEEAM analysis. This boundary is reasonable because by accounting for the EE and CO_2 emissions associated with waste construction materials and waste transportation, there is incentive to minimize the quantity of waste when seeking to reduce the energy and CO_2 impacts of the project. In addition, waste disposal methods are generally similar throughout the U.S. and will have similar energy and CO_2 emissions impacts for a unit of disposed waste.

4.3.1.4 Material Recycling

Waste materials that are reused or recycled are included in the SEEAM as a benefit to the project where they are used as an input. This may be a subsequent component of the current project (as in the case study in this paper), or may be a later construction project at another location.

When materials are reused for any subsequent construction without requiring any additional refining or processing, they are considered to have zero EE and CO_2 emissions when assessing the impacts of subsequent construction. This assumption is reasonable because the energy and CO_2 emissions associated with the virgin materials that were consumed to generate the reusable waste are accounted for and attributed to the project where the reusable waste was generated. Without additional processing of the waste for reuse, no additional energy or CO_2 emissions are involved in generating a useable material. In such cases, the only energy and CO_2 emissions associated with utilizing the reusable material for construction result from transportation and site operations. For the case where additional processing is required to recycle a waste material into a useful product, the energy and CO_2 emissions from processing a unit of the material become the EEC and CC for the recycled material. Material transportation and site operations energy and CO_2 emissions for reused or recycled materials should be determined in the same way they are when virgin materials are used. When reused or recycled materials are used for construction, a comparison can be made between using the reused/recycled material or its virgin alternative in order to determine the EE and CO_2 emissions savings (or cost) associated with reuse or recycling.

4.3.1.5 Other Exclusions and Exceptions

The SEEAM does not include impacts that occur over the life of the facility after the completion of construction. This exclusion is based on the assumption that when improved ground meets the project technical performance requirements, it will not require any additional maintenance or improvement. In those instances where ground improvement designs do require operational energy or maintenance (such as active biological systems, thermal systems, or pumping), the analysis boundaries should be expanded to include any operational energy and CO_2 emissions over the design life. The operational impacts may be determined using EECs and CCs for the appropriate materials and/or fuels consumed over the design life, following the same methods described later for construction. Operational energy and CO_2 emissions must be added to the initial construction energy and emissions to fully represent the impact of such designs.

Some existing case studies have extended the boundaries of EE assessment to include consideration for demolition and recycling (Chau et al. 2008; Soga et al. 2011). This consideration is relevant for foundation systems (particularly concrete and/or steel footings or piling) but not necessarily applicable to improved ground. The reason is that in ground improvement, the primary material is the existing soil, with its properties altered to meet the demands of the project. In addition, the improved ground may continue to be useful long after the facility it initially supported is retired and demolished. As such, the SEEAM does not include any energy from end of life demolition, disposal or recycling.

4.3.2 SEEAM Analysis Methodology

This section presents the calculation methodology for conducting the complete SEEAM analysis when using a database of EECs and CCs. The SEEAM analysis incorporates four major stages for ground improvement construction: 1) material production, 2) transportation to the site, 3) operations on-site, and 4) transportation of waste off-site, as depicted in Figure 4.1. These four stages involve three types of computations: 1) input material production, 2) transportation, and 3) site operations (fuel related energy and emissions).

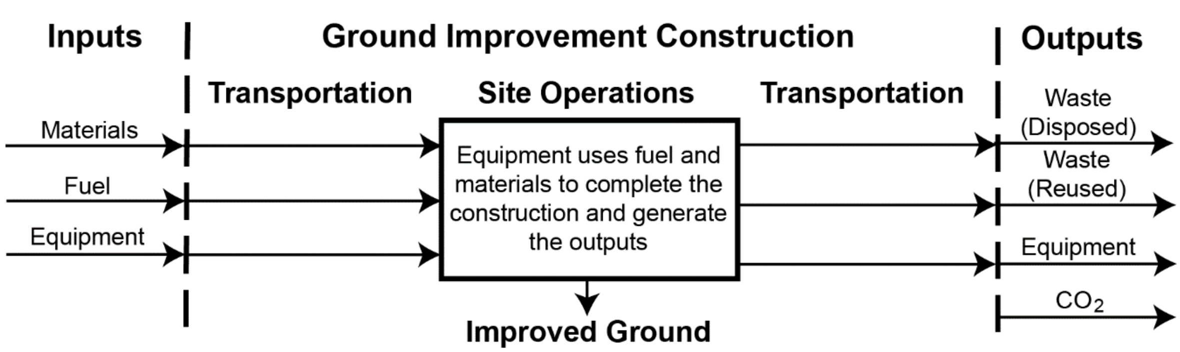

Figure 4.1 Flow diagram of the Streamlined Energy and Emissions Assessment Model.

4.3.2.1 Analysis for Embodied Energy

4.3.2.1.1 Materials

The total EE associated with input materials (EE_M) is computed by summing the product of the quantity of each material used Q_i, and the corresponding material EEC, (EEC_i) for all n materials involved in the construction (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011):

$$EE_M = \sum_{i=1}^{n} [Q_i * EEC_i]. \tag{4.1}$$

EECs and CCs for selected construction materials are included in Table 4.1.

4.3.2.1.2 Material and Waste Transportation

Material and waste transportation energy is computed differently depending on the mode of transportation. The most common mode of transportation for construction materials and wastes in the U.S. is by heavy duty truck. In the SEEAM, the energy and emissions associated with trucking are based on the amount of fuel consumed by the transport vehicles. The total quantity of a particular fuel (e.g., diesel, gasoline) consumed by m vehicles making trips to or from a construction site (Q_{FT}) is determined by:

$$Q_{FT} = \sum_{j=1}^{m} \frac{D_j}{FE_j} (N_j), \tag{4.2}$$

where D_j is the one-way travel distance from the supplier or waste disposal facility to the site, FE_j is the fuel economy, and N_j is the total number of one-way trips made by the j^{th} vehicle over the course of the project. The fuel economies and approximate payload capacity of several common commercial vehicles used in construction are included in Table 4.2, for use in estimating the number of trips required to move a known quantity of material or waste. Note that each different type of transportation fuel (e.g., diesel, gasoline) will have its own Q_{FT}.

Table 4.2 Fuel economy of common construction vehicles (data from Davis et al. 2012).

Vehicle Information			Average Fuel Economy km/L
Vehicle Description	Truck Class (1 - 8)	Payload Capacity kN	
Minivan or small pickup truck	1	7	7.48
SUV (sport utility vehicle) or full size pickup truck	2	11	6.08
SUV or full size pickup truck	2	16	6.08
Full size pickup truck	3	23	4.46
Medium duty truck	4	32	3.61
Medium duty truck	5	39	3.36
Medium duty truck	6	51	2.98
Light Heavy Duty Truck	7	82	2.72
Heavy Duty Truck	8	240	2.42

The total EE from fuel consumed for transportation (F_{EET}) is the energy associated with producing and combusting the transportation fuel. It is determined by summing the product of the quantity of each specific fuel (e.g., diesel, gasoline) consumed $(Q_{FT})_k$ and its EEC $(EEC_F)_k$ for all f fuels consumed for materials transportation (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011):

$$F_{EET} = \sum_{k=1}^{f}[(Q_{FT})_k * (EEC_F)_k]. \tag{4.3}$$

Relevant EECs and CCs for transportation fuels are included in Table 4.1.

Other means of transportation of construction materials and waste include rail and water freight. In these cases, the energy and emissions are based on coefficients for transporting a unit mass of material a unit distance, such as per tonne-km. For transportation via these modes, the total EE associated with transporting n materials or wastes may be determined by:

$$T_{EE} = \sum_{i=1}^{n}[M_i * D_i * (EEC_T)_i], \tag{4.4}$$

where T_{EE} is the total EE from the transportation of materials by rail and water, M_i is the mass, D_i is the one-way distance from the supplier or waste disposal facility to the site and $(EEC_T)_i$ is the

EEC for the mode of transportation of the i^{th} material or waste. EECs and CCs for freight are included in Table 4.3.

Table 4.3 Rail and water freight energy and CO_2 emissions coefficients.

	EEC (MJ/tonne-km)	CC (kg CO_2/tonne-km)	Reference
Water Freight	0.157	0.029	Energy: Davis et al. (2012) CO_2: EPA (2014)
Rail Freight	0.238	0.018	Energy: Determined by using fuel coefficients from Shillaber et al. (2014) to convert CO_2 emissions to energy from diesel fuel. CO_2: EPA (2014)

The EE in the project from all transportation (EE_T) is found by:

$$EE_T = F_{EET} + T_{EE} \tag{4.5}$$

4.3.2.1.3 Site Operations

For construction site operations, on-site consumption of a combustible fuel (e.g., diesel, gasoline) by q pieces of equipment is estimated based on the method in Shillaber et al. (2014):

$$Q_F = \sum_{l=1}^{q} [P_l * LF_l * (BSFC) * T_l], \tag{4.6}$$

where Q_F is the quantity of a given fuel (e.g., diesel, gasoline) consumed by machines on-site, P_l is the maximum rated engine power, LF_l is the engine load factor, and T_l the total time of operation for the l^{th} machine working on-site. *BSFC* is the brake specific fuel consumption for the specific fuel of interest (e.g., diesel, gasoline). The engine load factor describes the average fraction of the maximum available engine power required to perform the work; some average load factors are available from the U.S. EPA (2010). General recommended values of BSFC for diesel and gasoline engines are 0.275 L/kW-hr and 0.445 L/kW-hr, respectively (Shillaber et al. 2014).

Where grid electricity is used to power on-site machinery, the method for determining consumption of electricity is slightly modified from the method for combustion fuels based on information published by the U.S. Department of Energy (1997). In this case, the quantity of electricity consumed by q electric machines is given by:

$$Q_E = \sum_{l=1}^{q} \left(\frac{(P_l)(LF_l)}{\eta_l} \right) T_l, \tag{4.7}$$

where Q_E is the quantity of electricity consumed by all electric machines, P_l is the maximum rated output mechanical power, η_l is the efficiency, LF_l the load factor, and T_l the total time of operation for the l^{th} electric motor.

The total EE in the project from site operations (EE_S) may be found by:

$$EE_S = \sum_{k=1}^{f} [(Q_F)_k * (EEC_F)_k] + [Q_E * EEC_E], \tag{4.8}$$

where $(Q_F)_k$ is the total quantity and $(EEC_F)_k$ is the EEC of the k^{th} fuel consumed by all machines, where f fuels are used in the construction. EEC_E is the EEC for electricity.

4.3.2.1.4 Waste Materials

As stated previously, only waste material transportation is included in the analysis, which is accounted for by following the methodology for transportation (Eq. 4.2, 4.3, 4.4, 4.5). However, for wastes that can be reused or recycled, the project where the waste is subsequently used receives the benefit in terms of EE and CO_2 from utilizing the material, as described previously in the explanation of boundary conditions.

4.3.2.1.5 Combined Total

The total EE for ground improvement by the SEEAM is determined by summing the contributions from all input materials, transportation and site operations (Inui et al. 2011):

$$Total\ EE = EE_M + EE_T + EE_S \tag{4.9}$$

4.3.2.2 CO_2 Emissions

The CO_2 emissions are computed following the same approach used for EE. The quantities of CO_2 emissions associated with materials, transportation, and site operations are computed by replacing the EECs in Eq. 4.1, Eq. 4.3, Eq. 4.4, and Eq. 4.8 with the appropriate CC, respectively. Overall total CO_2 emissions are determined by (Inui et al. 2011):

$$Total\ CO_2 = M_{CO_2} + T_{CO_2} + S_{CO_2}, \tag{4.10}$$

where M_{CO2} is the total material CO_2 emissions, T_{CO2} is the total transportation CO_2 emissions, and S_{CO2} is the total site operations CO_2 emissions.

4.4 EXAMPLE APPLICATION

The SEEAM methodology was used to determine the EE and CO_2 emissions associated with raising the crest elevation of levee section LPV 111 in New Orleans, LA. There are significant details regarding the design alternatives and technical aspects of this project in the literature. When constructed, the LPV 111 project was the largest application of Deep Soil Mixing (DSM) in the United States (Cali et al. 2012). The DSM spoil was also recycled as levee fill (Druss et al. 2012); therefore, this project is an excellent example of ground improvement with waste reuse.

4.4.1 LPV 111 Project Background

LPV 111 is an 8.5 km long levee section in New Orleans that serves to protect the city from flooding. The project involved raising the levee crest about 3 m, to reach the 100 year flood protection level. Due to the close proximity of a neighboring wildlife refuge, a traditional earthen fill levee could not be constructed to the higher elevation because the required stability berms would encroach on the protected land (Cali et al. 2012). Three viable design alternatives included DSM, use of prefabricated vertical drains (PVDs) to improve the foundation soils for embankment support, and a reinforced concrete T-wall (Cali et al. 2012). For comparison and to demonstrate the usefulness of the SEEAM in design decision making, a SEEAM analysis was performed for each of these alternatives.

4.4.2 SEEAM Analysis of the Deep Soil Mixing Design

The DSM alternative selected for final design of LPV 111 consisted of panels of improved soil installed perpendicular to the crest line of the levee. Additional deep mix elements were installed underneath the levee crest between the deep mix panels and geogrid was installed over the mixed zone to reduce potential differential settlement (Cooling et al. 2012). A cross section and plan view of a typical LPV 111 section with DSM are shown in Figure 4.2. Based on bench scale laboratory and full scale field testing, a binder consisting of 25% Portland cement and 75% slag was selected to achieve the needed final properties for the deep mixed elements (Bertero et al. 2012).

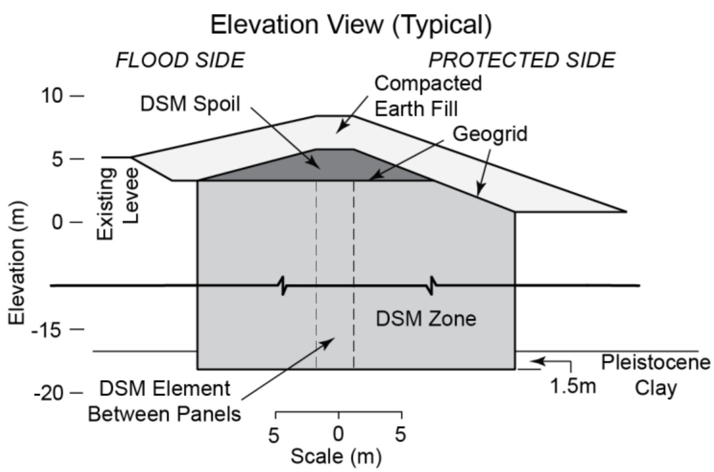

Figure 4.2 Typical elevation and plan view of the Deep Soil Mixing design for LPV 111, adapted from Cooling et al. (2012).

4.4.2.1 Deep Soil Mixing Quantities

To complete the deep mixing construction, 8 deep mixing rigs employing two different mixing methods used a total of 417,000 tonnes of binder and 454,000 m^3 of potable water to treat 1,400,000 m^3 of foundation soil (Schmutzler et al. 2012). The cement and slag in the binder were both transported to the New Orleans batch plant by barge. The cement was sourced from Festus, MO and the slag was sourced from Chicago, IL (T. Leffingwell, personal communication, 2014).

It is estimated that over 18,130 cement tankers carrying 23 tonnes of binder were delivered to the grout plants on-site from a cement batch plant about 1.6 km away from the site (F. Leoni, personal communication, 2013). On average, an additional 1.6 km of trucking was estimated to occur on-site (along the levee) to reach the grout plants for a total transportation distance of 3.2 km. In total, the DSM rigs, grout pumps, grout plants and spoil removal excavators used a total of 3,902,000 L of diesel fuel to complete the deep mixing phase of the project.

4.4.2.2 Embankment Construction Quantities

Construction of the levee embankment over the DSM elements required 841,000 m^3 of clay fill (Cali et al. 2012). Of this required quantity of fill, 400,000 m^3 of DSM spoil material, called Recycled Embankment Material (REM), was used in place of clay borrow (Druss et al. 2012). This spoil material is a waste from the DSM operation, and would normally be transported off-site for disposal. Since the material could be used for constructing the levee embankment, the need to transport and dispose of the waste was eliminated.

The clay fill was sourced from several locations, ranging from 18 km to 56 km away from the site, and was transported predominantly by heavy duty trucks (J. Gardner, personal communication, 2014). Since precise quantities transported from each location could not be obtained, all clay was assumed to be transported by heavy duty truck an average distance of 37 km.

Equipment for excavating the clay from the borrow sources and loading trucks was estimated to consume a total of 210,000 L of diesel fuel based on production information from Gardner (personal communication, 2014). Equipment for spreading and compacting the REM and the clay fill on-site was estimated to consume a total of 1,960,000 L of diesel fuel based on production rate information for embankments from RSMeans (2011) and the specifications of selected Caterpillar machines (Caterpillar 2012).

For additional embankment stability, a total of 376,000 m^2 (Kelsey 2012) of geogrid with an estimated mass of 395 tonnes was used to reinforce the embankment and resist differential settlement. The geogrid was assumed to be transported 1,130 km by heavy duty truck from the supplier in Charlotte, NC in 17 round trips.

4.4.3 SEEAM Results for the Deep Mixing Design

Following the methodology described previously and using the EECs and CCs in Table 4.1, vehicle fuel economies in Table 4.2, and freight EECs and CCs from Table 4.3, along with the quantities in the preceding section, the total EE in the completed LPV 111 project is 1,174,000 GJ, with 147,000 tonnes of total CO_2 emissions. For perspective, a gasoline fueled half ton pickup truck (e.g., Ford F-150/Chevrolet Silverado 1500/Ram 1500) with a fuel economy of 6.4 km/L (15 mpg) would need to travel 331,400,000 km to generate this much CO_2. This distance is equivalent to 432 round trips from Earth to the Moon. If the useful lifetime of a pickup truck is 322,000 km, then these emissions would result from the operational lifetime of 1,029 pickup trucks.

If the DSM spoil material was not recycled as embankment fill and was instead disposed as waste, the total EE in the completed project would increase to 1,278,000 GJ, with 155,000 tonnes of CO_2 emissions. Therefore, recycling the DSM spoil material results in reductions in EE and CO_2 emissions of 104,000 GJ (8.9%) and 8,000 tonnes (5.4%), respectively. In addition to the EE and CO_2 emission reductions, recycling the spoil also saves landfill space, reduces land use impacts from borrowing additional material and cuts down on traffic and road wear from the additional trucking for waste transportation. All of these factors are also important for sustainable development.

4.4.3.1 Boundary Conditions

The SEEAM boundary conditions exclude equipment and vehicle manufacture. To demonstrate the validity of this exclusion, consider the DSM component of the LPV 111 levee construction. The DSM alone is responsible for 998,000 GJ of EE and 134,500 tonnes of CO_2 emissions. The equipment performing the mixing (large drill rigs, grout plants, grout mixers, grout pumps, cement silos) had an estimated combined mass of 1,100 tonnes. Assuming all this equipment to be made entirely of steel (the primary material composing most machines), this combined weight of machinery can be used with an EEC and CC for steel to approximate the EE and CO_2 emissions from equipment manufacture. Using the general virgin steel EEC and CC in Table 4.1, there are approximately 39,100 GJ of EE and 3,000 tonnes of CO_2 emissions from manufacturing 1,100 tonnes of equipment. If the equipment is in service for 10 projects over its lifetime, the EE and CO_2 emissions associated with each project are 3,910 GJ and 300 tonnes, respectively. This is 0.4% of the EE and 0.2% of the CO_2 emissions associated with the DSM at LPV 111. Even if the manufacturing process for the machinery doubled the EE and CO_2 emissions as compared to general virgin steel, the equipment would still amount to less than 1% of the total EE and CO_2 emissions for the DSM project, assuming the equipment has a useful life of 10 projects. Therefore, it is reasonable to ignore the contribution of equipment manufacturing in EE and CO_2 emissions assessments for this type of ground improvement.

4.4.4 SEEAM Analysis of the Prefabricated Vertical Drains Design

An alternate ground improvement design for LPV 111 involved the use of PVDs to increase the rate of consolidation of foundation soils in order to achieve the shear strength needed for stability of an earthen levee in a reasonable period of time. In addition to the PVDs for improvement of the foundation soils, the embankment design included high strength geogrid for additional stability, and a cement/bentonite cutoff wall along the crest line of the levee to limit seepage (URS Group 2008). A typical cross section of the levee for this design alternative is shown in Figure 4.3. The quantities of materials for this design option have been estimated based on preliminary design and cost estimating information from the LPV 111 Engineering Alternatives Report (URS Group 2008).

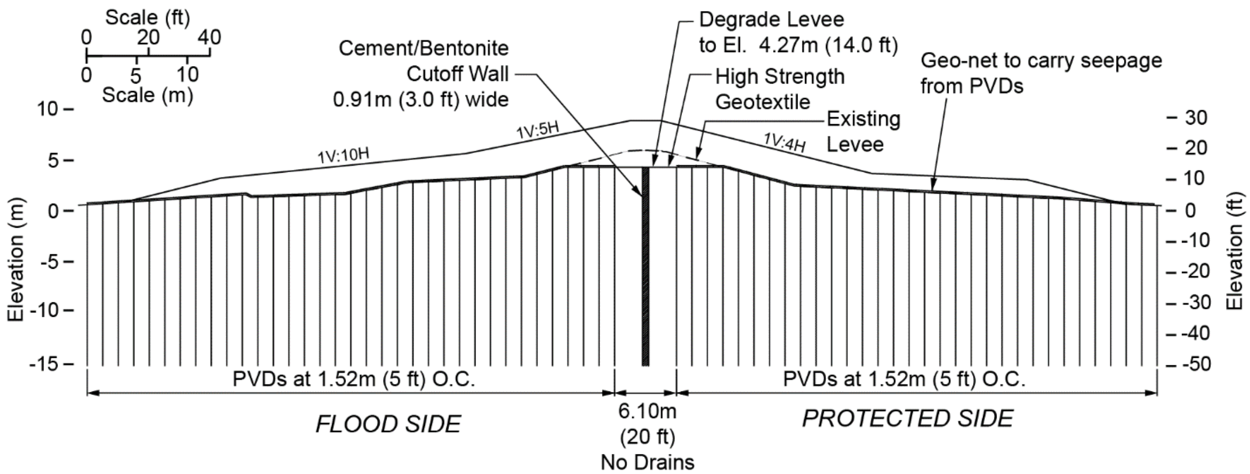

Figure 4.3 Typical LPV 111 levee profile for the Prefabricated Vertical Drains design, adapted from URS Group (2008).

4.4.4.1 PVD Quantities

The PVD design alternative requires 7,500,000 m of polypropylene PVDs, which have a mass of approximately 580,100 kg. The PVDs were assumed to be transported by heavy duty truck a distance of 1,175 km in 24 round trips from a supplier in North Carolina. Installing the PVDs was estimated to consume about 430,500 L of diesel fuel.

A drainage layer for the PVDs was estimated to require 714,600 kg of high density polyethylene (HDPE) geonet and 191,300 kg of polypropylene geotextile separator fabric. The geonet and geotextile were assumed to be transported by heavy duty truck to the construction site from a distance of 604 km in a combined total of 38 round trips.

4.4.4.2 Embankment Construction Quantities

Raising the levee crest elevation for the PVD design option requires placing and compacting about 1,418,000 m^3 of clay for the embankment, with 1,322,000 m^3 of clay borrow and 96,000 m^3 of site material being re-compacted after degrading the existing levee for PVD installation. The clay borrow was assumed to be sourced from the same locations as for the DSM design option, being transported to the site by heavy duty trucks an average distance of 37 km in 115,330 round trips. For stability, the embankment includes layers of geogrid, estimated to have a total mass of 1,534 tonnes. The geogrid was assumed to be transported by heavy duty trucks a distance of 1,130 km in 63 round trips. Based on production rate information from RSMeans (2011), it was estimated that degrading the existing levee and constructing the earth embankment would require 3,327,000 L of diesel fuel. An additional 622,000 L of diesel fuel was estimated to be consumed to extract the clay borrow based on production information from Gardner (personal communication, 2014).

4.4.4.3 Cement/Bentonite Cutoff Wall Quantities

The cement/bentonite cutoff wall was estimated to have a total excavated volume of 148,600 m^3, requiring 24,816 tonnes of Portland cement and 6,895 tonnes of bentonite. The cement was assumed to be supplied from the same plant that supplied the DSM binder, with a transport distance by heavy duty truck of 3.2 km for a total of 1,079 round trips. As with the DSM alternative, the cement was assumed to be delivered to the batch plant in New Orleans from Festus, MO by barge. The bentonite was assumed to be supplied from northern Wyoming, being transported to the site by heavy duty truck a distance of 3,050 km in 282 round trips. The total quantity of water needed to construct the cement/bentonite cutoff wall was estimated to be 137,841,000 L. Excavation for the cement/bentonite cutoff wall was assumed to be completed by cranes using clamshell buckets, consuming an estimated total of 263,600 L of diesel fuel. All excavated material was assumed to be transported by heavy duty truck a distance of 40 km to a disposal facility in 12,960 round trips.

4.4.4.4 Results

Based on these estimated quantities for the PVD design for LPV 111, the total EE would be 809,000 GJ, with 64,000 tonnes of total CO_2 emissions. For comparison, Chau et al. (2012) performed an EE analysis for a design alternative for a portion of a U.K. rail link that involved a 7.3 km long embankment with PVDs. Their analysis yielded 640,000 GJ of EE for the embankment. These results are quite comparable considering the rail embankment assessed by Chau et al. (2012) is more than 1 km shorter, is of lesser height and has steeper side slopes than the embankment at LPV 111.

4.4.5 SEEAM Analysis for the Reinforced Concrete T-Wall Design

A non-ground improvement design alternative for LPV 111 consisted of a reinforced concrete T-wall supported by driven steel piles. For comparison between ground improvement alternatives and a conventional deep foundation solution, an abbreviated SEEAM analysis for the T-wall was performed, including only the materials in the assessment.

4.4.5.1 Reinforced Concrete T-Wall Quantities

Quantities for the concrete T-wall have been based on a typical T-wall section for LPV 111 received from URS Corporation (T. Cooling, personal communication, 2014). The T-wall section has an overall height of 5.33 m, with a base slab that is 6.10 m wide and 1.22 m thick, as shown in Figure 4.4. The wall is supported by four, 42.06 m HP14x73 steel piles across the width of the base slab, spaced at 2.29 m along the levee alignment. A PZ-22 steel sheet pile runs continuously along the centerline of the levee beneath the T-wall to a depth of 20.95 m. It is assumed that reinforcing steel will occupy 2% of the cross sectional area of the T-wall.

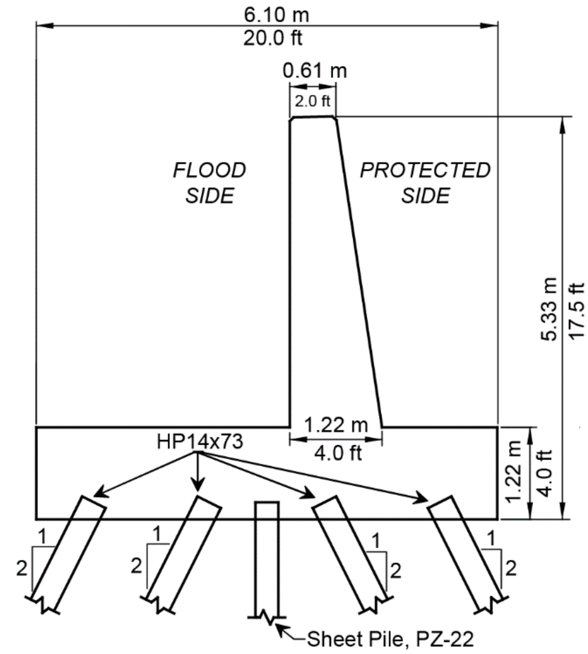

Figure 4.4 Typical LPV 111 Reinforced Concrete T-wall cross section.

Based on the T-wall section and a levee length of 8,330 m (URS Group 2008), construction will require 91,350 m^3 of 25 MPa concrete with 14,630 tonnes of reinforcing steel. A total of 14,576 steel HP14x73 piles with a total mass of 66,600 tonnes are required to support the T-wall, along with 18,730 tonnes of steel sheet pile.

4.4.5.2 Results

Considering the estimated material quantities only, the EE in the reinforced concrete T-wall would be 2,755,000 GJ with 211,000 tonnes of CO_2 emissions. The actual energy and emissions including other factors such as material transportation, formwork, and site operations for excavation and pile driving would be even higher.

4.5 DISCUSSION

4.5.1 Comparison of Results for LPV 111 Design Alternatives

An EE and CO_2 emissions assessment was not part of the decision process between LPV 111 design alternatives; the DSM design option was chosen for construction based on risk and reliability, cost, environmental impact (e.g., land use change, wetlands impact, sediment transport, etc.), construction schedule, required right-of-way and operations and maintenance (Cali et al. 2012). In this section, the three analyzed design alternatives are compared based on EE, CO_2 emissions and selected performance criteria, which support the final design decision made prior to construction.

A summary of the computed EE and CO_2 emissions for the three LPV 111 alternatives is given in Table 4.4, along with the estimated cost from the Engineering Alternatives Report (URS Group 2008). Based on the SEEAM analysis, the PVD design results in the least EE and CO_2 emissions; the reinforced concrete T-wall results in the most. Even though the concrete T-wall analysis only accounted for materials, this design involves more than 2.3 times as much energy and more than 1.4 times as much CO_2 emissions as the DSM option that was constructed at LPV 111. The concrete T-wall was also estimated to cost almost 50% more than the DSM supported embankment.

Table 4.4 Comparison of LPV 111 design alternatives.

LPV 111 Design Alternative	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Cost** (URS Group 2008)	**Comment(s)**
Deep Soil Mixing	1,174,000	147,000	$ 372,800,000	- As-built final design. - Deep mixing completed in 14 months.
Prefabricated Vertical Drains	809,000	64,000	$ 361,000,000	- Construction time exceeds 20 month limit.
Pile Supported Concrete T-Wall	2,755,000	211,000	$546,600,000	- EE and CO_2 results are for materials only. - T-wall not suited for ship impact loading.

Of the two ground improvement design alternatives, the PVD design would result in EE and CO_2 emissions reductions of 31% and 56%, respectively, over the as-built DSM design option. The PVD option was also estimated to cost $11.8 million (3.3%) less than the DSM option (URS Group 2008).

Aside from the fact that the T-wall is not well suited for potential vessel impact loading from the adjacent navigable waterway (URS Group 2008), considering the preceding facts, it is also not optimal for LPV 111 because it is more expensive and would have resulted in significantly greater EE and CO_2 emissions than the ground improvement alternatives. This finding agrees with other studies (Egan and Slocombe 2010; Spaulding et al. 2008) that have demonstrated ground improvement techniques result in less environmental impact than conventional deep foundation solutions.

Based on comparing the SEEAM results for the ground improvement alternatives at LPV 111, it also appears that the as-built DSM design was not the best option, as it results in both greater cost and EE and CO_2 emissions impact as compared to the PVD design alternative. However, the LPV 111 project had additional criteria focused on protecting the city of New Orleans from flooding, which can have severe social and economic consequences. These criteria mandated the levee be raised to the 100 year flood protection level within 20 months of notice being issued to the contractor to start work (Cali et al. 2012). Due to limitations in the rate of consolidation of the foundation soils, construction for the PVD design option would require between 2.6 and 3.8 years, which is greater than the 20 month requirement for achieving 100 year flood protection (URS Group 2008). Even though the DSM design option was more expensive and involved more EE and CO_2 emissions, it could be completed within 14 months (Cali et al. 2012), thereby meeting the tight time constraint for achieving flood protection. As such, it proved to be a better alternative because it met all the project performance requirements, despite having higher cost and greater EE and CO_2 emissions.

4.5.2 Comparison with Other Assessment Tools

In 2012, the Deep Foundations Institute (DFI) partnered with the European Federation of Foundation Contractors (EFFC) to develop a consistent methodology for conducting carbon footprint analyses within the geotechnical industry (Lemaignan and Wilmotte 2013). Accompanying the methodology is a user friendly spreadsheet tool called the Geotechnical Carbon Calculator, which computes the greenhouse gas (GHG) emissions associated with deep foundations and ground improvement construction projects, presenting the results as an equivalent quantity of carbon dioxide (CO_{2eq}) (Carbone 4 2014; Lemaignan and Wilmotte 2013). Like the SEEAM, the Geotechnical Carbon Calculator uses published CCs (Lemaignan and Wilmotte 2013).

The EFFC-DFI Geotechnical Carbon Calculator version 2.3 (Carbone 4 2014) was used to perform the analysis for the DSM design option at LPV 111 using the recommended database of CCs in the tool. The analysis yielded total computed emissions of 148,000 tonnes of CO_{2eq}. This result is 1,000 tonnes (0.7%) greater than the CO_2 emissions that result from the SEEAM analysis, but it does not include barge transport of cement and slag to the batch plant prior to being trucked onto the site. Removing barge transport from the SEEAM analysis reduces the quantity of CO_2 emissions from 148,000 tonnes to 128,500 tonnes. With this adjustment, the Geotechnical Carbon Calculator result is 19,500 tonnes (15.2%) greater than the CO_2 emissions determined by the SEEAM.

There are several factors contributing to this discrepancy between the two analyses. First, the Geotechnical Carbon Calculator includes consideration for mobilization and equipment manufacturing (by default ratios in this analysis), which were not considered in the SEEAM analysis. Equipment manufacturing was specifically excluded based on the SEEAM boundary conditions. Mobilization may be factored into the SEEAM by adding additional transportation, but this specificity is not deemed necessary when performing the analysis to screen design alternatives. Taking these factors out of the total emissions, the Geotechnical Carbon Calculator result decreases to 143,000 tonnes CO_{2eq}, which is 14,500 tonnes (11.3%) greater than the SEEAM result without barge transport. Second, the Geotechnical Carbon Calculator handles transportation of materials differently, by using an emissions coefficient per distance traveled for heavy trucking rather than the fuel economy of the vehicles. Third, the Geotechnical Carbon Calculator lacks the ability to thoroughly consider geosynthetics, as the only plastics within its database are PVC pipes and polypropylene. While polypropylene was used to represent the geogrid for this analysis, geosynthetics are often made of high density polyethylene, nylon and other plastics. Fourth, the CCs for the materials and other inputs are not identical in the databases of the two tools. The material CCs in the recommended database in the Geotechnical Carbon Calculator come from European sources. By contrast, the SEEAM uses several material CCs that are U.S. specific. Most notably for this analysis, the Portland cement and slag CCs in the SEEAM are based on U.S. production, which is not the case for the CCs for these materials in the recommended database in the Geotechnical Carbon Calculator. Finally, the Geotechnical Carbon Calculator represents GHG emissions in the form of CO_{2eq}, while the SEEAM accounts for emissions of CO_2 alone. This fact means the EFFC-DFI calculator should compute a larger amount of carbon emissions by virtue of accounting for other GHGs in the total, which implies the results for the two calculators based on CO_2 emissions alone differ by less than 11.3%.

Even though the results from the two assessment tools differ, they are close enough to suggest it is reasonable to use the narrower boundaries and simplifications in the SEEAM for screening project alternatives in the planning and design phase. However, for carbon emissions assessments performed during the construction process, the Geotechnical Carbon Calculator currently has the ability to readily include more details than the SEEAM, allowing it to provide more detailed results for carbon footprint assessment when all the necessary input information is known.

Regardless of when or why the assessment is being conducted, the SEEAM provides more information to the user than the Geotechnical Carbon Calculator by also accounting for EE. As discussed in the companion paper (Shillaber et al. 2015), carbon emissions assessments are often performed by converting energy units into a mass of carbon emissions (Menzies et al. 2007), which implies that energy is the basis for carbon emissions assessments. With different fuels and methods of energy production in different nations, the corresponding CO_2 emissions can vary significantly. As such, EE tends to be more reliable for international use (Hammond and Jones 2011a). Therefore, it is advantageous to consider EE in addition to CO_2 emissions in environmental impact assessments for construction, as in the SEEAM.

4.5.3 Challenges for the SEEAM and EE and CO_2 Assessments of Geotechnical Works

The following four factors can make it challenging to perform EE and CO_2 analyses of geotechnical designs (Inui et al. 2011):

1) Geotechnical design is strongly site specific,
2) Fewer design varieties are available,
3) The installation process described at the design stage often does not reflect what happens on-site,

4) The service life is often longer than that of buildings, and negligible operational energy is required.

The first three factors listed are also relevant for ground improvement techniques and will influence the output of the SEEAM analysis. The service life and operational energy do not impact the SEEAM because of the established boundary conditions.

Of the first three factors, the difference between the design assumptions and what actually occurs on-site is the most difficult to address. For example, the SEEAM requires that estimates of material and fuel quantities be made prior to construction in order to compute the total EE and CO_2 emissions of design alternatives. This can be a significant source of uncertainty in the analysis for ground improvement techniques, where the quantity of materials used can be highly variable based on actual field conditions. This uncertainty could be addressed through a sensitivity study, performed by varying the quantities of required materials, transportation and site operations to show the impact of a given activity on the total EE and CO_2 emissions.

Additional uncertainty is introduced into the analysis through the use of EECs and CCs. While the coefficients represent typical industry average production for materials and fuel, they do not represent the actual energy and emissions that are associated with the specific production processes that may be involved with supplying a construction site. For example, of the four common production processes for Portland cement in the U.S., the weighted mean EEC is 4.8 MJ/kg with a standard deviation of 0.98 MJ/kg, and the weighted mean CC is 0.927 kg CO_2/kg with a standard deviation of 0.105 kg CO_2/kg, derived from data by Marceau et al. (2006). Additional information regarding the reliability and sources of uncertainty for EECs and CCs is described in the companion paper (Shillaber et al. 2015). Despite the uncertainty in coefficients, as long as the same coefficients are used for assessments, the SEEAM does provide information that can be helpful in selecting construction materials and processes that minimize energy and CO_2 emissions impacts. Developing a formal framework for accounting for uncertainty in EE and CO_2 emissions assessments for ground improvement is the subject of significant continuing work.

At present, guidance for typical or expected reasonable values of EE and CO_2 emissions for various ground improvement techniques and associated projects are not available because there are too few projects where EE and CO_2 emissions have been estimated. It is anticipated that guidance will become available as accounting for environmental impacts becomes more common in practice.

4.6 SUMMARY AND CONCLUSION

The boundaries and methodology of a Streamlined Energy and Emissions Assessment Model (SEEAM) were presented in this paper. The SEEAM can be used for quantifying two environmental impact factors for geotechnical construction: embodied energy (EE) and CO_2 emissions. Since the SEEAM includes both EE and CO_2 emissions as environmental impact factors, the authors believe it is currently one of the most useful environmental impact assessment methodologies available for ground improvement projects.

A case history applying the SEEAM analysis to the LPV 111 levee project in New Orleans, LA provides both illustration of the method and some guidance in using the SEEAM. This analysis shows that in constructing the levee as designed, using Deep Soil Mixing (DSM) to improve the foundation soils and recycling the DSM spoil material as embankment fill, 1,174,000 GJ of energy were consumed and 147,000 tonnes of CO_2 were released to the environment. To generate this quantity of CO_2 emissions, a typical gasoline fueled half-ton pickup truck in the U.S. would need to travel the equivalent distance of 432 round trips between Earth and the Moon. Using the DSM spoil material for levee construction resulted in saving 104,000 GJ of energy and 8,000 tonnes of CO_2 emissions compared to disposing the spoil and borrowing additional clay fill.

In addition to showing the quantities of EE and CO_2 in the final constructed levee, a comparison was made to two other design alternatives. These included a ground improvement design using prefabricated vertical drains (PVDs) and a pile supported reinforced concrete T-wall. Overall, the reinforced concrete T-wall design involved the largest amount of EE and CO_2 emissions (2,755,000 GJ and 211,000 tonnes, respectively, for materials alone) and the PVD design involved the least (809,000 GJ and 64,000 tonnes, respectively). In this case, the highest and lowest estimated costs were also associated with the concrete T-wall design and the PVD design, respectively.

While the PVD design alternative had the lowest energy and CO_2 emissions impact and cost, the construction time was controlled by the rate of consolidation of the foundation soils and exceeded the time constraint for achieving needed flood protection. Therefore, despite having slightly greater cost and EE and CO_2 emissions, the DSM solution was actually the best option of the three for sustainable development because it met all performance requirements.

Quantifying environmental impacts such as EE and CO_2 emissions for different alternatives can be helpful in making geotechnical design decisions for sustainable development. However, the users of environmental impact assessment methodologies like the SEEAM should not apply them blindly, basing a "sustainable" design decision on environmental impact results alone. If that approach were followed at LPV 111, the PVD design option would have been selected instead of the DSM option. As a consequence, the additional needed flood protection would have taken two to three times longer to attain, at the risk of flooding in the city of New Orleans with potentially disastrous social and economic consequences.

The SEEAM method is a tool, only providing quantitative information about certain environmental impacts (EE and CO_2 emissions). When evaluating designs, engineers should consider the information provided by a SEEAM assessment alongside monetary cost and the ability to meet all performance requirements. When armed with all three pieces of information, engineers are better equipped to select a feasible design alternative that contributes to sustainable development.

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Chapter 5: Sustainability Considerations in Deep Mixing Applications, with Examples from LPV 111 in New Orleans, LA

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Relevant Appendices:

Appendix E: SEEAM Results for Analyses of LPV 111 Design Alternatives

Appendix F: LPV 111 SEEAM Analysis – Supporting Calculations

5.1 ABSTRACT

This paper addresses two primary factors affecting the sustainability of Deep Mixing Methods (DMMs): construction materials and handling of the spoil from wet mixing methods. We examine these factors within a life-cycle embodied energy (EE) and carbon dioxide (CO_2) emissions accounting framework, using the LPV 111 project in New Orleans, LA as a case history. The underlying assumption is that project planning and preliminary design have determined that a DMM is the best ground improvement alternative for achieving the broader aims of sustainable development. While EE and CO_2 emissions are direct measurements of environmental impact alone, we illustrate how their minimization can also influence the social and economic consequences of the project. It is recommended that DMMs use lower energy and carbon material alternatives to Portland cement and lime in the binder whenever possible, with preference given to locally sourced materials. Currently available alternative cementitious materials include fly ash and slag, which are waste products from other processes. In addition, recycling the spoil material from wet mix methods on-site is recommended. If the material cannot be recycled on-site, transporting it to a processing and recycling center for later use as fill is preferred over landfilling.

Keywords: Sustainability, Deep Mixing Methods, Embodied Energy, Carbon, Spoil Recycling

5.2 INTRODUCTION

Within the geotechnical community there is an increased appreciation for sustainability considerations, which are an important component of the planning, design, construction, operation and maintenance of projects. An assessment of project sustainability includes holistic life cycle thinking, systems analysis, environmental impact assessment, use of safe and benign materials, awareness of local societies and cultures, social equity, protecting human health and well-being, and monetary costs (Abraham 2006). Since ground improvement is a principal practice domain of geotechnical engineers, it is important that geo-professionals play a role in addressing the sustainability for these projects. In this paper, we illustrate by case history how different materials and methods associated with deep mixing projects can impact overall project sustainability through quantifying project embodied energy (EE) and carbon dioxide (CO_2) emissions. EE is defined as all energy consumed to bring something into its present state (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011). Recommendations are then made for how adverse environmental impacts of Deep Mixing Methods (DMMs) may be minimized, leading to more sustainable geotechnical construction.

EE and CO_2 emissions are measures of environmental impact that may be quantified via a Life Cycle Analysis (LCA). In its full form, LCA is an analysis of all the environmental impacts and their consequences resulting from the entire lifetime of a product, including extraction of raw materials, manufacturing, use and final disposal (EPA 2006; Menzies et al. 2007). Conducting full LCAs requires considerable time and effort, even for projects with few materials and environmental impacts (Shillaber et al. 2015a). However, LCAs may be "streamlined" by limiting the assessment to specific impact factors, and/or limiting the analysis boundaries (Todd and Curran 1999). Focusing the assessment on EE and CO_2 emissions is a form of LCA streamlining. The advantage of streamlining is that the impacts of more complex ground improvement projects can be evaluated without the time and effort required for a full LCA.

Sustainability considerations exist in three key realms: environment, society and economy (Parkin 2000). Many societal issues are considered during the overall project planning and incorporated into project performance criteria and specifications. Since methods to quantify and minimize monetary costs are already common practice in geotechnical engineering, reducing environmental impact by minimizing EE and CO_2 emissions is a key step toward sustainable development that is within the control of geotechnical engineers engaged in ground improvement projects (Shillaber et al. 2015a).

Recently, methods have been developed for conducting EE, and/or CO_2 emissions assessments for geotechnical works; e.g., the EFFC-DFI Geotechnical Carbon Calculator (Carbone 4 2014; Lemaignan and Wilmotte 2013), and the Streamlined Energy and Emissions Assessment Model (SEEAM) developed by Shillaber et al. (2015b). For the analysis presented herein, the SEEAM has been used.

The SEEAM is a streamlined LCA method that quantifies EE and CO_2 emissions from the extraction and manufacturing of materials through the completion of construction. The major components of the SEEAM analysis are: 1) material impacts; 2) material transportation impacts; 3) site operations impacts; and 4) waste transportation impacts. Generally, the analysis is performed by multiplying the total quantity of a material, transportation, or fuel by respective unit coefficients of EE and CO_2 emissions; additional details are given in Shillaber et al. (2015b).

5.3 CASE HISTORY PROJECT: LEVEE LPV 111 IN NEW ORLEANS, LA

The LPV 111 project in New Orleans, LA is the largest application of DMMs within the U.S. to date (Cali et al. 2012). The project involved raising the crest elevation of an 8.5 km long levee section by about 3 m in order to reach the 100 year flood protection level. At LPV 111, the footprint for an earthen levee without ground improvement would have extended into protected lands. To prevent this, design options included: 1) a DMM supported embankment; 2) use of Prefabricated Vertical Drains (PVDs) to strengthen the foundation soils by preconsolidation; 3) a pile supported reinforced concrete T-wall (Cali et al. 2012). Ultimately, the DMM option was selected for construction.

The DMM design at LPV 111 involved installing panels of overlapping 1.6 m diameter cylindrical deep mixed columns. The deep mixed panels were installed perpendicular to the crest line of the levee and had a design unconfined compressive strength of 690 kPa (Cooling et al. 2012). The columns extended 1.5 m into a stiff Pleistocene clay layer underlying approximately 21 m of existing clay levee fill, soft clays, peat and organic clays (Cooling et al. 2012). Between the panels, additional deep mixed columns were installed beneath the levee crest centerline, and geogrid was installed over the mixed zone prior to embankment construction to reduce potential differential settlement (Cooling et al. 2012).

The design of the embankment fill was based on guidelines from the U.S. Army Corps of Engineers Hurricane Protection Office. These require fill to be classified as CL or CH based on ASTM D2487, with no more than 35% sand, no more than 9% organic material, and a plasticity index of 9 or more (Cooling et al. 2012). In addition to borrow material, the wet method DMM spoils were dried in stockpiles on-site for 3 to 7 days, and then used as embankment fill (Druss et al. 2012). Typical elevation and plan views of the DMM supported levee design are shown in Figure 5.1.

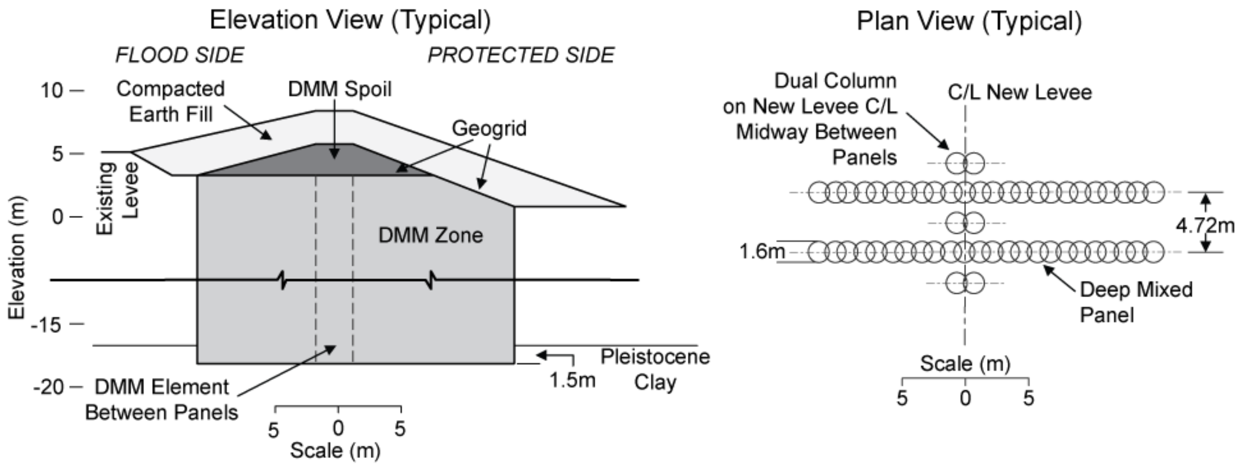

Figure 5.1 Typical sections of the Deep Soil Mixing zone at LPV 111 (adapted from Cooling et al., 2012)

DMM construction at LPV 111 involved 417,000 tonnes of binder, 454,000 m^3 of water and over 3.9 million liters of diesel fuel to treat 1.4 million m^3 of foundation soil; a binder ratio of about 0.3 tonnes/m^3 (Schmutzler et al. 2012; Shillaber et al. 2015b). Additional quantities of materials for embankment construction and material transportation are detailed by Shillaber et al. (2015b). At LPV 111, the best performing binder based on bench scale and field testing was used for construction; it was composed of 75% slag (a waste material from steel manufacturing) and 25% Portland cement (Bertero et al. 2012).

After construction was completed, Shillaber et al. (2015b) compared the EE and CO_2 emissions of the three major LPV 111 design alternatives using the SEEAM, as shown in Table 5.1.

Table 5.1 Embodied energy and CO_2 emissions for LPV 111 design alternatives, data from Shillaber et al. (2015b).

LPV 111 Design Alternative	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Estimated Cost (URS Group 2008)
Deep Soil Mixing	1,174,000	147,000	$ 372,800,000
Prefabricated Vertical Drains	809,000	64,000	$ 361,000,000
Pile Supported Concrete T-Wall	2,755,000[a]	211,000[a]	$546,600,000

[a]Value represents materials alone; site operations, material and waste transportation not included.

The DMM design was selected for construction based on risk and reliability, cost, environmental impact, construction schedule, required right-of-way and operation and maintenance considerations (Cali et al. 2012). While the PVD alternative had the least EE and CO_2 emissions, construction time would have exceeded schedule requirements (URS Group 2008). Therefore, the DMM alternative was the most sustainable design given all the selection criteria, including cost and performance considerations. Herein, we examine the EE and CO_2 emissions of materials and methods associated with DMM more closely.

5.4 SEEAM RESULTS FOR SUSTAINABILITY OPTIMIZATION OF DEEP MIXING METHODS

Once selected, a DMM design can be further optimized for sustainability by addressing material selection and usage, as well as spoil handling considerations. To demonstrate the influence of these factors, the EE and CO_2 emissions for three different DMM scenarios for LPV 111 were analyzed: 1) the as-built design using the slag-Portland cement binder with recycling of DMM spoil; 2) a binder of 100% Portland cement with recycling of DMM spoil; and 3) the as-built design binder with disposal of the DMM spoil instead of recycling.

Tables 5.2 and 5.3 summarize the contribution of various aspects of the construction to the total EE and CO_2 emissions. The proportions of the total EE and CO_2 emissions associated with each aspect of the construction for each scenario are shown graphically in Figures 5.2-5.4.

Table 5.2 LPV 111 Deep mixing and embankment construction embodied energy summary.

	As Built[a] (GJ)	100% Portland Cement Binder[b] (GJ)	No DMM Spoil Recycling[c] (GJ)
Materials	762,000	2,038,000	762,000
Materials Transportation	151,000	127,000	197,000
Site Operations	261,000	261,000	269,000
Waste Transportation	0	0	50,000
TOTAL	**1,174,000**	**2,426,000**	**1,278,000**

Table 5.3 LPV 111 Deep mixing and embankment construction CO_2 emissions summary.

	As Built[a] (tonnes CO_2)	100% Portland Cement Binder[b] (tonnes CO_2)	No DMM Spoil Recycling[c] (tonnes CO_2)
Materials	105,000	388,000	105,000
Materials Transportation	22,000	18,000	26,000
Site Operations	20,000	20,000	20,000
Waste Transportation	0	0	4,000
TOTAL	**147,000**	**426,000**	**155,000**

Notes for Tables 5.2 and 5.3:

[a] Design includes 75% slag, 25% cement binder and recycling of DMM spoil as embankment fill.

[b] Design includes recycling DMM spoil as embankment fill.

[c] The as-built design without recycling of DMM spoil as embankment fill.

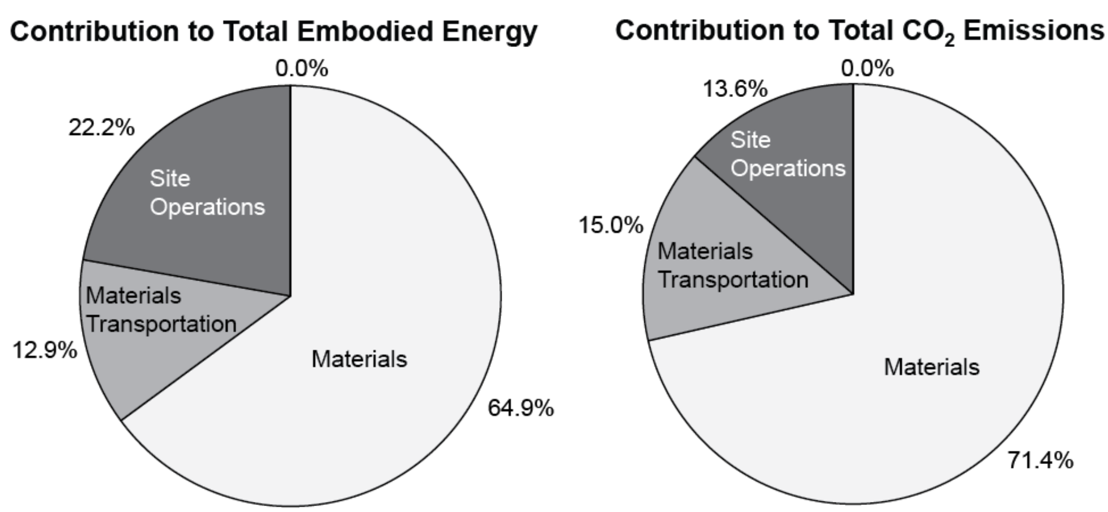

Figure 5.2 Contribution from various components of the construction to total embodied energy and CO_2 emissions for LPV 111, as built, including recycling of deep mixing spoil as embankment fill.

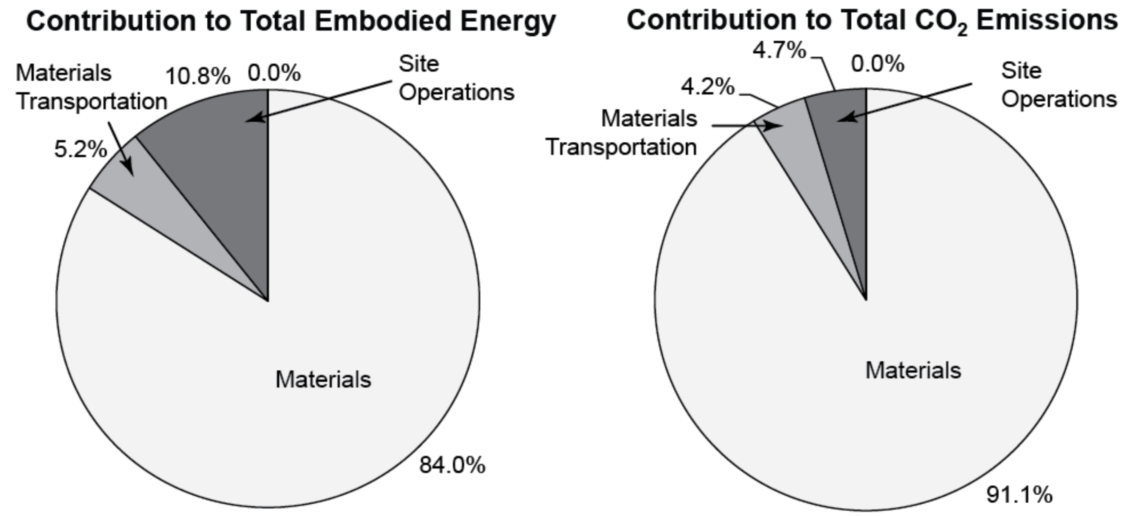

Figure 5.3 Contribution from various components of the construction to total embodied energy and CO_2 emissions for LPV 111, 100% Portland cement binder, including recycling of deep mixing spoil as embankment fill.

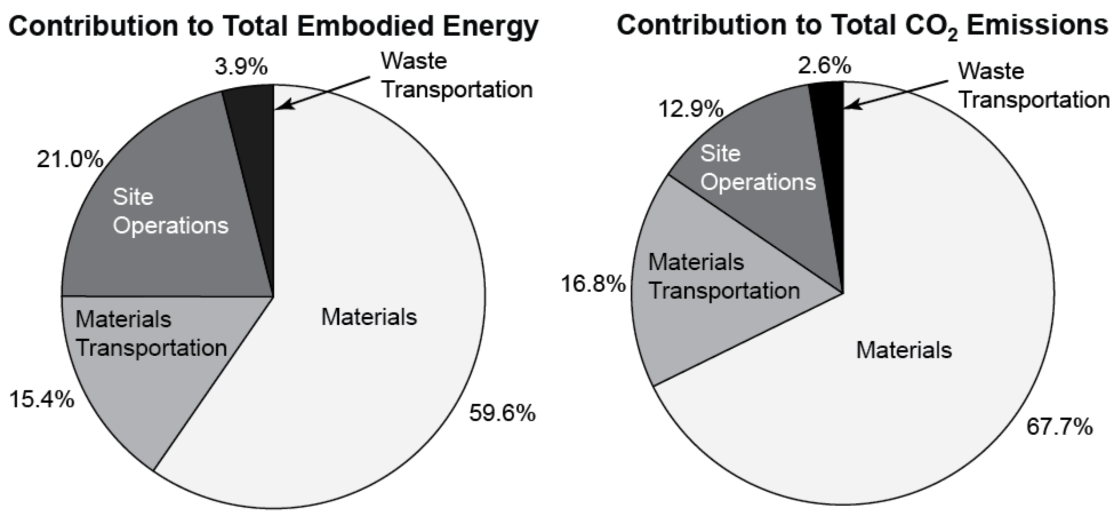

Figure 5.4 Contribution from various components of the construction to total embodied energy and CO_2 emissions for LPV 111, as built design without deep mixing spoil recycling.

5.4.1 Influence of Material Selection

As shown in Figures 5.2-5.4, materials are responsible for the largest proportion of EE and CO_2 emissions for all three of the LPV 111 DMM alternatives explored in this analysis. This finding agrees with those of other researchers conducting EE and CO_2 emissions assessments of geotechnical works (Chau et al. 2008; Chau et al. 2012; Inui et al. 2011; Soga et al. 2011).

The 100% Portland cement binder would result in total project EE and CO_2 emissions of 2,426,000 GJ and 426,000 tonnes, respectively. This is 106.6% more EE and 189.8% more CO_2 emissions than the as-built design. The very large difference in the EE and CO_2 emissions between these scenarios is illustrated graphically in Figure 5.5. For this DMM scenario, materials account for 84.0% of total EE and 91.1% of total CO_2 emissions (Figure 5.3), compared to 64.9% of total EE and 71.4% of total CO_2 emissions for the as-built design with the 75% slag, 25% Portland cement binder (Figure 5.2).

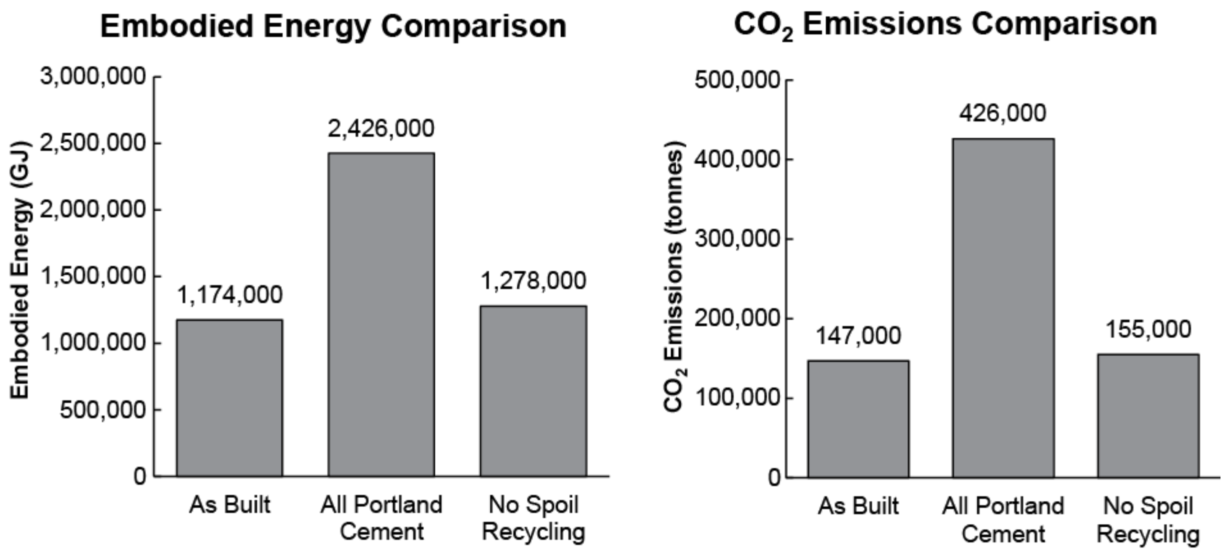

Figure 5.5 Comparison of total embodied energy and CO_2 emissions for three deep mixing scenarios.

5.4.2 Influence of Spoil Handling

Disposing of the DMM spoils instead of recycling them as embankment fill would result in total project EE and CO_2 emissions of 1,278,000 GJ and 155,000 tonnes, respectively. This is 8.9% more EE and 5.4% more CO_2 emissions than the as-built design with on-site spoil recycling. See Figure 5.5 for a graphical comparison.

As shown in Figures 5.2-5.3, there is no contribution to EE or CO_2 emissions from waste transportation when the DMM spoil is recycled on-site and used as embankment fill. This is based on the assumption that all of the generated DMM spoil is used as fill and no other waste is transported from the site. When the DMM spoil is not recycled (Figure 5.4), waste transportation accounts for 3.9% of the total EE and 2.6% of the total CO_2 emissions for the project. While the proportion of the total EE and CO_2 emissions associated with waste handling is small, wasting the DMM spoil also requires importing more embankment fill. As a result, the EE and CO_2 emissions for materials transportation and site operations are increased relative to the as-built design (see Tables 5.2-5.3, Figure 5.2 and Figure 5.4).

5.5 DISCUSSION

The significantly higher EE and CO_2 emissions for the 100% Portland cement binder result from the greater energy and CO_2 emissions intensity of Portland cement compared to slag. Despite being generated by a highly energy and emission intensive process (i.e., steel production), slag is a waste byproduct; the EE and CO_2 emissions from the process by which it is generated are associated with the produced material (steel) and not the waste byproduct (slag). When slag is used as a construction material, the only energy and CO_2 emissions linked to it are those associated with processing it into a useful form.

Even though the slag/cement binder for LPV 111 was selected based on its physical performance (Bertero et al. 2012), its environmental performance in terms of EE and CO_2 emissions is also superior to binders that utilize higher proportions of Portland cement. Binders that utilize lime would also have a significant influence on total project environmental impacts via EE and CO_2 emissions, since the production process of lime is similar to that of Portland cement.

Holt et al. (2010) and Jefferson et al. (2010) warn that using a single impact factor (e.g., EE or CO_2 emissions) for sustainability does not necessarily account for other societal, economic or environmental issues which may be more significant. While this concern is legitimate, there is also a deep interrelatedness of the three dimensions of sustainability in that environmental impacts such as EE and CO_2 emissions can have environmental, social and economic consequences (Murphy 2012).

For example, from the LPV 111 assessment comparing binder materials, the 100% Portland cement binder results in significantly more EE and CO_2 emissions for the finished project than the 75% slag, 25% Portland cement binder. The additional non-renewable material and energy resources consumed to produce the Portland cement reduces the supply of those resources for society in the future. A decrease in supply could lead to increased costs. Since the amount of energy and materials consumed is also linked to potential social and economic consequences, the slag/cement binder is superior from an environmental, social and economic perspective.

Further benefits of using the slag/cement binder are derived from recycling a waste material (slag) as a building material. This usage diverts the slag from the waste stream, where it would otherwise be disposed. Disposal results in tipping fees and the usage of solid waste landfill capacity, which reduces the space available for additional waste at existing disposal facilities and ultimately leads to more demand for additional waste landfills to accommodate disposal needs. Siting and constructing additional solid waste disposal facilities results in changes to land use and has other effects on society and the economy, particularly resistance from local communities.

The same benefits of diverting material from the waste stream are realized by recycling DMM spoil on-site. In this case, the EE and CO_2 emissions savings are not nearly as significant as they are for binder material selection because the borrowed fill has a low energy and CO_2 emissions intensity. However, designing to eliminate the energy and CO_2 emissions from waste disposal still has social and economic benefits. Aside from saving tipping fees and waste disposal capacity, recycling DMM spoil on-site also results in reduced trucking requirements. This provides cost savings for the project, reduces wear and tear on roadways and reduces traffic.

In addition to reducing the waste stream, recycling DMM spoil as fill on-site reduces the quantity of imported material required to complete construction. Reducing the quantity of imported fill material consumed by the construction reduces trucking requirements, the amount of fuel consumed to extract the borrow material and the amount of land disturbed. Land is a limited resource; therefore land use changes resulting from the extraction of borrow material can be accompanied by significant adverse environmental, social and economic consequences. The land could potentially be left undevelopable in the future and natural habitats and ecosystems could be damaged. Transporting additional borrow material that could otherwise be replaced by recycled spoil involves the same societal and economic consequences as described for disposal trucking.

Thus, while the authors agree with Holt et al. (2010) and Jefferson et al. (2010) that quantifying EE and CO_2 emissions is not a complete environmental impact or sustainability assessment, quantifying and minimizing these factors in DMM design can have significant beneficial outcomes for the environment, society and project costs, which are all important considerations in sustainable development.

5.6 RECOMMENDATIONS FOR BEST PRACTICE

When preliminary project planning and design have determined that DMMs will best meet the goals of performance, cost, and sustainable development, it is recommended that EE and CO_2 emissions, and monetary cost be quantified and minimized in the final selected DMM design. In so doing, designers and contractors should pay particular attention to the selection of binder materials and the handling of DMM spoils, when applicable.

Binder alternatives that involve low EE and CO_2 emissions are recommended over traditional Portland cement and lime in order to achieve reductions in project EE and CO_2 emissions. At present, slag, fly ash and slag/cement or fly ash/cement blends may be good alternatives. However, to meet sustainable development goals, any acceptable DMM design must use a binder that achieves the project performance requirements, even if the EE and CO_2 emissions are greater than other alternatives. In addition to currently available materials, developing effective alternative binder materials for DMM is an area for future research. In selecting materials, it is also recommended that preference be given to locally available alternative binder materials in order to reduce material transportation and its associated impacts.

When wet deep mixing methods are utilized, designers and contractors should consider the possibility of recycling the spoil material on-site whenever possible. If adequate properties can be achieved, DMM spoil can be used as a locally sourced alternative fill material for use in the site working pad, or in structures like an earthen levee, dam or highway embankment. VandenBerge et al. (2015) recommend that locally sourced alternative fill materials be used for the sustainable development of earth structures; LPV 111 is a demonstration that this kind of spoil recycling is feasible and that required properties can be obtained (Druss et al. 2012).

If the project where a DMM is being utilized does not require any additional fill, or if the required fill properties cannot be achieved from the DMM spoils, it is recommended that the DMM spoils be sent to a processing and recycling center for later use instead of to a waste landfill. That way, the processed spoil material can be supplied to another site for which it has suitable properties, reducing the land use impacts associated with both disposal of the spoils and borrowing of needed fill material in the future.

5.7 SUMMARY AND CONCLUSION

The influence of binder selection and spoil handling on the total EE and CO_2 emissions associated with DMMs have been explored using the LPV 111 project in New Orleans, LA as an example. The results of assessments for three different DMM scenarios at LPV 111 show that if the DMM binder was composed of 100% Portland cement, the EE and CO_2 emissions would be 106.6% and 189.8% greater than the as-built design that utilized a binder of 75% slag, 25% Portland cement, respectively. In addition, if the spoils from the DMM were disposed, the EE and CO_2 emissions would be 8.9% and 5.4% greater than the as built design with spoil recycling on-site, respectively.

Reducing project EE and CO_2 emissions by materials selection and on-site spoil recycling was shown to have an influence on environmental, social and economic factors. Some of these include natural resource availability, energy resource use and costs, traffic and road wear, land use demand, trucking fees, tipping fees and disposal facility capacity.

It is recommended that DMM designs that meet performance requirements should be optimized to minimize EE and CO_2 emissions, and monetary costs. Based on the analysis presented in this paper, there are two key approaches to minimize EE and CO_2 emissions associated with DMMs. First, use waste materials (such as slag or fly ash) or other low EE and CO_2 emissions alternatives to Portland cement and lime in the binder. Preference should be given to locally available binder materials to reduce the impacts associated with transportation. Second, recycle any DMM spoils. Preference should be given to recycling spoils on-site for a working pad or other construction, but transporting the spoil to a processing and recycling center for later use is preferred over waste landfilling.

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Chapter 6: A Framework to Account for Uncertainty in Energy and Carbon Assessment of Ground Improvement Works

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Relevant Appendices:

Appendix A: SEEAM Spreadsheet Calculator Screen Shots

Appendix B: SEEAM Spreadsheet Calculator User Manual

Appendix J: Development of Embodied Energy and CO_2 Emissions Coefficients' Lognormal Distribution Parameters

Appendix K: Comparing Monte Carlo Simulation and an Analytical Approach to Handling Uncertainty in SEEAM Analyses

Appendix L: Pearson Hall Rammed Aggregate Columns Construction Data and Unit Quantities

Appendix M: Pearson Hall SEEAM Spreadsheet Calculator Results and Monte Carlo Simulation Results Summaries

Appendix N: Kriging to Estimate Top of Rock Elevation at the Pearson Hall Construction Site

Appendix O: Comparison of Methods for Accounting for Subsurface Variability in SEEAM Analyses

Appendix P: Comparing the Total Embodied Energy and CO_2 Emissions of Project Alternatives

6.1 ABSTRACT

Embodied energy (EE) and carbon dioxide (CO_2) emissions assessments have become more common as sustainable development considerations are incorporated into geotechnical practice. To date, methods developed to conduct such assessments are deterministic; however, given the inherent variability in nature and in industrial processes, deterministic calculations for the EE and CO_2 emissions of a project are an incomplete representation of reality. In this paper, the development of a framework to account for uncertainty in assessments of total project EE and CO_2 emissions is described, using the construction of rammed aggregate columns for foundation support of a new dormitory building on the Virginia Tech campus as a case history. The framework uses the SEEAM method (Shillaber et al. 2015b) and Monte Carlo simulation to generate simulated data sets of total EE and CO_2 emissions for a project, based on variability in both the EE and CO_2 coefficients and the subsurface conditions. The framework assumes the EE and CO_2 emissions coefficients follow a lognormal distribution. The subsurface conditions of interest (e.g., undrained shear strength, permeability, top of rock elevation) are considered to follow the best fit distributions to histograms of values obtained from the geotechnical investigation. Using the Monte Carlo simulated data, the means, standard deviations and confidence intervals for total EE and CO_2 emissions can be determined. In addition, statistical inference can be used with the simulated data to determine if different project alternatives result in significantly different EE and CO_2 emissions. This information can assist geotechnical engineers in making more sustainable project decisions, thus adding value to their services.

CE Database subject headings: Uncertainty principles; Energy consumption; Energy efficiency; Carbon dioxide; Soil stabilization; Geotechnical engineering

6.2 INTRODUCTION

Advancements have been made in the field of geotechnical engineering to facilitate the development of more sustainable geotechnical works. These include qualitative assessment methods based on indicators, such as GeoSPeAR (Holt et al. 2010), and specialized quantitative assessment methods such as the multicriteria sustainability assessment system for pile foundations (Misra 2010; Misra and Basu 2012), the Social Sustainability Evaluation Matrix for geoenvironmental remediation (Reddy et al. 2014), the EFFC-DFI Geotechnical Carbon Calculator (Carbone 4 2014; Lemaignan and Wilmotte 2013), and the Streamlined Energy and Emissions Assessment Model (SEEAM) (Shillaber et al. 2015b; Shillaber et al. 2016). Qualitative methods such as GeoSPeAR are well suited to address a wide variety of sustainability concerns. The quantitative methods focus primarily on a single consideration for sustainability; for example, life cycle cost, Greenhouse Gas (GHG) emissions and energy consumption, or human health effects. While these methods alone do not provide complete information about how sustainable a project is, they are well suited to directly illustrate the magnitude of the increase or reduction in specific impacts due to changes in the project.

Geotechnical practice has not historically based decisions on the environmental impacts of projects; performance and cost are the key metrics in decision making (Shillaber et al. 2015a). As such, the recent development of streamlined life cycle analysis (LCA) methods for quantitative environmental impact assessment of geotechnical projects via emissions and embodied energy (EE) (i.e., all energy required to bring something to its present state (Chau et al. 2012; Inui et al. 2011; Soga et al. 2011)) can benefit engineers and clients by providing information that can enable them to make decisions that lead to more sustainable projects. However, existing streamlined LCA methods for the geotechnical profession (e.g., the EFFC-DFI Geotechnical Carbon Calculator and the SEEAM) are heavily dependent upon estimated or known construction quantities required for the design, as well as the values of unit energy and/or emissions coefficients for each construction material or activity. At their current stage of development, both methods are also deterministic and are not able to reflect the actual uncertainty that exists in the assessment. A critical next step in improving these analyses is to account for the uncertainty, presenting results in the form of a mean, standard deviation and confidence interval. Differences between project alternatives can then be assessed using the additional insight of statistical inference, rather than relying on a direct comparison of deterministic values.

In this paper, the development of a framework to incorporate uncertainty into estimates of EE and carbon dioxide (CO_2) emissions via the SEEAM method (Shillaber et al. 2015b) is presented. The framework utilizes Monte Carlo simulation to generate the resulting mean, standard deviation and 90% confidence interval for total EE and CO_2 emissions. Monte Carlo simulation is a stochastic statistical method that involves generating a simulated data set via discrete deterministic calculations (Fenton and Griffiths 2008; Kalos and Whitlock 1986). The confidence interval (CI) represents the upper and lower bounds between which a specified proportion of the simulated data lies (e.g., 90%). A case history project was used to develop the framework by comparing estimates of EE and CO_2 emissions resulting from actual construction quantities with estimates made using the design and subsurface data from the geotechnical investigation.

6.3 BACKGROUND

6.3.1 Uncertainty

There are two categories of uncertainty: 1) aleatory uncertainty; and 2) epistemic uncertainty. Aleatory uncertainty is natural randomness, which cannot be reduced or eliminated. An example is the spatial variation of a geotechnical parameter in a layer that is nominally uniform

(Nadim 2007). Epistemic uncertainty is uncertainty due to a lack of knowledge, such as measurement uncertainty, statistical uncertainty due to limited observations and model uncertainty. Epistemic uncertainty can be reduced or eliminated with additional data and/or better methods (Nadim 2007).

6.3.1.1 Uncertainty in Life Cycle Assessments of Energy and Carbon

There can be significant uncertainty in LCAs, potentially leading to different conclusions in comparative studies (de Koning et al. 2010). Three contributors to uncertainty in LCAs are: 1) the model, 2) scenarios, and 3) parameters and/or data (de Koning et al. 2010; Johnson et al. 2011). Model uncertainty is derived from the model structure and boundary conditions. Scenario uncertainty arises from the different choices made, which influence future states upon which the model depends. Parameter or data uncertainty is the uncertainty in the underlying data informing the analysis. These three sources of uncertainty in LCAs are primarily epistemic, but parameter uncertainty also has an aleatory component. Historically, LCAs have primarily focused on addressing parameter uncertainty, but model and scenario uncertainty (such as the selection of boundary conditions and the handling of wastes) can lead to significant differences in the outcome of the assessment, adversely affecting the reliability of comparisons of alternative products (de Koning et al. 2010).

Methods like the SEEAM provide consistent models for the comparison of different geotechnical alternatives. When consistent models and scenarios are used for LCAs, the primary source of uncertainty is that of the input parameters. Many researchers recommend using stochastic statistical methods, such as Monte Carlo simulation, to account for parameter uncertainty in LCAs (de Koning et al. 2010; Johnson et al. 2011; May and Brennan 2003; Ries 2003; Wang and Shen 2013). When sufficient data exists to define a distribution for the parameter, Monte Carlo simulation can proceed directly using a defined function that describes the distribution and a random number generator to produce random parameter values (Ries 2003). When there is insufficient data to define a distribution for the parameter, some researchers have developed methods of converting qualitative data into a theoretical probability distribution (May and Brennan 2003; Wang and Shen 2013). Johnson et al. (2011) offered a simpler method of selecting an input parameter distribution based on limited known information: 1) if a range of values is known, use the uniform distribution; 2) if the low, most likely and high values are known, use a triangular distribution; and 3) if variance is known, use the normal or lognormal distribution.

6.3.1.2 Sources of Uncertainty in Geotechnical Embodied Energy and CO_2 Emissions Assessments

Depending on the specific details of the project, there are three major sources of uncertainty that can affect energy and GHG emissions assessments made prior to construction: 1) subsurface conditions, 2) industry average EE and GHG emissions coefficients used in the analyses, and 3) GHG conversions to an equivalent quantity of CO_2 (CO_{2eq}) using Global Warming Potential (GWP) values. These GWP values are determined based on the ability of a GHG to absorb infrared radiation in a given period of time relative to CO_2 (IPCC 2013).

When accounting for uncertainty in energy and emissions estimates for geotechnical works, there are two distinct situations: 1) variable subsurface conditions do not have a significant influence on required construction quantities, and 2) variable subsurface conditions have a significant influence on construction quantities and the actual quantities may deviate significantly from the engineer's estimate based on conditions encountered during construction. In the first case, the geotechnical design accounts for subsurface variability and any major changes during construction are unlikely. An example is the application of deep soil mixing to create a seepage cutoff, where deep mixed elements are installed from the working grade to a specified tip elevation.

Examples of the second case include constructing geotechnical elements (e.g., drilled shafts, driven piles, rammed aggregate columns) that are specified to terminate at bedrock, and permeation grouting to create a seepage cutoff in sandy soils. In both of these cases, the variability in subsurface conditions (e.g., bedrock elevation, soil permeability) across the site can lead to significantly more or less material consumption than the engineer's estimate.

Since the SEEAM method involves computing CO_2 emissions and not GHG emissions, the uncertainty in GHG assessments involving conversions to CO_{2eq} is not a complicating factor. Engineers wishing to conduct GHG emissions assessments should be aware that the GWP values used to convert quantities of GHGs into CO_{2eq} involve significant uncertainty. For instance, according to the IPCC (2013), the 100 year GWP of methane (CH_4), a major GHG released to the atmosphere in addition to CO_2, is 28 with an uncertainty of +/-40%. This implies that 1 tonne of CH_4 emissions has a possible range of 16.8 to 39.2 tonnes of CO_{2eq}. Therefore, when GHG assessments are conducted, the GHGs included in the assessment and all associated GWP values must be reported.

6.4 COMPONENTS OF THE UNCERTAINTY FRAMEWORK

6.4.1 Assumptions

Two primary assumptions are made in the uncertainty framework for SEEAM analyses. First, the EE and CO_2 emissions coefficient values are lognormally distributed when the coefficient is known to be generated from more than one input value. Where only one coefficient value exists with no other data, the coefficient is assumed to be constant at the known value, not following a lognormal distribution. The lognormal distribution was selected for the EE and CO_2 emissions coefficients because it: 1) is commonly used to represent natural processes, 2) can be generated from a known mean and standard deviation similar to the normal distribution (Sleep and Duncan

2014), 3) is a recommended distribution for LCA parameters when variance is known (Ries 2003), 4) is typically the default distribution used for LCA parameters (Guo and Murphy 2012), and 5) does not contain non-zero frequencies for negative values of the parameter (Fenton and Griffiths 2008). Non-zero frequencies for negative values of the EE or CO_2 emissions coefficients are unrealistic for present ground improvement processes.

The second assumption is that the EE and CO_2 emissions from materials are independent from fuel related activities such as site operations and transportation. This independence means that the values of the coefficients are not related or dependent upon one another. For instance, a high value of a material EE or CO_2 emissions coefficient does not imply a high value of a transportation fuel coefficient. However, the coefficients for a fuel used for transportation are assumed to be the same for that fuel if it is used in site operations.

6.4.2 Coefficient Distribution Parameters

Developing an uncertainty framework for SEEAM analyses requires unit EE and CO_2 emissions coefficients that include the mean and standard deviation required to define their lognormal distributions. For each coefficient, the original recommended value presented by Shillaber et al. (2015b) is taken as the mean. Therefore, a deterministic SEEAM assessment yields the theoretical means of total EE and CO_2 emissions. Depending on the original source of the coefficient, the coefficient's standard deviation was either computed directly from input data, obtained from statistics in the Inventory of Carbon and Energy database (Hammond and Jones 2011), or obtained from an uncertainty analysis of life cycle emissions from petroleum fuels (Venkatesh et al. 2011).

Selected EE and CO_2 emissions coefficients for construction inputs are included in Table 6.1. A standard deviation is not available for all materials because insufficient data exists to determine a value in some cases. Materials for which the standard deviation is unknown use the mean value as a constant, without a lognormal distribution.

Table 6.1 Selected embodied energy and CO_2 emissions unit coefficients. The mean and standard deviation define a lognormal distribution for the coefficient.

Material	Unit	Embodied Energy		CO_2 Emissions		Reference
		Mean MJ/Unit	St Dev MJ/Unit	Mean kg CO_2/Unit	St Dev kg CO_2/Unit	
General Steel, Virgin	kg	35.4	12.07	2.71	0.92	ICE v2 Hammond and Jones (2011)
General Steel, World Avg. Recycled Content	kg	25.3	5.92	1.82	0.43	ICE v2 Hammond and Jones (2011)
Portland Cement (U.S.)	kg	4.8	0.98	0.927	0.105	Marceau et al. (2006)
Lime	kg	5.3	2.79	0.78	0.41	Based on ICE v2 Hammond and Jones (2011)
Slag (U.S.)	kg	0.721	0.210	0.021	0.011	Slag Cement Association (2014), ICE v2 Hammond and Jones (2011) for std dev.
Fly Ash	kg	0.1	0.02	0.008	0.002	Based on ICE v2 Hammond and Jones (2011)
Bentonite	kg	1.65		0.101		Jiang et al. (2011); Carnegie Mellon University Green Design Institute (2008)
Aggregate: Sand and Gravel or Crushed Rock	kg	0.083	0.12	0.0048	0.0069	Based on ICE v2 Hammond and Jones (2011)
Sand	kg	0.081	0.23	0.0048	0.0136	Based on ICE v2 Hammond and Jones (2011)
General Plastics (Average)	kg	80.5	37.67	2.73	1.28	Based on ICE v2 Hammond and Jones (2011)
Polyethylene (General)	kg	83.1	32.77	2.04	0.80	Based on ICE v2 Hammond and Jones (2011)
PVC (General)	kg	77.2	21	2.61	0.71	Based on ICE v2 Hammond and Jones (2011)
Water	L	0.01		0.001		ICE v2 Hammond and Jones (2011)
Diesel	L	43.0	1.43	3.25	0.11	Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
Gasoline	L	39.7	1.23	2.83	0.09	Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
Compressed Natural Gas (CNG)	kg	55.5		2.87		Shillaber et al. (2014)
Electricity (U.S. Avg. Generation Mix)	kW-hr	8.74		0.627		Shillaber et al. (2014)

6.4.3 Monte Carlo Simulation

In the uncertainty framework, Monte Carlo simulation is used to generate simulated data sets of total EE and CO_2 emissions, where each value in the data sets is computed by direct application of the SEEAM method. The EE and CO_2 emissions coefficients used for each computed value in each data set are randomly generated. This is accomplished by randomly generating a number between 0 and 1, then inverting the cumulative lognormal distribution function using the randomly generated number and the coefficient mean and standard deviation in order to determine the coefficient value, similar to the method described by Ries (2003). Descriptive statistics and CIs of total EE and CO_2 emissions can be determined directly from the simulated data sets. By plotting the simulated data in histograms, possible realizations of the distributions of total EE and CO_2 emissions can be observed.

An important consideration with Monte Carlo simulation is how many values are required in the simulated data set to achieve the desired level of accuracy in the results. Often, engineers are concerned with extreme values (e.g., probability of failure), however, in this case it is desirable to generate an accurate mean. Therefore, the appropriate number of simulated values in the data set must be determined based on the desired maximum mean error. With the SEEAM method, the selected maximum mean error is +/-2.5% of the mean value, with 90% confidence. This maximum mean error was selected because it can be readily achieved with a moderate number of values in the Monte Carlo simulated data set and generally reflects the degree of accuracy in the input data. Assuming the Monte Carlo simulated data set is approximately normally distributed, the mean error is acceptable if Eq. 6.1, derived using information in Fenton and Griffiths (2008), holds true:

$$0.025\hat{\mu}_g \geq t_{\frac{\alpha}{2},n-1}\frac{\hat{\sigma}_g}{\sqrt{n}} \tag{6.1}$$

where n is the number of values in the simulated data set, $\hat{\mu}_g$ and $\hat{\sigma}_g$ are the mean and standard deviation of the simulated data set, t is the statistic from the t-distribution and α is the desired significance level. For 90% confidence, α = 0.1.

For the case history project described in this paper, a minimum of 600 values are required in the simulated data set to generate +/-2.5% error in the mean with 90% confidence. For the analysis presented herein, a total of 1,000 values in the simulated data set were used (n = 1,000), which is more than sufficient to obtain the desired level of accuracy in the resulting mean.

6.4.4 Accounting for Subsurface Variability

As described previously, for some geotechnical designs and ground improvement technologies, the construction quantities are directly dependent upon site subsurface conditions. Therefore, in order to determine the quantities needed for completing the SEEAM analysis, the relationship between the uncertain and controlling geotechnical parameters (henceforward called the key parameters) and construction quantities must be known. Key parameters may include shear strength, permeability, unit weight and subsurface stratigraphy details such as bedrock elevation. In some cases, there may only be one key parameter governing the design and construction quantities; in others it may be a combination of parameters. Values of each uncertain key parameter must be estimated at locations across the site using information obtained in the geotechnical subsurface and/or laboratory test programs. Then, construction quantities can be determined based on their relationship to the key parameters. Five possible methods for estimating each key parameter across the site or stratum of interest are described as follows and are summarized in Table 6.2:

Method 1) Perform Kriging, a geostatistical interpolation method (Fenton and Griffiths 2008), using data from the geotechnical subsurface and/or laboratory test programs in order to estimate the mean and standard deviation of each key parameter at each ground improvement location across the site. Assuming each key parameter follows a normal distribution at each location, randomly generate a value for each key parameter from the normal distribution at each location.

Method 2) Perform Kriging using data from the geotechnical subsurface and/or laboratory test programs in order to estimate the mean value of each key parameter at each ground improvement location across the site. Then, determine the mean and standard deviation of all estimated values of each key parameter from Kriging. Assuming each key parameter follows a normal distribution defined by the overall mean and standard deviation, randomly generate values of each key parameter at each location.

Method 3) Directly determine the mean and standard deviation of the values for each key parameter across the site (or a given stratum) as obtained from the subsurface and/or laboratory geotechnical test programs. Assuming each key parameter follows a normal distribution defined by this mean and standard deviation, randomly generate values of each key parameter at installation or improvement locations across the site.

Method 4) Plot a histogram of the values of each key parameter across the site (or a given stratum) as obtained from the subsurface and/or laboratory geotechnical test programs. Fit a theoretical distribution to each histogram and determine the appropriate distribution parameters. Use the theoretical distributions to randomly generate values of each key parameter at installation or improvement locations across the site.

Method 5) Directly determine the mean value for each key parameter across the site (or a given stratum) as obtained from the subsurface and/or laboratory geotechnical test programs. Assume the value of each key parameter is constant at this mean value.

Table 6.2 Summary of methods for estimating the values of each key parameter at locations of interest.

Method	Distribution for Key Parameter Estimation	Method of Determining Distribution Parameters	Key Parameter Estimation Method
1	Normal	Kriging generated mean and standard deviation at each location of interest.	Randomly generated from separate normal distributions at each location of interest.
2	Normal	Mean and standard deviation determined from values at all locations of interest as interpolated by Kriging.	Randomly generated from the single normal distribution for each location of interest.
3	Normal	Mean and standard deviation determined from observed values in the geotechnical investigation.	Randomly generated from the normal distribution for each location of interest.
4	Determined from data	Best fit theoretical distribution to a histogram of values from the geotechnical investigation.	Randomly generated from the best fit distribution for each location of interest.
5	None	Mean determined from values observed in the geotechnical investigation.	Assumed constant at the mean value.

6.4.4.1 Kriging Basics

As described, Methods 1 and 2 both estimate the value of the key parameter(s) across the site using geostatistical Kriging. Kriging generates a best estimate of the value of a spatially varying parameter between known data points (Fenton and Griffiths 2008) and may be performed using commercial software, such as ArcGIS (Esri 2013). With software, the user selects the best fit function to known field data plotted in a semivariogram, which shows the dissimilarity in values of the spatially varying parameter between locations separated by certain distance intervals (Goovaerts 1997). This function is then used in an algorithm to estimate the mean and standard deviation of the parameter of interest at desired locations where measurements were not made.

6.5 COMPARING METHODS OF ACCOUNTING FOR SUBSURFACE VARIABILITY

6.5.1 Case History Project for Analysis

In early 2014, construction began on Pearson Hall, a replacement dormitory on the Virginia Tech campus. The foundation design for the new building called for spread footings supported by a total of 364, 0.76 m diameter rammed aggregate columns. Of the columns, 322 were composed of Cement Treated Aggregate (CTA) and extended to bedrock. The remaining 42 columns were composed of Untreated Aggregate (UA) and were required to extend to various specified depths based on their location. The building footprint, along with the geotechnical boring locations and CTA and UTA column locations is shown in Figure 6.1.

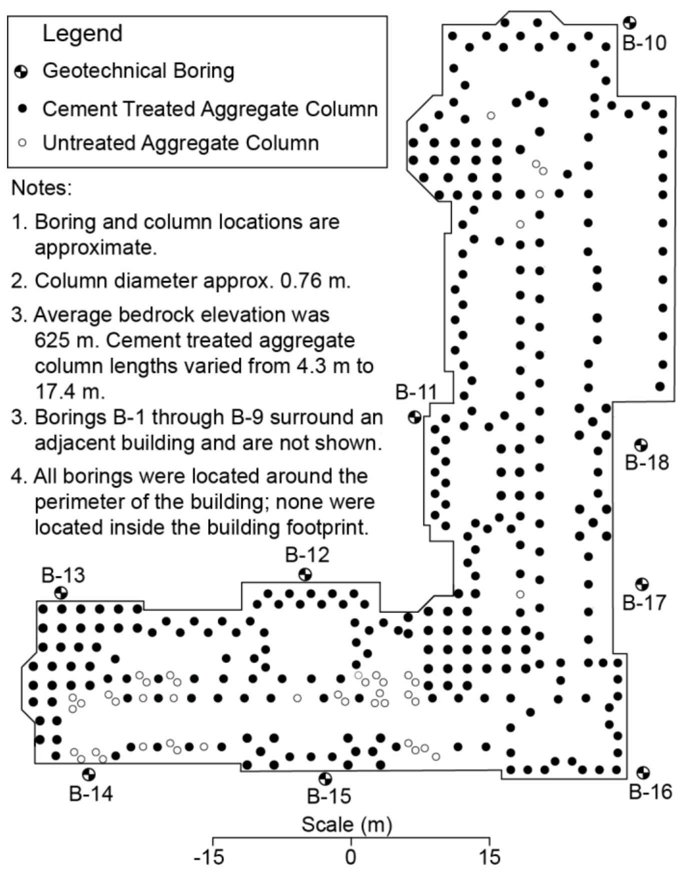

Figure 6.1 Rammed aggregate column layout and geotechnical boring locations around Pearson Hall at Virginia Tech.

Since the CTA columns were to extend to bedrock, the quantity of CTA for the project was directly dependent upon the elevation of bedrock across the site, which is variable. As such, this case history allows for considering uncertainty in both the EE and CO_2 emissions coefficients and the subsurface conditions. Subsurface data and foundation design information were readily available for the project; the contractor also kept and provided records of the fuel and materials consumed during construction.

6.5.1.1 As-Built Material Quantities

In total, 4,185 tonnes of CTA were used to construct 3,219 m of CTA columns at Pearson Hall. A total of 1,193 tonnes of UA were used to construct 752 m of UA columns and a working pad. The combined length of all installed columns was 3,971 m. The CTA columns contained 4% Portland cement by weight. These quantities correspond to about 52 kg of cement and 1,248 kg of aggregate per meter of CTA column, and about 1,405 kg of aggregate per meter of UA column. The equipment performing the construction consumed approximately 11,250 L of diesel fuel, or about 2.8 L per meter of constructed columns. The aggregate materials were delivered to the site in a total of 331 truckloads from a quarry 8 km away. The drilling process produced about 0.45 m^3 of cuttings per meter drilled. Since the drill cuttings were mixed with other waste earth materials from site construction activities, exact waste haul information for the cuttings was not available. Therefore, the waste cuttings were assumed to be transported off-site in trucks with an average load capacity of about 9.1 m^3, for 196 total truckloads of waste material. The waste disposal site was located 16 km from the construction site.

6.5.2 Comparing Methods of Embodied Energy and CO_2 Emissions Estimation

To compare the methods of accounting for subsurface variability in estimates of total EE and CO_2 emissions, Monte Carlo simulation was used with each of the five methods of accounting for subsurface variability, along with the SEEAM method, in order to generate estimates of total EE and CO_2 emissions for the rammed aggregate columns at Pearson Hall. Both the key parameter and the EE and CO_2 emissions coefficients were randomly generated in the Monte Carlo simulations. The different EE and CO_2 emissions estimates were then compared to each other, and to a Monte Carlo simulation conducted using the as-built construction quantities, which only considered variability in the EE and CO_2 emissions coefficients.

Since the CTA columns at Pearson Hall extend to bedrock, Top of Rock (TOR) elevation is the key parameter, as it controls column length and thus material and waste quantities. In this case, the material and waste quantities were determined by multiplying estimated column lengths by the average quantities of each material and waste per unit length of column, as determined from construction data. A summary of TOR elevations across the site as observed in the geotechnical borings is included in Table 6.3. This data was used in all five methods of accounting for subsurface variability. Borings for the geotechnical investigation were located outside the building footprint, while the rammed aggregate columns were installed within the building footprint, as shown in Figure 6.1.

Table 6.3 Geotechnical boring data for top of rock elevation across the Pearson Hall project site.

Boring	Surface Elevation (m)	Top of Rock Elevation (m)
B-1	638.6	625.9
B-2	639.5	627.1
B-3	640.1	631.9
B-4	640.1	626.8
B-5	636.4	624.2
B-6	637.0	620.9
B-7	637.3	627.6
B-8	637.6	620.9
B-9	637.6	617.8
B-10	640.1	624.1
B-11	640.1	617.6
B-12	638.9	622.9
B-13	638.6	620.3
B-14	637.6	625.4
B-15	637.6	617.8
B-16	637.3	620.6
B-17	637.6	622.1
B-18	639.8	624.5

The comparisons of EE and CO_2 emissions estimates were made using statistical inference. Since a theoretical distribution is not fit to the data as part of the Monte Carlo simulation and the results are not assumed to follow a normal distribution, statistical inference is best accomplished using nonparametric statistical hypothesis tests on the simulated data. The null hypothesis for these tests is that there are no significant differences in the EE and CO_2 emissions estimates based on the method of accounting for subsurface variability. The alternative hypothesis is that there are statistical differences between the estimates. When evaluating differences between the EE and CO_2 emissions estimates with nonparametric statistical hypothesis tests, a significance level, $\alpha = 0.1$ was used. The tests involve comparing generated p-values to the significance level, α, where the p-value represents the probability of obtaining a value equal to or more extreme than the observed value, assuming the null hypothesis is true (Ott and Longnecker 2010). When $p < \alpha$, the tests indicate significant differences. All statistical analyses were performed using the software package JMP Pro (SAS Institute 2013).

To begin the statistical comparison, the nonparametric Kruskal-Wallis test (Kruskal and Wallis 1952) was used with the simulated data sets of total EE and CO_2 emissions from all methods of accounting for subsurface variability. The Kruskal-Wallis test detects whether or not all the methods are estimating the same total EE and CO_2 emissions. However, when differences are detected, the Kruskal-Wallis test does not indicate which estimate is different. To determine that, the Steel-Dwass multiple comparison method is used to compare the EE and CO_2 emissions estimates between all pairs of methods of accounting for subsurface variability. The Steel-Dwass method was originally proposed independently by Steel (1960) and Dwass (1960), and was further elaborated on by Critchlow and Fligner (1991).

6.5.2.1 Results

The mean and standard deviation of the estimated total EE and CO_2 emissions from each method of accounting for subsurface variability are shown in Table 6.4. Overall, the methods involving Kriging (1 and 2) resulted in the highest estimated total EE and CO_2 emissions. Method 4 resulted in the lowest estimated EE and CO_2 emissions, and had the closest estimates to the total EE and CO_2 emissions resulting from the as-built construction quantities.

Table 6.4 Mean and standard deviation from Monte Carlo simulations for *n* = 1,000 values of total embodied energy and CO_2 emissions for Pearson Hall, by method of accounting for variability in the key subsurface parameter influencing material quantities (Top of Rock elevation).

Method	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	Std. Dev.	Mean	Std. Dev.
1	2,481	772	306	45
2	2,496	701	303	46
3	2,206	689	270	47
4	1,930	623	232	38
5	2,175	595	267	39
As-Built	**1,931**	**645**	**232**	**39**

For both total EE and CO_2 emissions, the Kruskal-Wallis test revealed that at least one of the methods estimates significantly different total EE and CO_2 emissions from the others ($p < 0.0001$ for both). Since at least one of the methods was significantly different, the nonparametric Steel-Dwass method was used to make all comparisons between the total EE and CO_2 emissions from all pairs of methods of accounting for subsurface variability.

6.5.2.1.1 Methods 1 and 2

Both Methods 1 and 2 involve Kriging to determine values of each key parameter across the site. For the Kriging performed in ArcGIS (Esri 2013) of TOR elevation at Pearson Hall, the exponential function was determined to be the best fit to the empirical semivariogram generated from the TOR elevations at the geotechnical boring locations. ArcGIS used the exponential semivariogram model to estimate the mean and standard deviation of TOR elevation at the desired CTA column locations across the site. Figure 6.2 shows 3D surface plots of the estimated TOR elevations and actual TOR elevations beneath Pearson Hall, where the actual elevations were those observed by the contractor. The mean difference in TOR elevation between the actual elevations and the Kriging estimates is 3.56 m; the minimum difference at any location is 0.02 m and the maximum difference is 10.61 m. As observed in Figure 6.2, the actual TOR surface is both more irregular, and generally lies at higher elevation than the TOR surface estimated by Kriging using data from the geotechnical borings. The irregularity in TOR elevation is not unexpected given the limestone/dolomite bedrock underlying the site is known to be highly variable in other locations. In addition, the drilling tools used for the borings may be better able to advance in variable quality rock than the auger used for the rammed aggregate columns. Overall, Kriging may not be the best method for interpolating TOR elevation in this situation because the site is small, there are relatively few input data values, there is no input data within the building footprint, and the input data are not spaced close enough to capture small separation distances over which significant spatial correlation likely occurs.

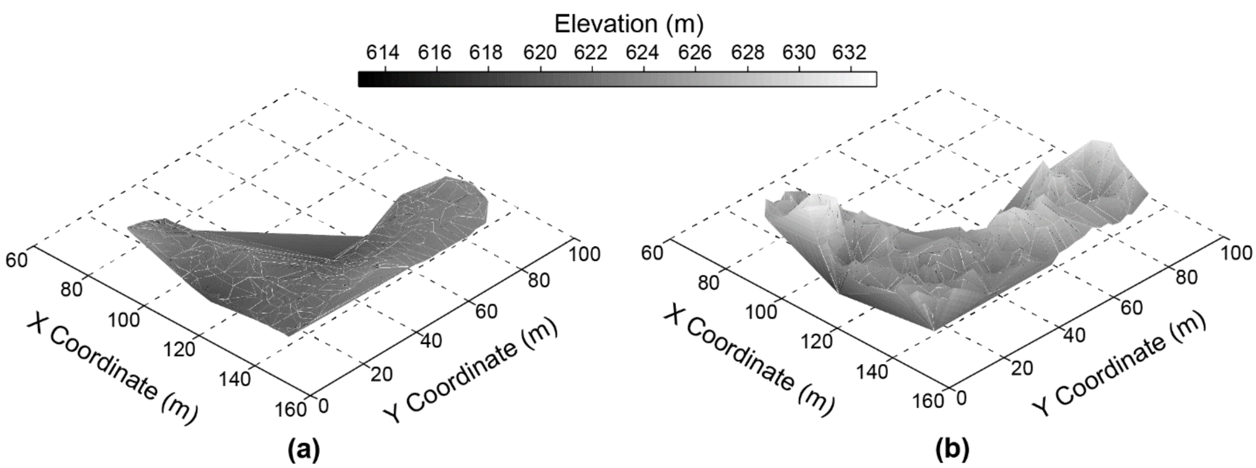

Figure 6.2 (a) Estimated top of rock surface generated using boring data and Kriging with an exponential semivariogram fit. (b) Actual top of rock surface generated based on the top of rock elevation observed by the contractor at each cement treated aggregate column location during construction. The actual top of rock surface is both more irregular, and generally at higher elevation than the estimated surface.

The Steel-Dwass comparison of Methods 1 and 2 revealed that these two methods are not significantly different from each other in the estimated total EE (p = 0.8164) or CO_2 emissions (p = 0.3241). Additionally, both methods estimate significantly different total EE and CO_2 emissions from Methods 3, 4 and 5, and estimate significantly different (greater) total EE and CO_2 emissions than are associated with the as-built material quantities. Methods 1 and 2 estimate the largest total

EE and CO_2 emissions of all the methods considered in this analysis. These results make sense given the difference between the estimated and actual TOR surfaces (Figure 6.2).

6.5.2.1.2 Methods 3 and 5

Method 3 involved determining the mean and standard deviation of the TOR elevation from the geotechnical borings, and then generating random TOR elevations at each CTA column location from a normal distribution defined by the mean and standard deviation. Method 5 simply involved determining the average TOR elevation from all geotechnical borings across the site and assuming the TOR elevation is constant at that value.

The Steel-Dwass comparison of Methods 3 and 5 revealed there is no statistically significant difference in the total EE ($p = 0.9890$) or CO_2 emissions ($p = 0.8069$) estimates between these two methods. Both methods also estimate significantly greater total EE and CO_2 emissions than are associated with the as-built material quantities. While larger than the as-built EE and CO_2 emissions, the estimated total EE and CO_2 emissions from Methods 3 and 5 are significantly less than the estimates from Methods 1 and 2.

6.5.2.1.3 Method 4

Method 4 involved plotting a histogram of TOR elevation, as observed in the geotechnical borings, and then fitting a theoretical distribution to the observed histogram. In this case, a uniform distribution was the best fit to the histogram, defined by the minimum (617.6 m) and maximum (631.8 m) TOR elevations observed in the borings, as shown in Table 6.3. Based on this distribution, TOR elevation at each CTA column location was randomly generated to determine the construction material quantities.

Method 4 results in the smallest mean total EE and CO_2 emissions estimates, and the closest mean total EE and CO_2 emissions to the values associated with the as-built material quantities. In fact, based on the Steel-Dwass multiple comparisons, the EE and CO_2 emissions estimates from

Method 4 do not differ from the as-built total EE and CO_2 emissions with statistical significance (EE, $p = 0.9817$; CO_2, $p = 0.9975$). The estimates of total EE and CO_2 emissions from Method 4 are significantly different from all other methods.

6.5.3 Key Conclusions Regarding the Methods of Accounting for Subsurface Variability

Some key conclusions from the comparison of estimates of total EE and CO_2 emissions for the Pearson Hall case history project made using the five different methods of accounting for subsurface variability are:

1. Kriging may be detrimental to estimates of total EE and CO_2 emissions for sites where a key parameter is highly variable over short distances. In this case, Methods 1 and 2 resulted in the largest estimates of total EE and CO_2 emissions for the rammed aggregate columns at Pearson Hall. Kriging may be beneficial for making EE and CO_2 emissions estimates for larger projects with more input data and a key parameter that does not exhibit significant variability over short distances.
2. There is no benefit to using the more complex method of generating values of TOR elevation from a normal distribution defined by the mean and standard deviation of TOR elevation observed in the geotechnical borings (Method 3) over simply assuming TOR elevation is constant at the mean value observed in the borings (Method 5).
3. Method 4 of accounting for subsurface variability provides the most accurate estimates of total project EE and CO_2 emissions for the Pearson Hall project. Therefore, Method 4 is recommended as a starting point for use in a complete framework to account for uncertainty in total EE and CO_2 emissions estimates for geotechnical ground improvement projects. When the normal distribution is the best fit to the histogram of the key parameter(s), Method 4 converges to Method 3. Since Method 3 was not significantly different from Method 5 for the

Pearson Hall case history project, it may be justified in such instances to simply use Method 5 for the analysis. Analyses of additional case history projects could confirm these conclusions.

6.6 THE RECOMMENDED FRAMEWORK

The resulting framework for estimating total EE and CO_2 emissions using the SEEAM method with information available prior to construction is presented in Figure 6.3. Additional explanatory notes for Steps 2, 4, 5, 7, 8, 9, 10 and 11 are included in the following paragraphs.

In Step 2, the material and waste quantities for the construction may be a function of the key geotechnical parameter(s) across the site, or in a particular stratum. In the analysis for the installation of rammed aggregate columns at Pearson Hall, this step was accomplished by determining the amount of materials required and drill cuttings generated per unit length of column. In the absence of construction data, the specified density and estimated compression of surrounding soil could be used to estimate material quantities per unit length.

In Step 4, the distributions that are fit to the histograms should be valid theoretical probability distributions. Example distributions that may be applicable include (but are not limited to) the normal, lognormal, uniform, and triangular distributions. When there are multiple key parameters, they will not necessarily follow the same type of distribution.

For Step 5, randomly generate values of each key geotechnical parameter at locations where ground improvement will be performed from the best fit theoretical distributions determined in Step 4. Each location will have different randomly generated values of each key parameter. Use the value(s) of the key parameter(s) at each location with the function(s) generated in Step 2 to determine the estimated quantities of materials and waste at each improvement location.

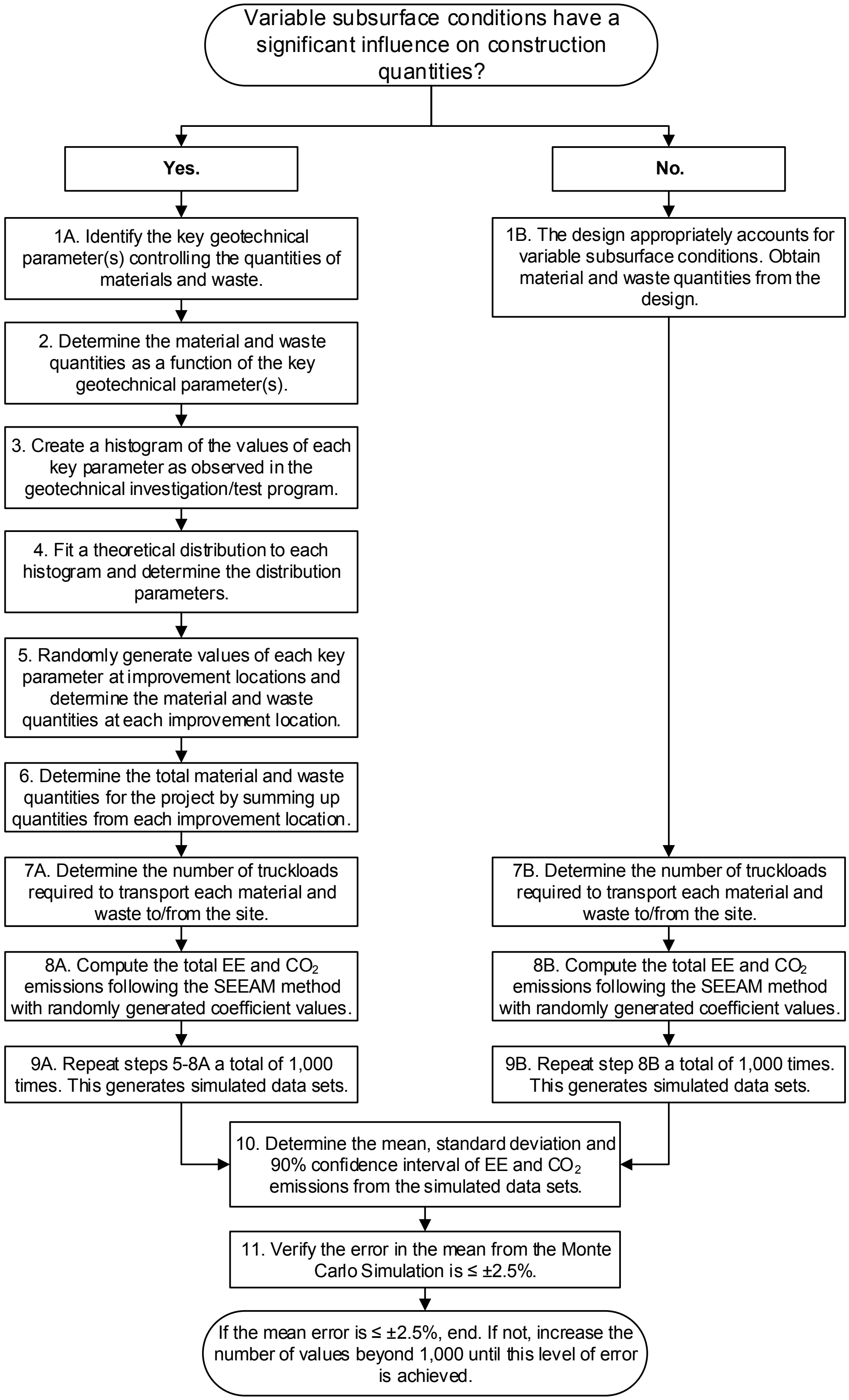

Figure 6.3 Framework for accounting for uncertainty in embodied energy and CO_2 emissions estimates conducted prior to construction. Two possible pathways exist depending on whether or not variable subsurface conditions have a significant influence on construction quantities.

For Step 7 (A and B), if the material and/or waste will be transported by heavy duty trucks, determine the number of truckloads that are required for each over the course of the project. If the material or waste will be transported by other means (e.g., rail or water), it is not necessary to determine the number of "loads" of material that must be transported to or from the site. The SEEAM accounts for these forms of transportation based on the total mass of material alone, which is determined in Step 6 or Step 1B.

In Step 8, follow the SEEAM method (Shillaber et al. 2015b) to determine the total EE and CO_2 emissions associated with the total material and waste quantities determined in Step 6, and the transport quantities determined in Step 7. Randomly generate the values of the EE and CO_2 emissions coefficients for each material used in the project from lognormal distributions defined by the mean and standard deviation of the material coefficients presented in Table 6.1.

Step 9 (A and B) generates 1,000 values of total EE and CO_2 emissions for the project, which constitute simulated data sets. This step completes the Monte Carlo simulation. The simulated data set is recommended to begin with n = 1,000 values because in most cases, this should be sufficient to estimate the mean with an error less than +/-2.5%.

For Step 10, the mean and standard deviation may be determined directly for each of the n = 1,000 simulated data sets for total EE and CO_2 emissions. The lower and upper bounds of the 90% CI are defined by the values of total EE and CO_2 emissions for which 5% (50 out of 1,000) and 95% (950 out of 1,000) of the generated values are less than, respectively. If desired, histograms of total EE and CO_2 emissions may be generated.

Step 11 is accomplished using Eq. 6.1, based on 90% confidence ($\alpha = 0.1$) and the mean and standard deviation generated in Step 10. If the error is $\leq \pm 2.5\%$ of the generated mean value, the analysis is sufficient. If the error is not $\leq \pm 2.5\%$ of the generated mean value, then repeat Steps

5 through 8A (or repeat Step 8B alone if subsurface variability does not have a significant influence on construction quantities) to generate additional possible values of total EE and CO_2 emissions, thus increasing *n*. Repeat Steps 10 and 11 with all generated values to check if the error has been sufficiently reduced. If not, continue adding simulated values of total EE and CO_2 emissions until the error is reduced to $\leq \pm 2.5\%$ of the generated mean value.

6.6.1 Uncertain Factors Not Addressed by this Framework

There are several other uncertain factors that influence SEEAM analyses when conducted prior to construction that are not addressed by this framework. Each of these additional sources of uncertainty could be accounted for with additional methods or additional data. These include:

1) The haul distances for construction materials and wastes, which may not be known prior to construction.
2) The varying amounts of the same material (e.g., aggregate, excavated waste soil) in a truckload of that material.
3) The varying fuel economy of material and waste transportation vehicles of the same size/class based on amount of load, traffic conditions, driver habits and engine technology.
4) Construction equipment selection, including the type, size and power rating.
5) Construction equipment fuel consumption, based on variation in activity, load (dependent on subsurface conditions and tooling), and engine fuel conversion efficiency (i.e., the ratio of flywheel power to the rate of fuel energy supplied to the engine (Shillaber et al. 2014)).

6.7 APPLICATION: COMPARING DESIGN ALTERNATIVES BASED ON EMBODIED ENERGY AND CO_2 EMISSIONS ESTIMATES

Using Monte Carlo simulation to account for uncertainty in EE and CO_2 emissions estimates made prior to construction allows different design alternatives to be compared, and conclusions regarding any differences in EE and CO_2 emissions between alternatives to be drawn with statistical inference. Comparisons between more than two alternatives can be made using the same nonparametric statistical hypothesis tests that were used to detect statistically significant differences between the EE and CO_2 emissions estimates generated using the five different methods of accounting for uncertainty in the key geotechnical parameter (i.e., the Kruskal-Wallis test and the Steel-Dwass method of making multiple comparisons). When only two alternatives are compared, the nonparametric Wilcoxon Rank Sum test, described by Wilcoxon (1945) and Mann and Whitney (1947), may be used.

It is also possible to compare two (and only two) alternative designs by taking the difference between them, as described by de Koning et al. (2010). This is done by subtracting every Monte Carlo generated value of EE and CO_2 emissions for one of the alternatives from the corresponding Monte Carlo generated value from the other alternative to generate difference data sets for EE and CO_2 emissions. The means of the difference data sets may then be determined, and the difference data for EE and CO_2 emissions may be plotted in histograms. If the mean of the difference data is near zero and/or the histogram appears to significantly overlap zero, then the two alternatives are likely not significantly different. If the mean difference is greater or less than zero and the histogram does not cross zero, or only crosses zero in the extreme of its tail, then it is likely the two alternatives involve significantly different EE and/or CO_2 emissions. The location of the histogram (i.e., the sign of the difference) provides an indication of which alternative involves less EE and/or CO_2 emissions.

To draw stronger conclusions when the tail of the histogram overlaps zero, the proportion of the difference values that are greater than or less than zero may be determined by querying the difference data. The proportion of values greater than or less than zero provides an indication of the strength of any conclusions regarding the difference between alternatives. For example, if 2%

of the difference values are less than zero, then there is a 98% chance that one alternative is greater than the other; therefore, the two alternatives are most likely significantly different. If 20% of the values are less than zero, then the alternatives are most likely not different. Shillaber et al. (2016) describe how to practically implement this method of comparing alternatives in more detail.

As an example application of these methods, consider a comparison of the EE and CO_2 emissions generated from the Deep Soil Mixing (DSM) and Prefabricated Vertical Drains (PVDs) design alternatives for levee LPV 111 in New Orleans, LA as described by Shillaber et al. (2015b). Holding the material quantities constant, Table 6.5 shows the deterministic results from Shillaber et al. (2015b) along with the results from a Monte Carlo simulation that considers coefficient variability. Overall, the mean EE and CO_2 emissions generated from the Monte Carlo simulation agree very well with the values generated in the deterministic assessment. The nonparametric Wilcoxon Rank Sum test was used to compare the Monte Carlo simulated data sets of total EE and CO_2 emissions from each alternative. The test revealed the DSM and PVD alternatives have significantly different total EE and CO_2 emissions ($p < 0.0001$ in both instances), with PVDs resulting in less EE and CO_2 emissions than DSM.

Table 6.5 Deterministic and Monte Carlo simulation results for total embodied energy and CO_2 emissions for the deep soil mixing and prefabricated vertical drains alternatives for levee LPV 111, using fixed material quantities.

Method of Analysis		Deep Soil Mixing		Prefabricated Vertical Drains	
		Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Deterministic (Shillaber et al. 2015b)		1,174,000	147,000	809,000	64,000
Monte Carlo Simulation	Mean	1,173,000	147,000	810,000	64,000
	St. Dev.	121,500	11,490	66,600	3,470
	90% CI Low	987,000	129,200	717,000	58,500
	90% CI High	1,390,000	167,000	921,000	69,500

Table 6.6 presents the mean of the difference between Monte Carlo simulated data sets from the two alternatives (DSM – PVDs); histograms of the difference data sets for total EE and CO_2 emissions are shown in Figure 6.4. In this case, the means of the difference (DSM – PVDs) for both EE and CO_2 emissions are greater than zero, which indicates the DSM is likely responsible for more EE and CO_2 emissions than the PVDs. The histograms of EE and CO_2 emissions for the difference confirm this conclusion; only the extreme left tail of the EE difference histogram extends below zero (Figure 6.4a), while the CO_2 emissions difference histogram contains no values that are less than zero (Figure 6.4b). When querying the EE difference data, only 4 of the 1,000 EE difference values (0.4%) were less than zero, while none of the CO_2 emissions difference values were less than zero. This fact confirms the DSM involves more total EE and CO_2 emissions than the PVDs for LPV 111.

Table 6.6 Mean difference in total embodied energy and CO_2 emissions between the deep soil mixing and prefabricated vertical drains alternatives for levee LPV 111, based on *n* = 1,000 values of total embodied energy and CO_2 emissions from Monte Carlo simulation.

Method of Analysis	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Monte Carlo Simulation Difference (DSM – PVDs)	364,000	83,200

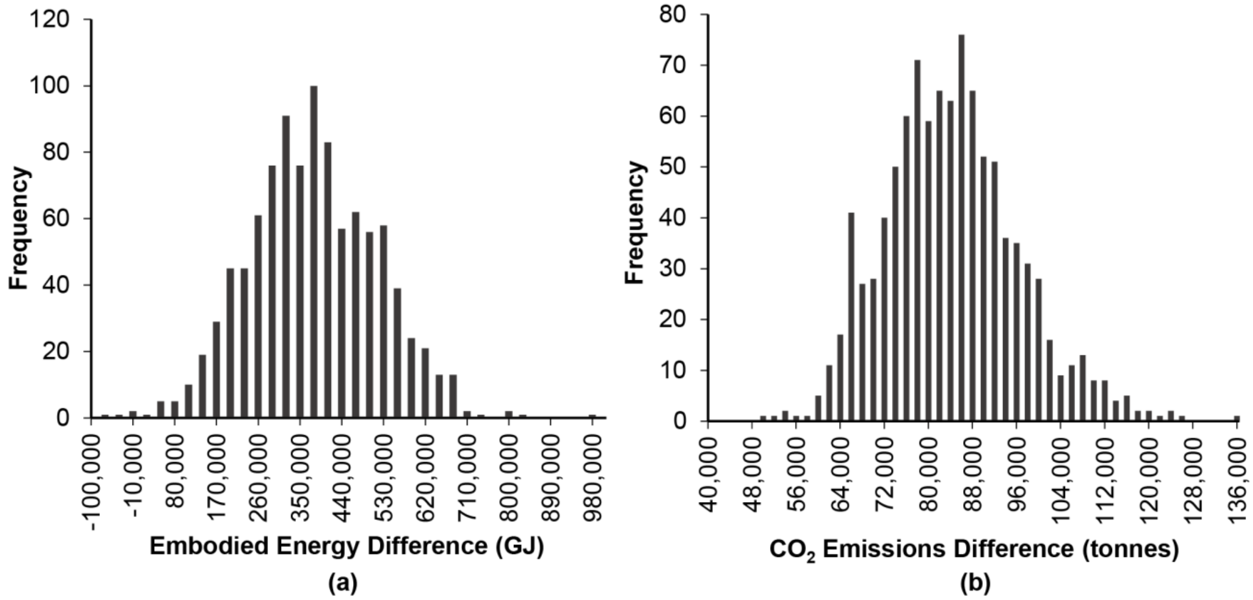

Figure 6.4 (a) Histogram of the difference in total embodied energy between the deep soil mixing and prefabricated vertical drains alternatives for levee LPV 111. (b) Histogram of the difference in total CO_2 emissions between the deep soil mixing and prefabricated vertical drains alternatives for levee LPV 111. Both histograms include 1,000 values in the data set.

6.8 SUMMARY AND CONCLUSION

In this paper, a framework for making life cycle embodied energy (EE) and carbon dioxide (CO_2) emissions estimates that include uncertainty is presented for geotechnical ground improvement works. The framework was developed by comparing estimates of EE and CO_2 emissions generated using the subsurface investigation and design information with the actual EE and CO_2 emissions determined from the as-built construction quantities for a case history project. The framework is based on the deterministic SEEAM method (Shillaber et al. 2015b; Shillaber et al. 2016) and uses Monte Carlo simulation to account for variability in both the subsurface conditions and the EE and CO_2 emissions coefficients. The mean, standard deviation and 90% confidence interval for total project EE and CO_2 emissions may be determined from the Monte Carlo simulated data. The EE and CO_2 emissions coefficients are assumed to follow a lognormal distribution, while the distribution for the geotechnical condition governing the design and material quantities is determined by fitting a theoretical distribution to a histogram of values as observed in the geotechnical subsurface and/or laboratory test program.

For competing geotechnical design alternatives, the Monte Carlo simulated data for total EE and CO_2 emissions may be used with nonparametric statistical hypothesis tests to evaluate whether the design alternatives result in total EE and CO_2 emissions that differ with statistical significance. Two alternatives may also be compared qualitatively by taking the difference between corresponding simulated values of EE and CO_2 emissions from each alternative to generate difference data sets, then determining the mean of the difference data and plotting the difference data in histograms. If the mean of the differences is not near zero and the histogram does not significantly cross zero, then the two alternatives result in different total EE or CO_2 emissions. These methods were demonstrated using the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for levee LPV 111 in New Orleans, LA from construction information presented by Shillaber et al. (2015b).

The framework presented herein does not address all sources of uncertainty in EE and CO_2 emissions assessments of ground improvement works; doing so requires the development of additional methods to better inform all the steps in the framework. Particular areas with remaining uncertainty to be addressed include various aspects of material transportation, and the selection and operation of construction equipment on-site. Additional data could also reduce the assumptions that are currently needed as part of the framework, thereby improving the results.

6.9 ACKNOWLEDGEMENTS

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Chapter 7: Uncertainty in Estimates of Embodied Energy and CO_2 Emissions for Ground Improvement: The Influence of Material Haul Distance

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Relevant Appendices:

Appendix Q: Supporting Analysis for the Influence of Material Haul Distance on Estimated Embodied Energy and CO_2 Emissions by the SEEAM

7.1 ABSTRACT

Geotechnical engineers now have the tools to estimate total embodied energy (EE) and carbon dioxide (CO_2) emissions and may use this information in order to better incorporate sustainable development principles into ground improvement projects. In the early stages of a project, uncertainty arises in EE and CO_2 emissions estimates because many details regarding the specific materials and their sources may be unknown. Therefore, the influence of uncertainty on EE and CO_2 emissions estimates may be significant and should be determined. The Streamlined Energy and Emissions Assessment Model (Shillaber et al. 2015b) is used in this paper to evaluate the influence of material haul distance on total EE and CO_2 emissions. The case history projects analyzed include the construction of 364 rammed aggregate columns for foundation support of Pearson Hall on the Virginia Tech campus and the installation of deep soil mixing columns to support an earthen embankment for levee LPV 111 in New Orleans, LA. The actual material haul distances were 8 km for Pearson Hall and ranged from 3.2 km to 1,130 km for LPV 111. Assuming no change in transportation mode or efficiency with increasing distance, it was determined that for each multiple of the as-built haul distances, total project EE increases by 4.9% for Pearson Hall and 4.5% for LPV 111; total project CO_2 emissions increase by 3.1% for Pearson Hall and 2.7% for LPV 111.

7.2 INTRODUCTION

The need to design for sustainable development in civil engineering practice has led to the advent of environmental impact assessment tools tailored to geotechnical practice. These include the Geotechnical Carbon Calculator (Carbone 4 2014) and the Streamlined Energy and Emissions Assessment Model (SEEAM) (Shillaber et al. 2015b). Environmental impact assessment tools such as the Geotechnical Carbon Calculator and the SEEAM provide data which can enable geotechnical engineers to make decisions more consistent with the principles of sustainable development (Shillaber et al. 2015a).

The Geotechnical Carbon Calculator and the SEEAM are rooted in Life Cycle Assessment (LCA) principles. LCA is a method for quantitatively evaluating the environmental impacts of a product or process over its lifetime (EPA 2006). LCAs may be simplified to account for specific impact factors within narrowed boundary conditions by a process known as streamlining (Todd and Curran 1999). The Geotechnical Carbon Calculator and the SEEAM both implement LCA streamlining. The differences between these methods are described by Shillaber et al. (2015b).

Typically, many construction details that are important inputs into environmental assessment methods are not known at the design stage (e.g., the quantities of materials and fuel required for construction, material and waste haul distances). Uncertainty in estimated geotechnical construction quantities arises from variability in the subsurface conditions, the size of construction equipment, the cost and availability of materials from suppliers, and which material suppliers are used during construction. Based on two case history projects, this paper presents an evaluation of the degree to which varying material haul distance influences the results of embodied energy (EE) (i.e., all energy that is consumed to bring something into its current state (Chau et al. 2008)) and carbon dioxide (CO_2) emissions assessments conducted using the SEEAM.

Recommendations are made for how to select material haul distances for energy and/or carbon assessments conducted at the design stage.

7.2.1 The SEEAM Method

The SEEAM is a streamlined LCA method that quantifies EE and CO_2 emissions for ground improvement projects, with boundaries extending from the extraction of raw materials through the completion of construction (Shillaber et al. 2015b). In the SEEAM analysis, total EE and CO_2 emissions include those from: 1) materials (from raw material extraction until they are ready for delivery to the construction site), 2) materials transportation (delivery of materials from suppliers to the construction site), 3) site operations (equipment activity on-site), and 4) waste transportation (transporting waste from the site to a disposal facility). The methodology primarily consists of multiplying the quantities of materials, transportation, or fuel by corresponding unit coefficients of EE and CO_2 emissions (Shillaber et al. 2015b).

7.2.2 Case History Projects

Two case history projects were analyzed to evaluate the influence of material haul distance on total EE and CO_2 emissions. These were (1) the construction of rammed aggregate columns to support shallow foundations for Pearson Hall on the Virginia Tech campus, and (2) the application of Deep Soil Mixing (DSM) to improve the foundation soils for support of levee LPV 111 in New Orleans, LA. These projects were selected because of their differences in size, ground improvement technology used, number of materials, and the availability of construction data.

7.2.2.1 Rammed Aggregate Columns - Pearson Hall

Pearson Hall is a new 6 story replacement dormitory building at Virginia Tech. The foundation design called for shallow foundations supported by 0.76 m diameter rammed aggregate columns. In total, 364 rammed aggregate columns were installed, of which 322 were specified to be composed of cement treated aggregate (CTA) and extend to bedrock. The remaining 42 columns were composed of untreated aggregate (UA) and were to extend to various depths based on their location under the structure.

The contractors and university provided records of material and fuel quantities, as well as installation logs for each column. In total, 3,219 m of CTA columns with an average length of 10 m were constructed using 4,185 tonnes of CTA. A total of 752 m of UA columns with an average length of 5 m and the working pad were constructed of a total of 1,193 tonnes of UA. The aggregate materials were delivered from a supplier located 8 km from the site in a total of 331 truckloads. Machinery used for installing the columns consumed a total of 11,250 liters of diesel fuel.

7.2.2.2 Deep Soil Mixing Columns - Levee LPV 111

LPV 111 is a section of levee in New Orleans, LA that was overtopped and heavily damaged during Hurricane Katrina in 2005 (Cali et al. 2012). Subsequently, the crest elevation of the 8.5 km long levee was raised by about 3 m in order to withstand a 100 year flood event (Cali et al. 2012). The final design consisted of an earthen embankment supported by panels of overlapping 1.6 m diameter DSM columns. The DSM increased the shear strength of the foundation soils to enable minimizing the footprint of the embankment and help limit settlement (Cooling et al. 2012).

DSM construction involved the use of 417,000 tonnes of 75% slag, 25% Portland cement binder and 454,000 m^3 of water to treat 1.4 million m^3 of foundation soil (Schmutzler et al. 2012). The binder was delivered to the site by 23 tonne cement tankers; it is estimated that over 18,130 truckloads of binder were used for the construction (Schmutzler et al. 2012; Shillaber et al. 2015b). The embankment was constructed of 400,000 m^3 of DSM spoil recycled as embankment fill and 441,000 m^3 of compacted borrow soil (Druss et al. 2012). Additional embankment stability was provided by 376,000 m^2 of geogrid with a mass of approximately 395 tonnes (Kelsey 2012; Shillaber et al. 2015b). In total, the equipment consumed about 6.1 million liters of diesel to complete all construction at LPV 111 (Shillaber et al. 2015b).

7.3 METHOD

To determine the influence of different material haul distances on total project EE and CO_2 emissions, a parametric study of the Pearson Hall and LPV 111 projects was conducted in which material haul distances via heavy duty truck were varied. For Pearson Hall, four nearby aggregate suppliers were located, and the distance from each to the construction site was determined using Google Maps. Then, conventional SEEAM analyses were performed for the project considering each different supplier.

A different method was followed for LPV 111 because the DSM required materials from more than one source. Instead of locating nearby suppliers of each material, a series of increasing multiples of the actual haul distances from the suppliers was applied. For example, a multiple of 1 corresponds to the actual distances and a multiple of 2 doubles all the distances. LPV 111 also involved material transportation by barge; however, the barge distances were not adjusted in this analysis.

7.3.1 Assumptions for Analysis

Five assumptions were made in this evaluation for quantifying the influence of material haul distance on total project EE and CO_2 emissions, as follows:

1) There is no change in transportation mode or increase in transportation efficiency with increasing material haul distance.
2) When used, distance multiples are applied equally to all materials and haul distances when more than one material and material supplier are used for the construction (e.g., LPV 111).

3) Only transportation of materials from the location supplying the construction site is considered to be variable in this assessment. Transportation of materials from their production location to a local supplier is not varied in this analysis.
4) All vehicles hauling materials to the construction site operate at the average fuel economy for the vehicle class (primarily U.S. Class 8, heavy duty trucks).
5) Transportation for mobilization and demobilization, as well as worker commuting was not considered in this assessment.

7.4 RESULTS

7.4.1 Pearson Hall

The aggregate suppliers ranged in distance from 8 km to as far as 77 km from the project site, as shown in Table 7.1. Supplier 1 was used for construction; the distance from Supplier 1 to the construction site is taken as a base distance. The distance multiple, *M*, shown in Table 7.1, is the ratio of the supplier distance to the base distance. The distance multiple was determined for each of the possible suppliers for Pearson Hall in order to compare results between the two case history projects.

Table 7.1 Truck haul distances from potential suppliers of aggregate and cement treated aggregate for Pearson Hall for use in the SEEAM analysis.

Aggregate Supplier	Distance (km)	Distance Multiple, *M*
1 (actual)	8	1.0
2	25	3.1
3	42	5.3
4	77	9.6

Figure 7.1 shows the increase in total EE and CO_2 emissions for the rammed aggregate columns with increasing distance multiple, *M*. The increase in EE and CO_2 emissions with *M* is linear, with total project EE and CO_2 emissions increasing by 94 GJ (4.9%) and 7 tonnes (3.1%)

per unit increase in M, respectively. The maximum distance (77 km, $M = 9.6$) resulted in a 42% increase in total EE and a 26% increase in total CO_2 emissions over the minimum distance (8 km, $M = 1.0$). The proportions of the total EE and CO_2 emissions for materials transportation, materials, site operations and waste transportation vs. distance multiple, M, for Pearson Hall are shown in Figure 7.2.

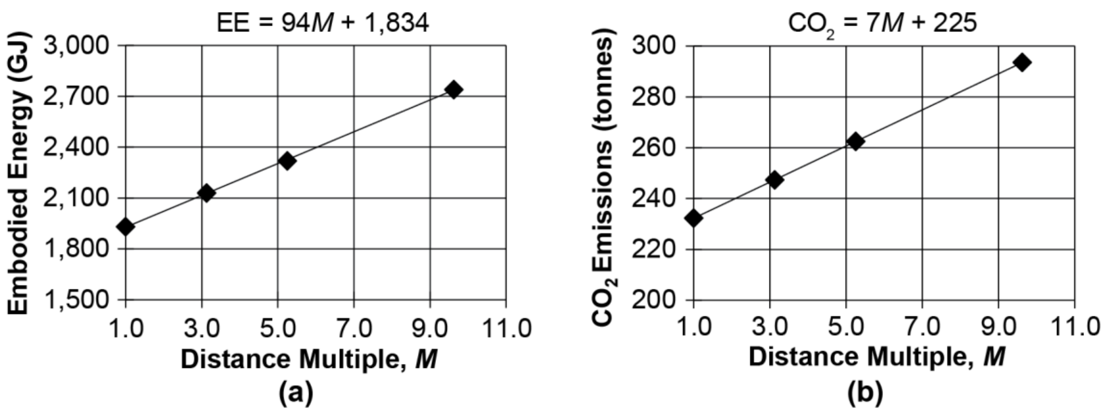

Figure 7.1 (a) Increase in total EE and (b) increase in total CO_2 emissions for Pearson Hall with increasing multiples of truck haul distance for materials.

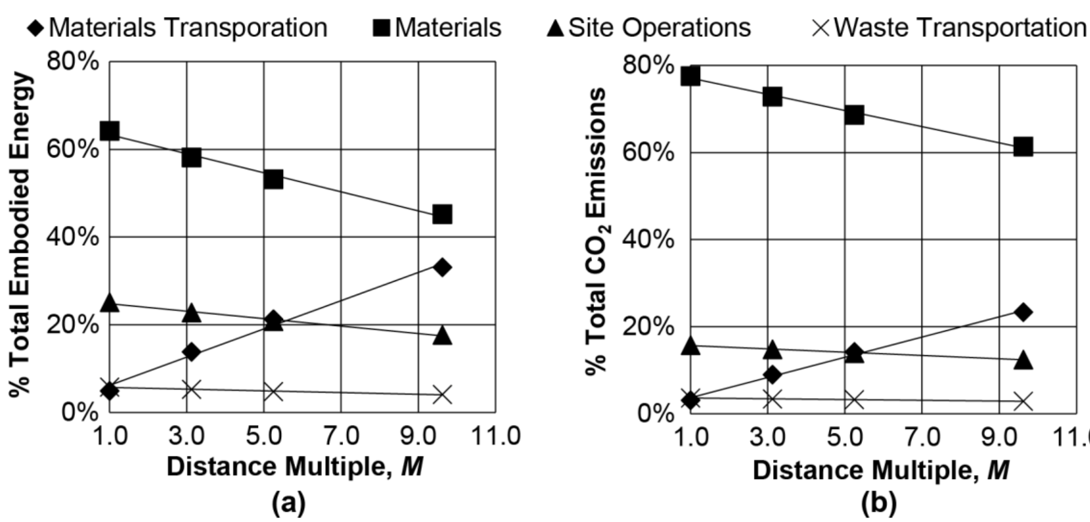

Figure 7.2 (a) Proportion of total EE, and (b) proportion of total CO_2 emissions vs. material truck haul distance multiple, M, for Pearson Hall.

7.4.2 Levee LPV 111

Materials were delivered to LPV 111 by more than one mode of transportation. In this analysis, only the variation in trucking distance was considered. The actual truck haul distances were used as base distances. These values were then multiplied by distance multiples of 2, 3 and 4 and the total project EE and CO_2 emissions were determined for each case. Haul distances for each material and each distance multiple, *M*, are shown in Table 7.2.

Table 7.2 Truck haul distances used in the SEEAM analysis for each major construction material in the LPV 111 project, by multiple of the actual distances.

Distance Multiple, *M*	Haul Distance (km)		
	Binder	Geogrid	Borrow Soil
1 (actual)	3.2	1,130	37
2	6.4	2,260	74
3	9.6	3,390	111
4	12.8	4,520	148

Figure 7.3 shows the increase in total EE and CO_2 emissions with each multiple, *M*, of material haul distances. It was determined that the increase in EE and CO_2 emissions with *M* is linear, with total project EE and CO_2 emissions increasing by 53,300 GJ (4.5%) and 4,000 tonnes (2.7%) per unit increase in *M*, respectively. With all haul distances at 4 times the actual supplier distances, total EE is 14% greater and CO_2 emissions 8% greater than the actual construction case. The proportions of the total EE and CO_2 emissions for materials transportation, materials, site operations and waste transportation vs. distance multiple, *M*, for LPV 111 are shown in Figure 7.4.

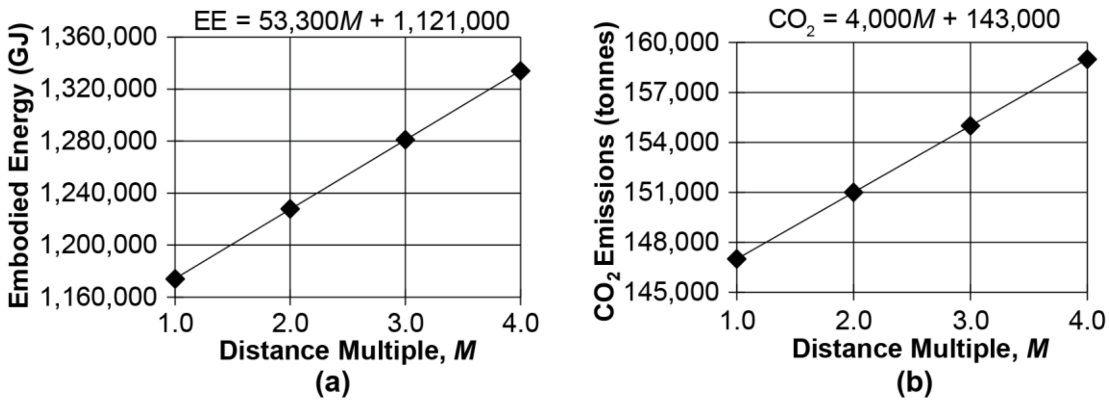

Figure 7.3 (a) Increase in total EE and (b) increase in total CO_2 emissions for LPV 111 with increasing multiples of truck haul distances for all materials.

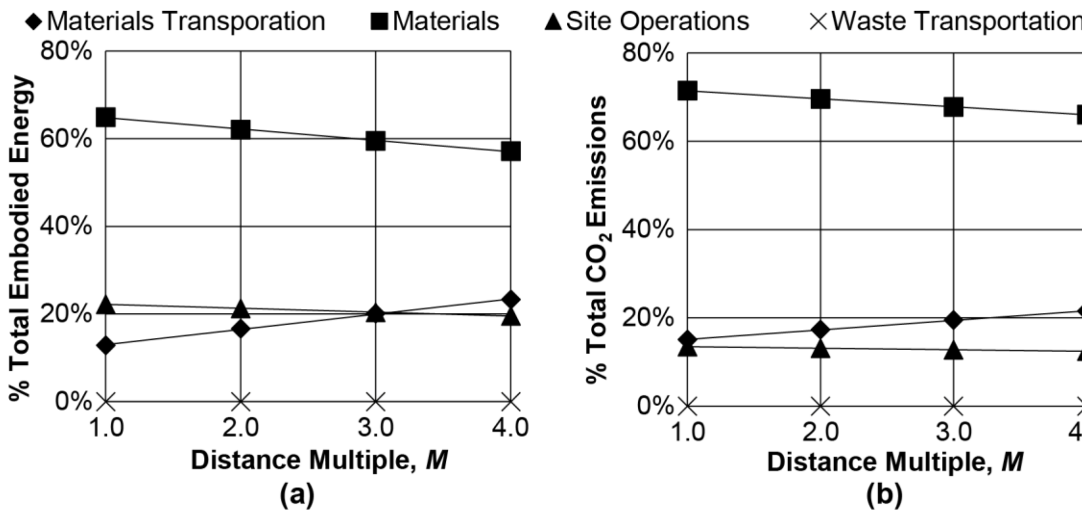

Figure 7.4 (a) Proportion of total EE, and (b) proportion of total CO_2 emissions vs. material truck haul distance multiple, *M*, for LPV 111.

7.5 DISCUSSION

The preceding results for the percentage increases in total EE and CO_2 emissions with increasing truck haul distance multiple, M, are similar for Pearson Hall and LPV 111, despite substantial differences between the techniques, materials used and the size of the projects. For instance, the increase in total EE with M is 4.9% for Pearson Hall and 4.5% for LPV 111. Considering both projects, the average increase in total EE with each multiple of material haul distances is 4.7%. The increase in total CO_2 emissions with *M* is 3.1% for Pearson Hall and 2.7% for LPV 111. Considering both projects, the average increase in total CO_2 emissions with each multiple of material haul distances is 2.9%. Even with the greater percentage increase in total EE and CO_2 emissions with trucking distance associated with the Pearson Hall analysis, tripling the trucking distance ($M = 3$) for all materials results in less than a 10% increase in total EE and less than a 7% increase in total CO_2 emissions.

The linear increase in total EE and CO_2 emissions with increasing distance is attributed to how the SEEAM method accounts for transportation via heavy duty (U.S. Class 8) trucks. For every 1 km distance between a material supplier and the construction site, one round trip made by one heavy duty truck (2 km total distance traveled) is responsible for 0.0355 GJ of EE and 0.0027 tonnes of CO_2 emissions. This is true regardless of whether the truck is fully loaded or empty, as the SEEAM computes EE and CO_2 emissions for trucking based on the amount of fuel consumed by the vehicle given average vehicle fuel economy (Assumption 4). In actuality, there is some variability in vehicle fuel economy based on load, traffic conditions, driver habits, and vehicle age/engine technology. Incorporating additional research regarding the age of the truck fleet, loaded vs. unloaded truck fuel economy and typical local traffic conditions could increase the level of precision in the analysis.

The other assumptions in the assessment will have differing effects on the results. For example, the assumption that there is no change in transportation mode or efficiency with increasing distance will result in overestimating EE and CO_2 emissions compared to accounting for any increases in transportation efficiency with distance, or changes to the mode of transportation from heavy duty trucks to less energy and emissions intensive alternatives, such as rail. In contrast, excluding transportation for mobilization, demobilization and worker commuting results in underestimating the EE and CO_2 emissions associated with the project; however, these activities are common to all ground improvement alternatives and may have similar impacts. Finally, while it is likely that a given material will be transported from the same manufacturing plant to a supplier or distribution center by a constant mode of transportation, a situation could arise where this is not the case. For instance, the plant that normally provides the material to the supplier may not have sufficient capacity to keep up with demand, resulting in the same material being delivered to the supplier from a second plant. Such an occurrence could increase the EE and CO_2 emissions for the project if the second plant is located farther away from the supplier.

As expected, the proportion of the total EE and CO_2 emissions associated with materials transportation increases with increasing haul distance, as shown in Figures 7.2 and 7.4. In conjunction with the increase in the proportion of total EE and CO_2 emissions due to materials transportation, the proportion of total EE and CO_2 emissions associated with all other aspects of the construction decreases. Material transportation is not responsible for the largest proportion of total EE or CO_2 emissions for any of the distances considered in this analysis (up to $M = 9.6$ for Pearson Hall and $M = 4$ for LPV 111). In all cases, the production of the materials from raw material extraction until they are ready for delivery to the site is responsible for the largest proportion of total project EE and CO_2 emissions.

In addition to the uncertainty in the assessment due to unknown material haul distances, there is also uncertainty in the EE and CO_2 emissions coefficients for transportation fuels (e.g., diesel, gasoline) and the construction materials. For example, Venkatesh et al. (2011) report that the whole life emissions for gasoline have a coefficient of variation (COV) of 0.04, where the COV is defined as the ratio of the standard deviation to the mean. Based on statistics in the Inventory of Carbon and Energy database (Hammond and Jones 2011), many common construction materials exhibit COVs between 0.2 and 0.5 for EE, and some have COVs >1.0. This means that in reality, total project EE and CO_2 emissions will follow a distribution, which is shifted higher or lower based on material haul distances. Determining distributions of total EE and CO_2 emissions is beyond the scope of this paper.

7.6 RECOMMENDATIONS

When making estimates of total EE and CO_2 emissions at the design stage of ground improvement projects, the actual suppliers for construction materials may not be known. Therefore, it is recommended that a radial distance be established around the project site as a base distance for the trucking of each material. This radial base distance should encompass one or more reasonable suppliers for each material.

Given the results of the deterministic analyses on the Pearson Hall and LPV 111 case history projects presented herein, if the difference between the selected radial base distances used in the EE and CO_2 emissions estimates and the actual haul distances is less than a factor of 3 times the selected radial base distances, it is likely the actual EE and CO_2 emissions will differ by less than 10% from the estimated EE and CO_2 emissions (i.e., the distributions of total EE and CO_2 emissions will likely be shifted by <10% from the estimated distributions). At present, it is not confirmed if other ground improvement technologies and project sizes will exhibit similar results; however, this could be evaluated with data from additional case histories.

It is unlikely that all materials will have actual haul distances at the same multiple, M, of the selected base distances (Assumption 2). Some actual haul distances may result in $M < 1$ for some materials if the base distance encompasses more than one supplier, while others may have $M > 1$. As a result, it is likely that actual differences between the estimated and actual EE and CO_2

emissions will be smaller than the percent increases shown in the analyses of the case histories in this paper.

To contribute to sustainable development, geotechnical engineers should seek to minimize EE and CO_2 emissions by design through selected methods and materials, suppliers, and waste handling procedures. To minimize EE and CO_2 emissions, the nearest material supplier should be used whenever possible. However, substantial differences in price, supplier or material quality (Aretoulis et al. 2010), or a strong relationship between a particular supplier and the contractor or owner (Lu and Yang 2010) can influence supplier selection. Material quality can be particularly important for aggregates, which may have specifications for durability and reactivity that may preclude sourcing aggregate from the nearest supplier in favor of higher quality material from a greater distance (M. Valle, personal communication, 2015).

7.7 CONCLUSION

As sustainable development considerations in civil engineering practice continue to mature, quantitative environmental impact assessments will become more common in geotechnical practice. When these assessments are conducted at the design stage in order to estimate environmental impacts such as EE or CO_2 emissions to aid in deciding between alternatives, they involve uncertainty in material, fuel and transportation quantities.

This paper presents deterministic analyses of EE and CO_2 emissions for both a small and a large ground improvement project using the SEEAM method, in order to evaluate the influence of material truck haul distance on the results. It was shown that for each increasing multiple of selected base haul distances, project EE increases by an average of 4.7% and project CO_2 emissions increase by an average of 2.9%.

When conducting environmental assessments at the design stage, it is recommended for geotechnical engineers to locate potential suppliers for each material around the project site, then select a reasonable distance for the transportation of each material to the site for use in estimating the total EE and CO_2 emissions. It is likely that the actual haul distances will result in less than a 10% difference in project EE and CO_2 emissions from the estimate using a selected base distance, unless all the actual distances differ from the base distances by a factor of 3 or more. Analyzing additional case histories with a variety of project sizes and ground improvement technologies could confirm whether or not these conclusions have widespread applicability.

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Chapter 8: Conclusions and Engineering Significance

The chapters of this dissertation consist of three journal manuscripts and three conference paper manuscripts. The focus of all manuscripts is on the development and application of the Streamlined Energy and Emissions Assessment Model (SEEAM) for quantifying the embodied energy (EE) and carbon dioxide (CO_2) emissions associated with geotechnical works. The SEEAM is a streamlined life cycle analysis (LCA) method that was developed specifically for application with ground improvement technologies. The SEEAM assessment boundaries extend from the extraction of raw materials through the completion of construction, and the analysis utilizes published, industry average coefficients for energy and CO_2 emissions. While this sacrifices some of the specific energy and emissions details that may be pertinent for a particular project, the SEEAM provides a consistent framework for conducting EE and CO_2 emissions assessments in geotechnical engineering, which can facilitate comparing the environmental performance of project alternatives via EE and CO_2 emissions. Such a comparison of environmental impacts can become an integral part of the comprehensive geotechnical design decision process, which also considers cost, performance and other site and project-specific factors.

Given the established boundaries, coefficients, and recommended timing of the assessment (i.e., during design and prior to construction), SEEAM analyses involve uncertainty. Two primary contributors to uncertainty in the results which were addressed in this dissertation include the EE and CO_2 emissions coefficients and the subsurface conditions. Both may be accounted for using the framework presented in Ch. 6, which uses Monte Carlo simulation to repeat deterministic calculations in order to develop simulated data sets of possible values of total EE and CO_2 emissions. These simulated data sets facilitate presenting the results in the form of a mean, standard deviation and confidence interval, while also enabling statistical comparisons between different project alternatives and design options to be made with statistical inference. For example, with deterministic calculations alone, it may appear that one geotechnical alternative results in 10% more CO_2 emissions than another; however, when considering uncertainty and using statistical inference, it may be the two options do not result in significantly different CO_2 emissions. Knowing this is especially important if one alternative is much more expensive than another, or if one is projected to perform better over time.

The SEEAM methodology, boundary conditions and uncertainty considerations for the EE and CO_2 emissions coefficients were implemented in a user-friendly spreadsheet calculator. The SEEAM Spreadsheet Calculator facilitates quick evaluations of the EE and CO_2 emissions for geotechnical project alternatives. By analyzing competing design alternatives, the results from the assessment of each with the SEEAM Spreadsheet Calculator can be used to make comparisons of the environmental performance of geotechnical alternatives, or to identify the most significant contributors to environmental impact for a given geotechnical alternative. With this information, design changes and decisions can be made to minimize the energy and carbon impacts of geotechnical works, contributing to more sustainable civil infrastructure. A notable limitation of the SEEAM Spreadsheet Calculator is that while the underlying method has long-term applicability, the coefficients are time-dependent and could require future updating.

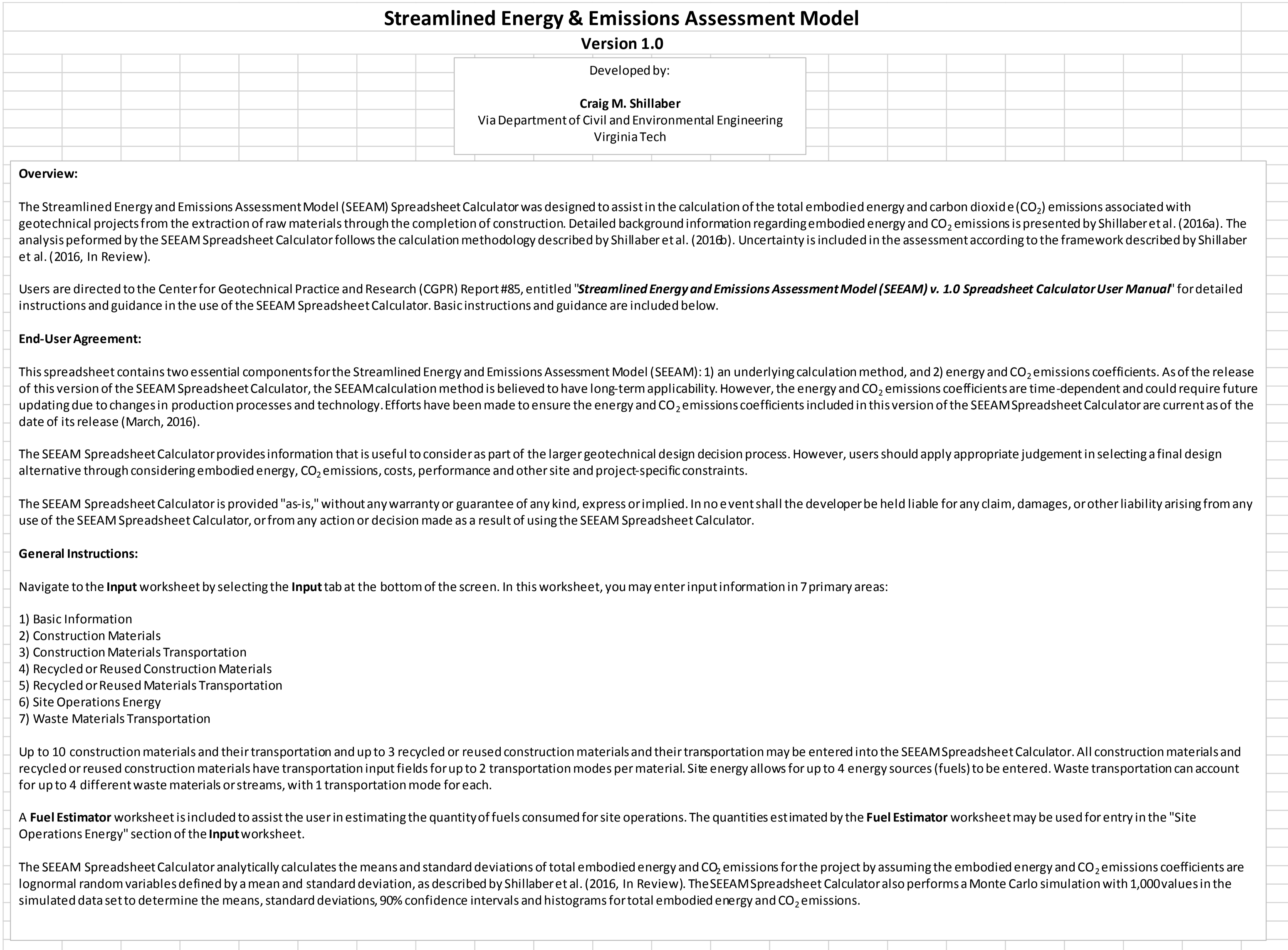
Overall, using the SEEAM method enables geotechnical engineers to bring environmental impact information via EE and CO_2 emissions into the design decision process. Considering EE and CO_2 emissions along with monetary cost, performance criteria and any other site or project-specific constraints can lead to the development of more sustainable geotechnical works, with less resource consumption and potential impact on climate change.

Appendix A: SEEAM Spreadsheet Calculator Screen Shots

This Appendix contains screen shots of the worksheets in the SEEAM Spreadsheet Calculator, v. 1.0, which runs in Microsoft Excel. The SEEAM spreadsheet calculator follows the boundaries and methodology described in Ch. 4 for performing calculations of total embodied energy and CO_2 emissions.

To account for uncertainty, the SEEAM Spreadsheet Calculator analytically computes a mean and standard deviation for embodied energy and CO_2 emissions based on uncertainty in the coefficients following the method described in Appendix K, using the coefficient lognormal parameters presented in Ch. 6 and Appendix J. In addition, the SEEAM Spreadsheet Calculator conducts a Monte Carlo simulation for 1,000 values in the simulated data sets for total embodied energy and CO_2 emissions and checks the accuracy of the mean for n = 1,000 values in the simulated data set. The Monte Carlo simulation methods are described in detail in Ch. 6 and Appendix K.

From the Monte Carlo simulation, the SEEAM Spreadsheet Calculator determines the mean, standard deviation, 90% confidence interval and histograms of total embodied energy and CO_2 emissions. The only uncertainty considered in the SEEAM Spreadsheet Calculator is from the embodied energy and CO_2 emissions coefficients. Accounting for subsurface variability in Monte Carlo simulation following the complete framework presented in Ch. 6 must be accomplished by manually setting up the Monte Carlo simulation with all necessary input information.



Streamlined Energy & Emissions Assessment Model

Version 1.0

Developed by:

Craig M. Shillaber
Via Department of Civil and Environmental Engineering
Virginia Tech

Overview:

The Streamlined Energy and Emissions Assessment Model (SEEAM) Spreadsheet Calculator was designed to assist in the calculation of the total embodied energy and carbon dioxide (CO_2) emissions associated with geotechnical projects from the extraction of raw materials through the completion of construction. Detailed background information regarding embodied energy and CO_2 emissions is presented by Shillaber et al. (2016a). The analysis peformed by the SEEAM Spreadsheet Calculator follows the calculation methodology described by Shillaber et al. (2016b). Uncertainty is included in the assessment according to the framework described by Shillaber et al. (2016, In Review).

Users are directed to the Center for Geotechnical Practice and Research (CGPR) Report #85, entitled "***Streamlined Energy and Emissions Assessment Model (SEEAM) v. 1.0 Spreadsheet Calculator User Manual***" for detailed instructions and guidance in the use of the SEEAM Spreadsheet Calculator. Basic instructions and guidance are included below.

End-User Agreement:

This spreadsheet contains two essential components for the Streamlined Energy and Emissions Assessment Model (SEEAM): 1) an underlying calculation method, and 2) energy and CO_2 emissions coefficients. As of the release of this version of the SEEAM Spreadsheet Calculator, the SEEAM calculation method is believed to have long-term applicability. However, the energy and CO_2 emissions coefficients are time-dependent and could require future updating due to changes in production processes and technology. Efforts have been made to ensure the energy and CO_2 emissions coefficients included in this version of the SEEAM Spreadsheet Calculator are current as of the date of its release (March, 2016).

The SEEAM Spreadsheet Calculator provides information that is useful to consider as part of the larger geotechnical design decision process. However, users should apply appropriate judgement in selecting a final design alternative through considering embodied energy, CO_2 emissions, costs, performance and other site and project-specific constraints.

The SEEAM Spreadsheet Calculator is provided "as-is," without any warranty or guarantee of any kind, express or implied. In no event shall the developer be held liable for any claim, damages, or other liability arising from any use of the SEEAM Spreadsheet Calculator, or from any action or decision made as a result of using the SEEAM Spreadsheet Calculator.

General Instructions:

Navigate to the **Input** worksheet by selecting the **Input** tab at the bottom of the screen. In this worksheet, you may enter input information in 7 primary areas:

1) Basic Information
2) Construction Materials
3) Construction Materials Transportation
4) Recycled or Reused Construction Materials
5) Recycled or Reused Materials Transportation
6) Site Operations Energy
7) Waste Materials Transportation

Up to 10 construction materials and their transportation and up to 3 recycled or reused construction materials and their transportation may be entered into the SEEAM Spreadsheet Calculator. All construction materials and recycled or reused construction materials have transportation input fields for up to 2 transportation modes per material. Site energy allows for up to 4 energy sources (fuels) to be entered. Waste transportation can account for up to 4 different waste materials or streams, with 1 transportation mode for each.

A **Fuel Estimator** worksheet is included to assist the user in estimating the quantity of fuels consumed for site operations. The quantities estimated by the **Fuel Estimator** worksheet may be used for entry in the "Site Operations Energy" section of the **Input** worksheet.

The SEEAM Spreadsheet Calculator analytically calculates the means and standard deviations of total embodied energy and CO_2 emissions for the project by assuming the embodied energy and CO_2 emissions coefficients are lognormal random variables defined by a mean and standard deviation, as described by Shillaber et al. (2016, In Review). The SEEAM Spreadsheet Calculator also performs a Monte Carlo simulation with 1,000 values in the simulated data set to determine the means, standard deviations, 90% confidence intervals and histograms for total embodied energy and CO_2 emissions.

Figure A.1 Screen shot of the "Overview" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Streamlined Energy & Emissions Assessment Model

Version 1.0

Input Information

This worksheet has 7 input areas for the user to complete:

1) Basic Information
2) Construction Materials (up to 10 materials)
3) Construction Material Transportation (up to 2 types or stages of transportation for each material)
4) Recycled or Reused Construction Materials (up to 3 materials)
5) Recycled or Reused Construction Material Transportation (up to 2 types or stages of transportation for each material)
6) Construction Site Energy (up to 4 different fuel types/energy sources)
7) Waste Material Transportation (up to 4 different waste materials/streams)

Basic Information:

Project Name:	
Company Name:	
Ground Improvement Method:	
Analysis Performed by:	

Figure A.2 Basic Information section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Construction Materials Information:

Material 1

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 2

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 3

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 4

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 5

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 6

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 7

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 8

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 9

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Material 10

Material Category	Material Sub-Type	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Select	Select	0		0.000	0.000	0.000

Figure A.3 Construction Materials Information section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Construction Materials Transportation:

Material 1

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 2

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 3

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 4

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 5

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 6

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 7

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 8

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 9

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Material 10

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Figure A.4 Construction Materials Transportation section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Recycled or Reused Construction Materials Information:

Recycled/Reused Material 1

Material Category	Material Description	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Recycled or Reused	Enter Description	0	Select	0.000	0.000	

Recycled/Reused Material 2

Material Category	Material Description	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Recycled or Reused	Enter Description	0	Select	0.000	0.000	

Recycled/Reused Material 3

Material Category	Material Description	Quantity	Unit	EEC MJ/Unit	CC (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)
Recycled or Reused	Enter Description	0	Select	0.000	0.000	

Figure A.5 Recycled or Reused Construction Materials Information section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Recycled or Reused Construction Materials Transportation:

Recycled/Reused Material 1

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Recycled/Reused Material 2

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Recycled/Reused Material 3

Transportation Stage	Description	Transportation Distance One Way (km)	No. Of One Way Trips	Transportation Mode	Transportation Vehicle Type	Payload (kg)	Vehicle Fuel	Unit	Vehicle Fuel Economy (km/L)	Transport EEC MJ/Unit	Transport CC (kg CO_2/Unit)	Fuel EEC MJ/Unit	Fuel CC (kg CO_2/Unit)
1	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
2	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Figure A.6 Recycled or Reused Construction Materials Transportation section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Construction Site Energy (Fuel Consumed)					
Energy Source 1					
Fuel Type	**Description**	**Quantity**	**Unit**	**EEC MJ/Unit**	**CC (kg CO_2/Unit)**
Select	Enter Description	0		0.000	0.000
Energy Source 2					
Fuel Type	**Description**	**Quantity**	**Unit**	**EEC MJ/Unit**	**CC (kg CO_2/Unit)**
Select	Enter Description	0		0.000	0.000
Energy Source 3					
Fuel Type	**Description**	**Quantity**	**Unit**	**EEC MJ/Unit**	**CC (kg CO_2/Unit)**
Select	Enter Description	0		0.000	0.000
Energy Source 4					
Fuel Type	**Description**	**Quantity**	**Unit**	**EEC MJ/Unit**	**CC (kg CO_2/Unit)**
Select	Enter Description	0		0.000	0.000

Figure A.7 Construction Site Energy (Fuel Consumed) section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Waste Materials Transportation:

Waste Material/Stream 1													
Quantity of Solid Waste (kg)	**Description**	**Transportation Distance One Way (km)**	**No. Of One Way Trips**	**Transportation Mode**	**Transportation Vehicle Type**	**Payload (kg)**	**Vehicle Fuel**	**Unit**	**Vehicle Fuel Economy (km/L)**	**Transport EEC MJ/Unit**	**Transport CC (kg CO_2/Unit)**	**Fuel EEC MJ/Unit**	**Fuel CC (kg CO_2/Unit)**
0	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
Waste Material/Stream 2													
Quantity of Solid Waste (kg)	**Description**	**Transportation Distance One Way (km)**	**No. Of One Way Trips**	**Transportation Mode**	**Transportation Vehicle Type**	**Payload (kg)**	**Vehicle Fuel**	**Unit**	**Vehicle Fuel Economy (km/L)**	**Transport EEC MJ/Unit**	**Transport CC (kg CO_2/Unit)**	**Fuel EEC MJ/Unit**	**Fuel CC (kg CO_2/Unit)**
0	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
Waste Material/Stream 3													
Quantity of Solid Waste (kg)	**Description**	**Transportation Distance One Way (km)**	**No. Of One Way Trips**	**Transportation Mode**	**Transportation Vehicle Type**	**Payload (kg)**	**Vehicle Fuel**	**Unit**	**Vehicle Fuel Economy (km/L)**	**Transport EEC MJ/Unit**	**Transport CC (kg CO_2/Unit)**	**Fuel EEC MJ/Unit**	**Fuel CC (kg CO_2/Unit)**
0	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A
Waste Material/Stream 4													
Quantity of Solid Waste (kg)	**Description**	**Transportation Distance One Way (km)**	**No. Of One Way Trips**	**Transportation Mode**	**Transportation Vehicle Type**	**Payload (kg)**	**Vehicle Fuel**	**Unit**	**Vehicle Fuel Economy (km/L)**	**Transport EEC MJ/Unit**	**Transport CC (kg CO_2/Unit)**	**Fuel EEC MJ/Unit**	**Fuel CC (kg CO_2/Unit)**
0	Enter Description	0.0	0	Select	Select	N/A	Select		N/A			N/A	N/A

Figure A.8 Waste Materials Transportation section of the "Input" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Streamlined Energy & Emissions Assessment Model

Version 1.0

Site Operations Fuel Consumption Estimator Worksheet

This worksheet has four (4) Energy Source input tables for the user to complete in order to estimate the total quantity of input fuel consumed for site operations. Themethod for estimating the quantity of fuel is derived from Shillaber et al. (2014).

This worksheet assumes typical engine efficiencies for 2014 in the BSFC (Brake Specific Fuel Consumption) values for the estimation of total fuel consumption. BSFC is the rate of fuel consumption per unit of flywheel power. Future developments in engine technology may reduce the BSFC, and therefore the total fuel consumption associated with the same applied power/construction activity/engine load.

To use this worksheet:
1) Select the Fuel Type for each Energy Source from the pull down menu.
2) On separate lines in each Energy Source table, select each type of machine consuming the specified fuel type from the pull down menu.
3) Enter the Gross Engine Power and Duration of Operation for each selected machine type. For combustion fuels, the worksheet will populate an average load factor from the EPA (2010). For electricity, the average load factor will state "Enter Override!". The user must input load factors for electric motors manually. Average load factors for combustion fuels may also be overridden by entering a value in the 'Load Factor Override' column.
4) Enter the number of machines for each Machine Type/Gross Engine Power/Duration of Operation/Load Factor combination.
5) The total quantity of each fuel (Energy Source) consumed by machines for site operations appears at the bottom of each Energy Source table. This value may be entered (manually) as the quantity of fuel for the corresponding Energy Source on the "Input" worksheet.

Basic Information:

Project Name:	0
Company Name:	0
Ground Improvement Method:	0
Analysis Performed by:	0

Figure A.9 Basic Information section of the "Fuel Estimator" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Energy Source 1

	Fuel Type	Consumption Unit				
	Select		$Q_F = (P)(LF)(BSFC)(T)$			
BSFC	0.000					
Number of Machines	Machine Type	Gross Engine Power P, (kW)	Duration of Operation T, (hrs)	Average Load Factor LF, (EPA 2010)	Load Factor Override LF	Fuel Consumption (in consumption units)
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
					TOTAL (enter for Energy Source 1 on the "Input" Worksheet)	0

Energy Source 2

	Fuel Type	Consumption Unit				
	Select		$Q_F = (P)(LF)(BSFC)(T)$			
BSFC	0.000					
Number of Machines	Machine Type	Gross Engine Power P, (kW)	Duration of Operation T, (hrs)	Average Load Factor LF, (EPA 2010)	Load Factor Override LF	Fuel Consumption (in consumption units)
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
					TOTAL (enter for Energy Source 2 on the "Input" Worksheet)	0

Energy Source 3

	Fuel Type	Consumption Unit				
	Select		$Q_F = (P)(LF)(BSFC)(T)$			
BSFC	0.000					
Number of Machines	Machine Type	Gross Engine Power P, (kW)	Duration of Operation T, (hrs)	Average Load Factor LF, (EPA 2010)	Load Factor Override LF	Fuel Consumption (in consumption units)
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
					TOTAL (enter for Energy Source 3 on the "Input" Worksheet)	0

Energy Source 4

	Fuel Type	Consumption Unit				
	Select		$Q_F = (P)(LF)(BSFC)(T)$			
BSFC	0.000					
Number of Machines	Machine Type	Gross Engine Power P, (kW)	Duration of Operation T, (hrs)	Average Load Factor LF, (EPA 2010)	Load Factor Override LF	Fuel Consumption (in consumption units)
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
Enter Number of Machines	Select	Enter Value	Enter Value		Override Load Factor?	
					TOTAL (enter for Energy Source 4 on the "Input" Worksheet)	0

Figure A.10 Energy Source input tables section of the "Fuel Estimator" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Streamlined Energy & Emissions Assessment Model

Version 1.0

Calculations

This worksheet presents the SEEAM calculations. It includes 5 sections summarizing the Embodied Energy and CO_2 emissions calculations.

1) Basic Information.
2) Materials: Energy and emissions to produce the materials.
3) Materials Transportation: Energy and emissions to transport materials to the construction site.
4) Site energy and emissions : Energy and emissions generated on site due to construction operations, from fuel consumption.
5) Waste Transportation: Energy and emissions to transport waste from the construction site to the disposal facility.

Basic Information

Project Name:	0
Company Name:	0
Ground Improvement Method:	0
Analysis Performed by:	0

Figure A.11 Basic Information section of the "Calculations" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TOTAL	**0**	**0**	**0**	**0**

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		SITE OPERATIONS TOTAL	**0**	**0**	**0**	**0**

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Figure A.12 Line by line calculations section of the "Calculations" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Streamlined Energy & Emissions Assessment Model

Version 1.0

Results

This worksheet presents the results of the SEEAM calculations and 1,000 point Monte Carlo simulation. It includes 4 sections summarizing the results of the Embodied Energy and CO_2 emissions calculations.

1) Basic Information.
2) Overall Totals - Calculated: Overall totals of embodied energy and CO_2 emissions, showing the percent constribution of Materials, Material Transportation, Site Energy and Waste Transportation.
3) Overall Totals - 1,000 Point Monte Carlo Simulation: Overall totals of Embodied Energy and CO_2 emissions as determined from a 1,000 point Monte Carlo simulation, showing the percent constribution of Materials, Material Transportation, Site Energy and Waste Transportation.
4) Histograms of total Embodied Energy and CO_2 emissions based on the 1,000 point Monte Carlo simulation.

Basic Information

Project Name:	0
Company Name:	0
Ground Improvement Method:	0
Analysis Performed by:	0

Overall Totals - Calculated

	Embodied Energy (GJ)					CO_2 Emissions (tonnes)				
	Mean	St Dev	Maximum	Minimum	% of Total	Mean	St Dev	Maximum	Minimum	% of Total
Materials	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
Materials Transportation	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
Site Operations	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
Waste Transportation	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
TOTAL	**0**	**0**			**#DIV/0!**	**0**	**0**			**#DIV/0!**

Overall Totals - Monte Carlo Simulation for 1,000 Values

	Embodied Energy (GJ)					CO_2 Emissions (tonnes)				
	Mean	St Dev	Maximum	Minimum	% of Total	Mean	St Dev	Maximum	Minimum	% of Total
Materials	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
Materials Transportation	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
Site Operations	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
Waste Transportation	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
TOTAL	**0**	**0**	**0**	**0**	**#DIV/0!**	**0**	**0**	**0**	**0**	**#DIV/0!**
Mean Error (%)	**#DIV/0!**					**#DIV/0!**				
% Different from Calculated	**#DIV/0!**	**#DIV/0!**				**#DIV/0!**	**#DIV/0!**			

Total Embodied Energy and CO_2 Emissions 90% Confidence Interval - Generated from Querying the 1,000 Monte Carlo Simulation Points

	EE (GJ)		CO_2 (tonnes)
5% < Value	#NUM!	5% < Value	#NUM!
Mean	0	Mean	0
95% < Value	#NUM!	95% < Value	#NUM!

	90% Confidence Interval	
	Low	High
Embodied Energy (GJ)	#NUM!	#NUM!
CO_2 Emissions (tonnes)	#NUM!	#NUM!

Figure A.13 Tables section of the "Results" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0. Pie graphs and histograms not shown. 0, #NUM! and #DIV/0! appear in cells because no input information is entered.

Streamlined Energy & Emissions Assessment Model

Version 1.0

1,000 Point Monte Carlo Simulation

This worksheet presents 1,000 lines of calculations for the Monte Carlo simulation of Embodied Energy and CO_2 emissions. This worksheet has 4 major sections:

1) Basic Information.
2) Input information: Data that has been transferred from the "Input" worksheet.
3) Monte Carlo Computations: 1,000 lines of discrete calculations of Embodied Energy and CO_2 emissions for the project.
4) Overall Totals: Overall totals of Embodied Energy and CO_2 emissions, as determined from the 1,000 point Monte Carlo simulation, showing the percent constribution of Materials, Material Transportation, Site Energy and Waste Transportation.

The Monte Carlo simulation is performed by generating random values of the Embodied Energy and CO_2 emissions coefficients when the mean and standard deviation for the coefficient are known. The coefficients are assumed to be distributed lognormally, ensuring only positive values (negative values for the coefficients are not physically reasonable). Where a standard deviation for a coefficient is unknown, the coefficient is used as a fixed value. Coefficients are assumed to be independent.

Basic Information

Project Name:	0
Company Name:	0
Ground Improvement Method:	0
Analysis Performed by:	0

Input Information

				EEC		CC		Biogenic CC		LN(EEC)		LN(CO_2)		LN(Biogenic CO_2)	
Material No.	Material Sub-Type	Material Qty	Unit	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
1	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
2	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
3	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
4	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
5	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
6	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
7	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
8	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
9	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		
10	Select	0		0	0.000	0	0	0	0	0.000	0.000	0.000	0.000		

				EEC		CC		LN(EEC)		LN(CO_2)	
Material No.	Material Sub-Type	Material Qty	Unit	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
RM1	Enter Description	0	Select	0.000	0	0.000	0	0.000	0.000	0.000	0.000
RM2	Enter Description	0	Select	0.000	0	0.000	0	0.000	0.000	0.000	0.000
RM3	Enter Description	0	Select	0.000	0	0.000	0	0.000	0.000	0.000	0.000

				EEC		CC		LN(EEC)		LN(CO_2)	
Energy Source No.	Site Energy	Quantity	Unit	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
ES1	Select	0		0	0.000	0	0	0.000	0.000	0.000	0.000
ES2	Select	0		0	0.000	0	0	0.000	0.000	0.000	0.000
ES3	Select	0		0	0.000	0	0	0.000	0.000	0.000	0.000
ES4	Select	0		0	0.000	0	0	0.000	0.000	0.000	0.000

				EEC		CC		LN(EEC)		LN(CO_2)	
	Fuel Type (Coefficients)		Unit	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
	Diesel		L	43	1.430	3.25	0.11	3.761	0.033	1.178	0.034
	Gasoline		L	39.7	1.230	2.83	0.09	3.681	0.031	1.040	0.032
	Electricity (U.S. Avg. Generation Mix)		L	8.74	0.000	0.63	0	2.168	0.000	-0.462	0.000
	Compressed Natural Gas (CNG)		kg	55.5	0.000	2.87	0	4.016	0.000	1.054	0.000

Figure A.14 Top left section of the "Monte Carlo" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Monte Carlo Computations

Fuel Coefficients																		Materials	
Compressed Natural Gas		Electricity		Diesel		Gasoline		1		2		3		4		5		6	
EEC MJ/kg	CC kg/kg	EEC MJ/kW-h	CC kg/kW-h	EEC MJ/L	CC kg/L	EEC MJ/L	CC kg/L	EE MJ	CO_2 (kg)	EE MJ	CO_2 (kg)	EE MJ	CO_2 (kg)	EE MJ	CO_2 (kg)	EE MJ	CO_2 (kg)	EE MJ	CO_2 (kg)
55.5	2.87	8.74	0.63	43.176	3.343	39.579	2.713	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	44.296	3.258	38.519	2.882	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.403	3.245	38.851	2.825	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.972	3.181	38.563	2.874	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	40.926	3.261	39.039	2.841	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.500	3.151	40.036	2.879	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.704	3.340	40.221	2.842	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.078	3.171	38.077	2.713	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	44.520	3.112	38.308	2.923	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	40.982	3.157	39.675	2.871	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	40.151	3.328	37.728	2.802	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.763	3.072	40.068	2.686	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.139	3.182	38.321	2.859	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.612	3.356	41.580	2.888	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	39.883	3.167	38.272	3.076	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.507	3.404	39.084	2.891	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.931	3.194	41.506	2.927	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.160	3.242	40.066	2.967	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.542	3.351	40.810	2.940	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.063	3.427	40.611	2.808	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.667	3.305	38.427	2.716	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.142	3.461	38.166	2.785	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.850	3.055	40.048	2.810	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.346	3.264	41.565	3.077	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.865	3.042	37.221	2.815	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	44.930	3.210	39.132	2.818	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.746	3.398	40.408	2.727	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	45.975	3.229	39.096	2.853	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.568	3.249	41.047	2.868	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	46.216	3.374	40.821	2.905	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.630	3.202	39.969	2.859	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	44.996	3.243	40.244	2.926	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.322	3.243	39.458	2.750	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.787	3.205	38.384	2.775	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	40.849	3.128	40.185	2.851	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.686	3.178	42.140	2.964	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.851	3.256	38.914	2.837	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	45.447	3.229	37.752	2.875	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	44.284	3.304	41.176	2.984	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	45.903	3.046	37.287	2.616	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	44.177	3.249	40.245	2.786	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	43.347	3.204	40.746	2.725	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	41.760	3.336	41.067	2.942	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.423	3.186	41.032	2.806	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	40.925	3.452	40.006	2.893	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	42.884	3.156	40.060	2.849	0	0	0	0	0	0	0	0	0	0	0	0
55.5	2.87	8.74	0.63	40.887	3.382	39.030	2.778	0	0	0	0	0	0	0	0	0	0	0	0

Figure A.15 Lower left section of the “Monte Carlo” worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Embodied Energy Coefficients					
Material	**Material Sub-Type**	**EEC**	**EEC St Dev**	**Unit**	**Reference**
Steel	General Steel, Virgin	35.4	12.07	MJ/kg	ICE v2 Hammond and Jones (2011)
	General Steel, World Avg. Recycled Content	25.3	5.92	MJ/kg	ICE v2 Hammond and Jones (2011)
	Steel Bar and Rod, Virgin	29.2		MJ/kg	ICE v2 Hammond and Jones (2011)
	Steel Bar and Rod, World Avg. Recycled Content	21.6		MJ/kg	ICE v2 Hammond and Jones (2011)
	Steel Pipe, Virgin	34.7		MJ/kg	ICE v2 Hammond and Jones (2011)
	Steel Pipe, World Avg. Recycled Content	24.9		MJ/kg	ICE v2 Hammond and Jones (2011)
	Engineered Steel Sections, Virgin	38.0		MJ/kg	ICE v2 Hammond and Jones (2011)
	Engineered Steel Sections, World Avg. Recycled Content	27.1		MJ/kg	ICE v2 Hammond and Jones (2011)
Cementitious Materials	Portland Cement (U.S.)	4.8	0.98	MJ/kg	Marceau et al. (2006)
	Lime	5.3	2.79	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	Slag (U.S.)	0.721	0.210	MJ/kg	Slag Cement Association (2014), ICE v2 Hammond and Jones (2011) for std deviation
	Fly Ash	0.1	0.02	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
Concrete	35MPa Concrete (Portland Cement Only)	1,630		MJ/m^3	Marceau et al. (2007)
	25MPA Concrete (Portland Cement Only)	1,390		MJ/m^3	Marceau et al. (2007)
	20MPa Concrete (Portland Cement Only)	1,140		MJ/m^3	Marceau et al. (2007)
	20MPa Concrete (20% Fly Ash by Weight)	944		MJ/m^3	Marceau et al. (2007)
	20MPa Concrete (25% Fly Ash by Weight)	895		MJ/m^3	Marceau et al. (2007)
	20MPa Concrete (35% Slag Cement by Weight)	853		MJ/m^3	Marceau et al. (2007)
	20MPa Concrete (50% Slag Cement by Weight)	732		MJ/m^3	Marceau et al. (2007)
	50MPa Precast Concrete (Portland Cement Only)	3,150		MJ/m^3	Marceau et al. (2007)
	70MPa Precast Concrete (2.4% Silica Fume)	2,900		MJ/m^3	Marceau et al. (2007)
Earth Materials	Bentonite	1.65		MJ/kg	Jiang et al. (2011); Carnegie Mellon University Green Design Institute (2008)
	Aggregate: Sand and Gravel or Crushed Rock	0.083	0.12	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	Sand	0.081	0.23	MJ/kg	ICE v2 Hammond and Jones (2011)
Plastics	General Plastics (Average)	80.5	37.67	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	High Density Polyethylene (HDPE) Resin	76.7	25.39	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	Low Density Polyethylene (LDPE) Resin	78.1	16.26	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	Polyethylene (General)	83.1	32.77	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	PVC (General)	77.2	21.00	MJ/kg	Based on ICE v2 Hammond and Jones (2011)
	Polypropylene (Injection Molding)	115.1		MJ/kg	ICE v2 Hammond and Jones (2011)
	Polypropylene (Oriented Film)	99.2		MJ/kg	ICE v2 Hammond and Jones (2011)
	Expanded Polystyrene	88.6		MJ/kg	ICE v2 Hammond and Jones (2011)
	General Purpose Polystyrene	86.4		MJ/kg	ICE v2 Hammond and Jones (2011)
	Rigid Polyurethane Foam	101.5		MJ/kg	ICE v2 Hammond and Jones (2011)
	Flexible Polyurethane Foam	102.1		MJ/kg	ICE v2 Hammond and Jones (2011)
Wood Products	Softwood (planed, dried lumber)	7.72	0.91	MJ/kg	Puettmann and Wilson (2005); Puettmann et al. 2010
	PNW Softwood (green lumber)	1.33		MJ/kg	Puettmann and Wilson (2005), density = 413 kg/m^3
	Softwood (plywood)	8.88	1.84	MJ/kg	Puettmann and Wilson (2005)
Water	Water	0.01		MJ/L	ICE v2 Hammond and Jones (2011)
Fuel	Diesel	43.0	1.43	MJ/L	Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
	Gasoline	39.7	1.23	MJ/L	Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
	Compressed Natural Gas (CNG)	55.5		MJ/kg	Shillaber et al. (2014)
	Electricity (U.S. Avg. Generation Mix)	8.74		MJ/kW-hr	Shillaber et al. (2014)

Figure A.16 Embodied Energy Coefficients from the "Material Coefficients Database" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

CO_2 Coefficients							
Material	Material Sub-Type	CC Mean	CC St Dev	CC (bio)	CC bio St Dev	Unit	Reference
Steel	General Steel, Virgin	2.71	0.92			kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	General Steel, World Avg. Recycled Content	1.82	0.43			kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Steel Bar and Rod, Virgin	2.59				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Steel Bar and Rod, World Avg. Recycled Content	1.74				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Steel Pipe, Virgin	2.71				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Steel Pipe, World Avg. Recycled Content	1.83				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Engineered Steel Sections, Virgin	2.82				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Engineered Steel Sections, World Avg. Recycled Content	1.89				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
Cementitious Materials	Portland Cement (U.S.)	0.927	0.105			kg CO_2/kg	Marceau et al. (2006)
	Lime	0.78	0.41			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	Slag (U.S.)	0.021	0.011			kg CO_2/kg	Slag Cement Association (2014), ICE v2 Hammond and Jones (2011) for std deviation
	Fly Ash	0.008	0.002			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
Concrete	35MPa Concrete (Portland Cement Only)	313				kg CO_2/m^3	Marceau et al. (2007)
	25MPA Concrete (Portland Cement Only)	262				kg CO_2/m^3	Marceau et al. (2007)
	20MPa Concrete (Portland Cement Only)	211				kg CO_2/m^3	Marceau et al. (2007)
	20MPa Concrete (20% Fly Ash by Weight)	171				kg CO_2/m^3	Marceau et al. (2007)
	20MPa Concrete (25% Fly Ash by Weight)	161				kg CO_2/m^3	Marceau et al. (2007)
	20MPa Concrete (35% Slag Cement by Weight)	142				kg CO_2/m^3	Marceau et al. (2007)
	20MPa Concrete (50% Slag Cement by Weight)	112				kg CO_2/m^3	Marceau et al. (2007)
	50MPa Precast Concrete (Portland Cement Only)	490				kg CO_2/m^3	Marceau et al. (2007)
	70MPa Precast Concrete (2.4% Silica Fume)	437				kg CO_2/m^3	Marceau et al. (2007)
Earth Materials	Bentonite	0.101				kg CO_2/kg	Jiang et al. (2011); Carnegie Mellon University Green Design Institute (2008)
	Aggregate: Sand and Gravel or Crushed Rock	0.0048	0.0069			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	Sand	0.0048	0.0136			kg CO_2/kg	ICE v2 Hammond and Jones (2011)
Plastics	General Plastics (Average)	2.73	1.28			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	High Density Polyethylene (HDPE) Resin	1.57	0.52			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	Low Density Polyethylene (LDPE) Resin	1.69	0.35			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	Polyethylene (General)	2.04	0.80			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	PVC (General)	2.61	0.71			kg CO_2/kg	Based on ICE v2 Hammond and Jones (2011)
	Polypropylene (Injection Molding)	3.93				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Polypropylene (Oriented Film)	2.97				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Expanded Polystyrene	2.55				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	General Purpose Polystyrene	2.71				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Rigid Polyurethane Foam	3.48				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
	Flexible Polyurethane Foam	4.06				kg CO_2/kg	ICE v2 Hammond and Jones (2011)
Wood Products	Softwood (planed, dried lumber)	0.190	0.05	0.40	0.10	kg CO_2/kg	Puettmann and Wilson (2005); Puettmann et al. 2010
	PNW Softwood (green lumber)	0.07		2.42E-05		kg CO_2/kg	Puettmann and Wilson (2005), density = 413 kg/m^3
	Softwood (plywood)	0.17	0.08	0.36	0.08	kg CO_2/kg	Puettmann and Wilson (2005)
Water	Water	0.001				kg CO_2/L	ICE v2 Hammond and Jones (2011)
Fuel	Diesel	3.25	0.11			kg CO_2/L	Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
	Gasoline	2.83	0.09			kg CO_2/L	Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
	Compressed Natural Gas (CNG)	2.87				kg CO_2/kg	Shillaber et al. (2014)
	Electricity (U.S. Avg. Generation Mix)	0.63				kg CO_2/kW-hr	Shillaber et al. (2014)

Figure A.17 CO_2 Emissions Coefficients from the "Material Coefficients Database" worksheet in the SEEAM Spreadsheet Calculator, v. 1.0.

Fuel Economy of Some Common Construction Vehicles							
Vehicle Information					Average Fuel Economy (MPG)	Average Fuel Economy (km/L)	Reference
Vehicle Description	Truck Class (1 - 8)	GVWR (lb)	Empty Weight (lb)	Payload Capacity (lb)			
Minivan or small pickup truck	1	<6,000	3,200 - 4,500	1,500	17.6	7.48	Davis et al. (2012)
SUV or full size pickup truck (1/2 ton)	2	6,001 - 8,500	4,500 - 6,000	2,500	14.3	6.08	Davis et al. (2012)
SUV or full size pickup truck (3/4 ton)		8,501 - 10,000	5,000 - 6,300	3,700			
Full size pickup truck (F350 or GM/Ram 3500 size)	3	10,001 - 14,000	7,650 - 8,750	5,250	10.5	4.46	Davis et al. (2012)
Medium duty truck (F450 or GM/Ram 4500 size)	4	14,001 - 16,000	7,650 - 8,750	7,250	8.5	3.61	Davis et al. (2012)
Medium duty truck (F550 or GM/Ram 5500 size)	5	16,001 - 19,500	9,500 - 10,000	8,700	7.9	3.36	Davis et al. (2012)
Medium duty truck (F650 or GM/Ram 6500 size)	6	19,501 - 26,000	11,500 - 14,500	11,500	7.0	2.98	Davis et al. (2012)
Light Heavy Duty Truck	7	26,001 - 33,000	11,500 - 14,500	18,500	6.4	2.72	Davis et al. (2012)
Heavy Duty Truck	8	>33,000	20,000 - 26,000	54,000	5.7	2.42	Davis et al. (2012)

Transportation Options
Road Vehicle
Water Freight
Rail Freight

Freight Energy and Emissions Coefficients (Non-trucking)					
	Energy (MJ/ton-mile)	Energy (MJ/tonne-km)	CO_2 (kg CO_2/ton-mile)	CO_2 (kg CO_2/tonne-km)	Reference
Water Freight	0.229	0.157	0.042	0.029	Energy: Davis et al. (2012) CO_2: EPA (2014)
Rail Freight	0.343	0.238	0.026	0.018	Energy: Determined by using fuel coefficients from Shillaber et al. (2014) to convert CO_2 emissions to energy from diesel fuel. CO_2: EPA (2014)

Figure A.18 "Transportation Tables" worksheet from the SEEAM Spreadsheet Calculator, v. 1.0.

Engine Load Factors for Some Common Pieces of Construction Equipment			
Machine	Average Load Factor (EPA 2010) Compression Ignition (Diesel)	Average Load Factor (EPA 2010) (Gasoline)	Average Load Factor (EPA 2010) (CNG)
Bulldozer	0.59	0.80	0.80
Compressor	0.43	0.56	0.56
Crane	0.43	0.47	0.47
Drill Rig	0.43	0.79	0.79
Excavator	0.59	0.53	0.53
Generator	0.43	0.68	0.68
Grout/Concrete Pump	0.43	0.69	0.69
Front End Loader	0.59	0.71	0.71
Plant (concrete, grout, slurry)	0.43	0.59	0.59
Roller/Compactor	0.59	0.62	0.62
Skid Steer	0.21	0.58	0.58
Water Pump	0.43	0.69	0.69

Figure A.19 "Load Factor Table" worksheet from the SEEAM Spreadsheet Calculator, v. 1.0.

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References

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Figure A.20 "References" worksheet from the SEEAM Spreadsheet Calculator, v. 1.0.

Appendix B: SEEAM Spreadsheet Calculator User Manual

This Appendix contains the user manual for the Streamlined Energy and Emissions Assessment Model (SEEAM) Spreadsheet Calculator and provides users of the SEEAM Spreadsheet Calculator with guidance on how to enter input information, view the results and compare project alternatives. Worked examples for two case history projects are included to demonstrate the SEEAM Spreadsheet Calculator.

This Appendix has been developed into Report #85 for the Center of Geotechnical Practice and Research (CGPR) at Virginia Tech. The reference information for the CGPR Report is as follows:

Shillaber, C. M., Mitchell, J. K., Dove, J. E. and Hamilton, M. (2016). "Streamlined energy and emissions assessment model (SEEAM) v. 1.0 spreadsheet calculator user manual." CGPR # 85, Center for Geotechnical Practice and Research, Blacksburg, VA.

INFORMATION FOR THE READER

The Streamlined Energy and Emissions Assessment Model (SEEAM) Spreadsheet Calculator described in this Appendix is intended to assist in the calculation of the total embodied energy and CO_2 emissions associated with geotechnical projects. The SEEAM Spreadsheet Calculator contains two essential components: 1) an underlying calculation method, and 2) energy and CO_2 emissions coefficients. As of the defense of this dissertation (March 1, 2016), the SEEAM calculation method is believed to have long-term applicability. However, the energy and CO_2 emissions coefficients are time-dependent and could require future updating due to changes in production processes and technology. Efforts have been made to ensure the energy and CO_2 emissions coefficients included in the SEEAM Spreadsheet Calculator are current as of the date this dissertation was defended.

The SEEAM Spreadsheet Calculator provides information that is useful to consider as part of the larger geotechnical design decision process. However, users should apply appropriate judgement in selecting a final design alternative through considering embodied energy, CO_2 emissions, costs, performance and other site and project-specific constraints.

B.1 OVERVIEW

The Streamlined Energy and Emissions Assessment Model (SEEAM) Spreadsheet Calculator was developed as a tool for computing the life cycle embodied energy and CO_2 emissions associated with geotechnical ground improvement works. The boundaries considered for the life cycle extend from raw material extraction through the completion of ground improvement construction. The results from the SEEAM assessment can be used to inform the ground improvement design decision process. Details regarding the background, SEEAM methodology and boundary conditions are presented in Shillaber et al. (2015a, b) (Chs. 2 and 4).

This manual provides detailed instructions and examples for using the SEEAM Spreadsheet Calculator. A first time user should begin with Sections B.1 and B.2. Section B.1 provides a brief background of the analysis method and an overview of the various worksheets in the SEEAM Spreadsheet Calculator. Section B.2 provides detailed guidance for using the calculator. Section B.3 is a discussion of applications of the SEEAM Spreadsheet Calculator, including methods that can be used to rationally compare the environmental impact of alternative designs and construction methods.

Sections B.4 and B.5 contain case history examples where the SEEAM method was applied. In addition to providing construction quantities, results and discussion from the analyses are presented. These examples were completed by a first time user of the SEEAM Spreadsheet Calculator, who was able to obtain comparable results to those presented in this manual without difficulty. Minor differences arose primarily due to slightly different interpretations of the given data; however, these variations did not lead to different conclusions. Section B.6 provides some basic guidance on how to select alternatives based on sustainability considerations.

B.1.1 Brief Overview of Analysis Methods

The SEEAM Spreadsheet Calculator only requires the user to enter total quantities of construction materials, energy sources, and transportation methods and distances. At the design stage (or at any point prior to construction), these quantities will inevitably need to be estimated. Therefore, the computed values of embodied energy and CO_2 emissions are also estimates.

Part of the SEEAM Spreadsheet Calculator implements a direct computational method (denoted as "Analytically Calculated" in the spreadsheet) to determine the mean and standard deviation of total embodied energy and CO_2 emissions for a ground improvement project. This method involves multiplying the quantities of construction inputs (e.g., materials, transportation distances, fuel) by unit coefficients for embodied energy and CO_2 emissions. To account for uncertainty, the unit coefficients are random variables defined by a mean and standard deviation (see Section B.1.2); they represent the amount of energy and emissions per unit of a construction input (e.g., kg, L, km). The total embodied energy and CO_2 emissions are equal to the sum of the contributions from all construction inputs.

For example, the mean embodied energy due to materials is computed by Eq. B.1, where EE_M is the embodied energy associated with construction materials, n is the total number of construction materials, Q_i is the quantity and EEC_i the mean of the unit embodied energy coefficient for the i^{th} construction material.

$$EE_M = \sum_{i=1}^{n}[Q_i * EEC_i]. \tag{B.1}$$

Mean CO_2 emissions are determined by replacing the mean of the unit embodied energy coefficient (EEC) by the mean of the unit CO_2 emissions coefficient (CC).

The results from these direct calculations are useful for obtaining an initial impression of embodied energy and CO_2 emissions for the project. Comparing different project alternatives requires only slightly more advanced methods, including accounting for uncertainty in more detail. This more advanced analysis is also implemented in the SEEAM Spreadsheet Calculator, and is responsible for the majority of the reported results. By following the guidance in this manual and becoming familiar with the function and layout of the SEEAM Spreadsheet Calculator, users will be able to use the SEEAM to evaluate and compare the embodied energy and CO_2 emissions of different project alternatives.

B.1.2 Consideration of Uncertainty in the Analysis

Variability is present in both the subsurface conditions (influencing material quantities), and in the unit coefficients of embodied energy and CO_2 emissions included in the SEEAM coefficient database.

In its present form, the SEEAM Spreadsheet Calculator does not address the influence of variability in subsurface conditions and its effect on the required material and fuel quantities. Doing so would require: 1) knowledge of the distributions for the specific geotechnical conditions that control the design, and 2) quantitative relationships between those geotechnical conditions and the required quantities of construction inputs (see Ch. 6). Since these factors are specific to a given project and the geotechnical technique(s) being implemented, they are not currently included in the SEEAM Spreadsheet Calculator. However, users who wish to evaluate the influence of variable subsurface conditions on total embodied energy and CO_2 emissions for a project may do a parametric study that varies the relevant geotechnical parameters and determines the construction quantities for each different set of conditions. Then, the construction quantities for each different set of conditions can be used to conduct separate analyses with the SEEAM Spreadsheet Calculator to determine total embodied energy and CO_2 emissions.

Variability in the unit embodied energy and CO_2 emissions coefficients is accounted for in the SEEAM Spreadsheet Calculator. This is the reason why the unit embodied energy and CO_2 emissions coefficients are treated as random variables defined by a mean and standard deviation. The mean and standard deviation for each unit coefficient in the SEEAM database were determined based on available values for each coefficient from life cycle environmental studies. When only one known value informed the coefficient, it was assumed to be the mean value, with no standard deviation. In such cases, there was insufficient information available to determine the actual variability in the coefficient.

Even though the computational method (described in Section B.1.1) determines values of the mean and standard deviation for total embodied energy and CO_2 emissions, the SEEAM Spreadsheet Calculator simultaneously performs a secondary analysis to account for the uncertainty in the embodied energy and CO_2 emissions coefficients through Monte Carlo simulation. Monte Carlo simulation is a stochastic statistical method used to generate a simulated data set via discrete deterministic calculations (Fenton and Griffiths 2008; Kalos and Whitlock 1986). Within the SEEAM Spreadsheet Calculator, Monte Carlo simulation is used to automatically generate simulated data sets of n = 1,000 values each for total embodied energy and CO_2 emissions (see Ch. 6 and Appendix K). Unlike the computational method, which only determines a mean and standard deviation of total embodied energy and CO_2 emissions, the simulated data sets generated by Monte Carlo simulation are used to estimate the mean, standard deviation, 90% confidence interval (i.e., the upper and lower bounds between which 90% of the simulated data lies) and histograms.

In the Monte Carlo simulation, the embodied energy and CO_2 emissions coefficients are randomly generated based on the assumption that they are lognormally distributed. The lognormal distribution for each unit coefficient is defined by the coefficient's mean and standard deviation. The discrete deterministic calculations that generate the values in the simulated data sets are of the same form as described in Section B.1.1; however, in this case the randomly generated value for the unit coefficient is used in place of the mean value. A second important assumption in the analysis is that the embodied energy and CO_2 emissions associated with materials are independent from those associated with fuel related activities (e.g., site construction operations, transportation). See Ch. 6 and Appendix K for more details about these assumptions.

The Monte Carlo simulation is automated in the SEEAM Spreadsheet Calculator. As a result, all of the calculations, including the random generation of unit coefficient values, are repeated every time an input in the SEEAM Spreadsheet Calculator is changed, or the file is saved or reopened. Due to automatic recalculations and randomization, the data sets, (i.e., realizations of possible values) for total embodied energy and CO_2 emissions generated by the Monte Carlo simulation will be slightly different every time a change is made in the file, even when the exact same input is used. Therefore, there is a certain degree of error in the mean, standard deviation, etc. as determined from the Monte Carlo simulation. The amount of error in the estimate of the mean from the Monte Carlo simulation is controlled by the number of values in the simulated data set. See Section B.2.3.3 for more information about quantifying the error in the mean from the Monte Carlo simulation. The results from the direct computational method ("Analytically Calculated") will be the same as long as the same input data is used.

While use of Monte Carlo simulation is not required to obtain basic results, the ability to present a confidence interval and histogram (which gives an indication of the shape of the distribution) for estimates of total project embodied energy and CO_2 emissions is an important feature of the SEEAM Spreadsheet Calculator. This cannot be accomplished with the direct computational method described in Section B.1.1. Therefore, Monte Carlo simulation is recommended for determining if statistically significant differences in the embodied energy and CO_2 emissions exist for different design alternatives (Section B.3). Comparing project alternatives using statistical methods can facilitate more meaningful conclusions regarding environmental performance.

B.1.3 SEEAM Spreadsheet Calculator Basics

The SEEAM Spreadsheet Calculator includes ten visible worksheets (See Appendix A for screen shots):

1) **Overview Worksheet**
2) **Input Worksheet**
3) **Fuel Estimator Worksheet**
4) **Calculations Worksheet**
5) **Results Worksheet**
6) **Monte Carlo Worksheet**
7) **Material Coefficients Database Worksheet**
8) **Transportation Tables Worksheet**
9) **Load Factor Table Worksheet**
10) **References Worksheet**

With the exception of the user input portions of the **Input** worksheet and the **Fuel Estimator** worksheet, all of the worksheets are "locked." This prevents the user from accidentally or intentionally changing formulas and information that are essential for proper function of the SEEAM Spreadsheet Calculator.

Six additional hidden worksheets are part of the inner workings of the calculations. These worksheets do not need to be viewed by the user. Two of the hidden worksheets deal with the development of the 90% confidence interval and histograms from the Monte Carlo simulation. Four contain information that is already available in the **Material Coefficients Database**, **Transportation Tables** and **Load Factor Table** worksheets, or as selection options on the **Input** worksheet or **Fuel Estimator** worksheet. The ten visible worksheets are briefly described as follows:

B.1.3.1 Overview Worksheet

The **Overview** worksheet contains information about the name and development of the SEEAM Spreadsheet Calculator, and includes basic instructions and information on the use of the SEEAM Spreadsheet Calculator.

B.1.3.2 Input Worksheet

The **Input** worksheet is where the user enters all input information for the project and the SEEAM analysis.

B.1.3.3 Fuel Estimator Worksheet

The **Fuel Estimator** worksheet allows the user to enter information regarding the construction equipment used on-site. The worksheet then estimates the total quantity of fuel that will be consumed by the equipment for site operations, which may be entered in the "Construction Site Energy (Fuel Consumed)" section of the **Input** worksheet.

B.1.3.4 Calculations Worksheet

The **Calculations** worksheet contains the formulas and results for all of the analytical calculations to determine the mean and standard deviation of both embodied energy and CO_2 emissions associated with each input material, fuel, or transportation.

B.1.3.5 Results Worksheet

The **Results** worksheet shows the results for the embodied energy and CO_2 emissions computations, obtained both analytically and through the Monte Carlo simulation. These include the mean, standard deviation and 90% confidence interval for each. Tables present the results from both analytical computations and the Monte Carlo simulation for n = 1,000 values of total embodied energy and total CO_2 emissions. Pie graphs show the proportion of total embodied energy and CO_2 emissions from materials, materials transportation, site construction operations and waste transportation. Histograms show the distribution of total embodied energy and CO_2 emissions resulting from the Monte Carlo simulation.

B.1.3.6 Monte Carlo Worksheet

The **Monte Carlo** worksheet contains a copy of the information entered on the **Input** worksheet, and then performs the SEEAM computations 1,000 times using randomly generated unit embodied energy and CO_2 emissions coefficients, assuming the coefficients follow a lognormal distribution defined by the coefficient mean and standard deviation shown on the **Material Coefficients Database** worksheet. For coefficients that do not have a standard deviation, the coefficient is assumed to be constant at the mean value (i.e., the standard deviation is zero).

B.1.3.7 Material Coefficients Database Worksheet

The **Material Coefficients Database** worksheet contains all of the material unit embodied energy coefficients (EECs) and CO_2 emissions coefficients (CCs) in the database that are needed for the analysis.

B.1.3.8 Transportation Tables Worksheet

The **Transportation Tables** worksheet contains information regarding vehicle types and fuel economies, as well as some energy and emissions coefficients related to material and waste transportation.

B.1.3.9 Load Factor Table Worksheet

The **Load Factor Table** worksheet contains average engine load factors for selected types of machines from the U.S. Environmental Protection Agency (EPA) (2010). Different load factors are presented for equipment consuming different fuels. See Section B.2.2.6.1 for a definition and application of engine load factors in the analysis.

B.1.3.10 References Worksheet

The **References** worksheet contains a list of references for the background and methodology used, as well as for the coefficients in the **Material Coefficients Database**, **Transportation Tables** and **Load Factor Table**.

B.2 USING THE SEEAM SPREADSHEET CALCULATOR

B.2.1 Setting up a Project Alternative File

To begin a SEEAM analysis for a project alternative, first open the SEEAM Spreadsheet Calculator Microsoft Excel Workbook (named SEEAM v1.xlsx). Once the SEEAM Spreadsheet Calculator is open, select "Save As" within Microsoft Excel, change the filename to "SEEAM v1_project alternative," where "project alternative" should be replaced by a descriptive name for the project alternative being analyzed.

Do not change the file type in the "Save As" dialog box. The SEEAM Spreadsheet Calculator workbook should be saved in standard Microsoft Excel Workbook format (.xlsx).

B.2.2 Entering Input Information

To enter input information, first select the **Input** worksheet. This worksheet contains 7 sections for user input:

1) **Basic Information**
2) **Construction Materials Information**
3) **Construction Materials Transportation**
4) **Recycled or Reused Construction Materials Information**
5) **Recycled or Reused Construction Materials Transportation**
6) **Construction Site Energy (Fuel Consumed)**
7) **Waste Materials Transportation**

On the worksheet, cells that require direct user input are shaded in light orange. Cells that require user input via selection from a drop down list are shaded in green. All other cells in the worksheet are locked and will populate automatically based on the user input. These cells cannot be edited by the user. Specific instructions for each of the seven user input sections follow.

B.2.2.1 Basic Information

Basic information includes the project name, company name, ground improvement method being analyzed, and the name of the engineer performing the analysis. All of this information may simply be typed into the appropriate line in the worksheet. See Figure B.1.

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Input Information

This worksheet has 7 input areas for the user to complete:

1) Basic Information
2) Construction Materials (up to 10 materials)
3) Construction Material Transportation (up to 2 types or stages of transportation for each material)
4) Recycled or Reused Construction Materials (up to 3 materials)
5) Recycled or Reused Construction Material Transportation (up to 2 types or stages of transportation for each material)
6) Construction Site Energy (up to 4 different fuel types/energy sources)
7) Waste Material Transportation (up to 4 different waste materials/streams)

Basic Information:

Project Name:	
Company Name:	
Ground Improvement Method:	
Analysis Performed by:	

Figure B.1 Input worksheet: Basic Information section.

B.2.2.2 Construction Materials Information

Construction material information includes the material type and quantities. The worksheet is set up to be able to accommodate up to 10 input materials of known/estimated quantity, which should be sufficient for most ground improvement technologies, particularly given the number of available materials in the database of coefficients. A method to account for more than 10 materials is described at the end of this section.

> **Note:** Do not input any recycled or reused waste material that is used as a construction material in this section. Enter these materials in the Recycled or Reused Construction Materials section instead.

To enter material information for each material, follow these steps:

1. Select a *Material Category* from the drop down list. Available material categories in the SEEAM Spreadsheet Calculator include:
    - Steel
    - Cementitious Materials

- Concrete
- Plastics
- Wood Products
- Earth Materials
- Water

2. Select a *Material Sub-Type* from the drop down list. Material Sub-Types fall under the material category, and describe a more specific material within that category. Material Sub-Types for each Material Category within the SEEAM Spreadsheet Calculator are as follows:

- Steel
    - General Steel, Virgin
    - General Steel, World Avg. Recycled Content
    - Steel Bar and Rod, Virgin
    - Steel Bar and Rod, World Avg. Recycled Content
    - Steel Pipe, Virgin
    - Steel Pipe, World Avg. Recycled Content
    - Engineered Steel Sections, Virgin
    - Engineered Steel Sections, World Avg. Recycled Content
- Cementitious Materials
    - Portland Cement (U.S.)
    - Lime
    - Slag (U.S.)
    - Fly Ash

- Concrete
    - 35 MPa (5,000 psi) Concrete (Portland Cement Only)
    - 25 MPa (3,600 psi) Concrete (Portland Cement Only)
    - 20 MPa (2,900 psi) Concrete (Portland Cement Only)
    - 20 MPa (2,900 psi) Concrete (20% Fly Ash by Weight)
    - 20 MPa (2,900 psi) Concrete (25% Fly Ash by Weight)
    - 20 MPa (2,900 psi) Concrete (35% Slag Cement by Weight)
    - 20 (2,900 psi) MPa Concrete (50% Slag Cement by Weight)
    - 50 MPa (7,200 psi) Precast Concrete (Portland Cement Only)
    - 70 MPa (10,100 psi) Precast Concrete (2.4% Silica Fume)

    Note: All concrete coefficients in the database represent the energy and CO_2 emissions associated with a unit of the representative concrete mix only. They do not account for reinforcement or formwork. The analysis for concrete may be refined by considering the total amount of cement, aggregate, water and other additive materials required for the specific mix design for the project.
- Plastics
    - General Plastics (Average)
    - High Density Polyethylene (HDPE)
    - Low Density Polyethylene (LDPE)
    - Polyethylene (General)
    - Polyvinyl Chloride (PVC) (General)
    - Polypropylene (Injection Molding)
    - Polypropylene (Oriented Film)

    - Expanded Polystyrene (EPS)
    - General Purpose Polystyrene
    - Rigid Polyurethane Foam
    - Flexible Polyurethane Foam
- Wood Products
    - Softwood (planed, dried lumber)
    - Pacific Northwest (PNW) Softwood (green lumber)
    - Softwood (plywood)

    Note: Wood products are biomass materials, with CO_2 emissions resulting both from fossil energy consumed to process the material into useful form, as well as from the later decay or combustion of the biomass (Puettmann et al. 2010). Emissions from the decay or combustion of biomass are known as biogenic carbon emissions (EPA 2011). In the SEEAM Spreadsheet Calculator results, the CO_2 emissions from wood products are the sum of the CO_2 emissions from fossil energy (captured by the CC) and those associated with the decay or combustion of wood biomass (captured by the biogenic CC). This ignores CO_2 uptake by trees and will result in an overestimate of actual CO_2 emissions when sustainable forest practices are used (i.e., when wood is not harvested at a rate faster than it may be naturally replenished).
- Earth Materials
    - Bentonite
    - Sand

- Aggregate: Sand and Gravel or Crushed Rock

- Water
    - Water

Enter the quantity of the material needed for construction. Make sure the quantity is entered in the appropriate units. The correct unit for input will be shown in the "Unit" column after the *Material Category* and *Material Sub-Type* have been selected. In general, the entered quantity should be in units of kilograms (kg) for solids, liters (L) for liquids, and m^3 for concrete.

See Figure B.2 for the input of Material 1 in the "*Construction Materials Information*" section of the **Input** worksheet.

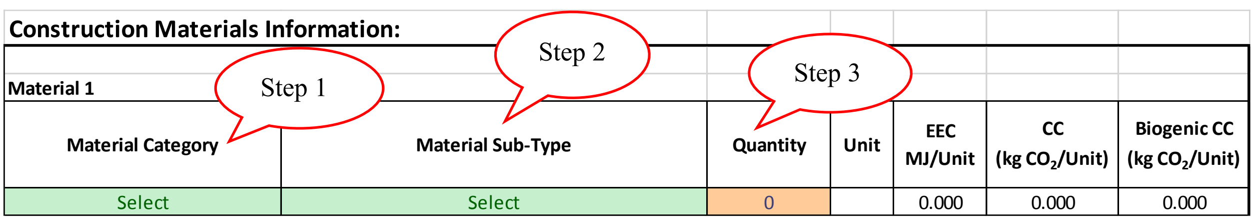

Figure B.2 Input section for Material 1, under "Construction Materials Information."

These steps may be repeated for Materials 1 through 10, as needed, in the appropriate lines on the **Input** worksheet. If fewer than 10 materials are used for the construction, leave the remaining "*Construction Materials Information*" input lines blank.

If more than 10 materials are required for construction, create a second SEEAM Spreadsheet Calculator file to input any remaining materials. To obtain the mean, standard deviation and confidence intervals for total embodied energy and CO_2 emissions, the complete Monte Carlo simulated data sets for total embodied energy and CO_2 emissions from each SEEAM Spreadsheet Calculator file (found in rows 62-1061 of columns CJ and CK on the **Monte Carlo** worksheet) must be combined. This may be accomplished by copying the values in the complete data sets from each SEEAM Spreadsheet Calculator workbook, then pasting them side-by-side in a separate spreadsheet file. Then, the corresponding values of total embodied energy and CO_2 emissions may be added together to create new data sets representing the total embodied energy and CO_2 emissions[1].

Microsoft Excel formulas for the mean and standard deviation can be used to determine these descriptive statistics of the "total" data sets, and histograms may be plotted. The confidence intervals may be found by sorting the "total" embodied energy and CO_2 emissions data sets in ascending order; the lower and upper bounds of a 90% confidence interval are defined by the values of total embodied energy and CO_2 emissions for which 5% (50 out of 1,000) and 95% (950 out of 1,000) of the generated values are less than, respectively. The pie graphs and other information presented on the **Results** worksheets in the SEEAM Spreadsheet Calculator files are not meaningful when more than 10 materials are used in the construction. Only the mean, standard deviation and confidence interval obtained by combining the Monte Carlo simulation data sets into "total" data sets are meaningful.

B.2.2.3 Construction Materials Transportation

To the right of each material input in the "*Construction Materials Information*" section of the worksheet is a corresponding "*Construction Materials Transportation*" input for the material. For each material, up to two modes of transportation are permitted. Two modes may be necessary for the case of materials transported in bulk by rail or water to a distribution center, and then by truck to the construction site. Most often, only one mode of transportation will be required for

[1] The method described here technically violates the SEEAM method in one regard: for a given fuel, the transportation of the additional materials (those in the second file) by truck will not be forced to use the same fuel coefficients as the truck transportation of the first 10 materials and the construction equipment in the Monte Carlo simulation. This criteria is held within the existing SEEAM Spreadsheet Calculator because the same fuel should have the same coefficients regardless of where it is used. Overall, the difference in results arising from potentially different fuel coefficients between the two files should be small and should not prevent the user from being able to draw reasonable conclusions.

input materials, as the user may only be able to determine transportation directly to the site from a supplier or distribution center.

The user may input transportation information for each material by the following steps:

1. Enter a description for the transportation, such as “Hauling steel rebar from supplier to site by truck.”
2. Enter the one-way travel distance in kilometers (km) for the transportation mode being entered. This will usually be the distance from the material supplier to the construction site (exceptions may include when accounting for transportation from a manufacturing facility to a distribution center in addition to transportation from the distribution center to the site).
3. Enter the number of one-way trips made by the vehicle to and/or from the construction site or distribution center. A value must be entered on this line for road transportation of liquids or any other material with a quantity in terms of a unit of volume rather than mass/weight. For road vehicles (trucking), the number of one-way trips may be left at “0” for any solid material with a unit of kilograms (kg). In this situation, the SEEAM Spreadsheet Calculator will estimate the number of trips based on the quantity of material and the selected vehicle payload (in kg) for the computation of total embodied energy and CO_2 emissions; however, the estimated number of trips is not shown on the **Input** worksheet. In this case, the SEEAM Spreadsheet Calculator assumes every vehicle makes a round trip (two one-way trips) to the site. Whenever possible, it is better to estimate the number of one-way trips and enter it into the spreadsheet directly rather than rely on the SEEAM Spreadsheet Calculator to estimate the number of trips.

When determining the number of one-way trips, note that in general, vehicles will make round trips (two one-way trips) to the construction site.

For water and rail freight, a value need not be entered for the number of one-way trips (i.e., it may be left at “0”). The SEEAM Spreadsheet Calculator determines the transport energy and emissions for rail and water freight based on the quantity of material transported (in kg) and the transport distance (in km).

> **Note:** In its present form, the SEEAM Spreadsheet Calculator is unable to account for the transportation of liquids or other materials with a unit of volume (e.g., L, m^3) by rail or water freight because the underlying method is based on the mass of material and the transportation distance. If the construction material being transported has volume units, the SEEAM Spreadsheet Calculator will return an error on the **Calculations** worksheet when rail or water freight is the selected mode of transportation. At this time, the only materials in the SEEAM Spreadsheet Calculator selection options that have volume units are water and concrete mixes. These materials are not likely to be delivered to the site by rail or water freight. Water is generally available from local municipal supply or trucked to the site; concrete is usually delivered in ready mix concrete trucks, or mixed on-site.

4. Select the *Transportation Mode* from the drop down list.

   Available transportation modes for selection within the SEEAM Spreadsheet Calculator are as follows:

   - Road Vehicle

- Water Freight
- Rail Freight

5. If "Road Vehicle" is the selected Transportation Mode, select the *Vehicle Type* from the drop down list for road vehicles. Vehicle type is not an applicable selection for water freight or rail freight and the only option in the drop down menu for these transportation modes is "N/A." Vehicle Types within the SEEAM Spreadsheet Calculator for road transportation are as follows:

- Road Vehicle:
    - Minivan or Small Pickup Truck
    - SUV or Full Size Pickup Truck (1/2 ton)
    - SUV or Full Size Pickup Truck (3/4 ton)
    - Full Size Pickup Truck (F350 or GM/Ram 3500 size)
    - Medium Duty Truck (F450 or GM/Ram 4500 size)
    - Medium Duty Truck (F550 or GM/Ram 5500 size)
    - Medium Duty Truck (F650 or GM/Ram 6500 size)
    - Light Heavy Duty Truck
    - Heavy Duty Truck

6. If "Road Vehicle" is the selected transportation mode, select the correct *Fuel Type* for the vehicle from the drop down list. For rail or water freight, leave this blank or select N/A from the drop down list. Available Fuel Types for road vehicles in the SEEAM Spreadsheet Calculator are as follows:

- Diesel
- Gasoline

At the completion of Step 6, all of the necessary coefficients will have automatically populated the **Input** worksheet. See Figure B.3 for the input of transportation information for Material 1.

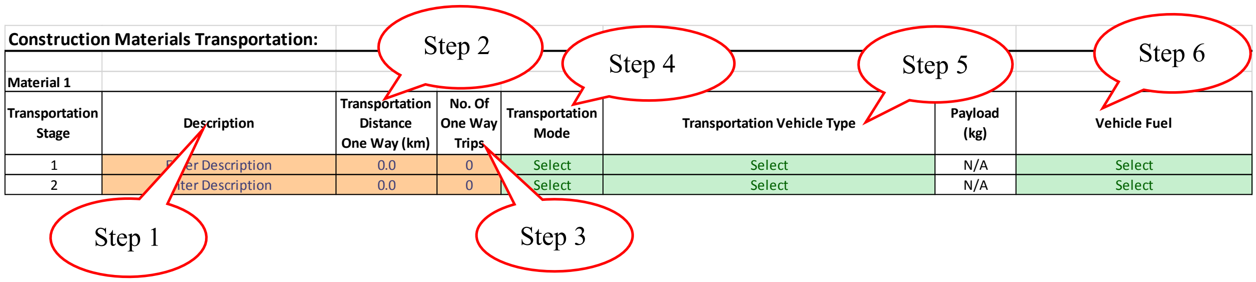

Figure B.3 Input section for transportation of Material 1, under "Construction Materials Transportation."

These steps should be repeated for each construction material transported to the site. There are inputs for up to 10 materials being transported, corresponding to the 10 construction materials. If fewer than 10 materials are transported to the site, leave the remaining "*Construction Materials Transportation*" input lines blank. If more than 10 materials are used for the construction, enter the transportation for additional materials along with the material quantities in a second SEEAM Spreadsheet Calculator file, and follow the procedure described at the end of Section B.2.2.2 to obtain total results.

B.2.2.4 Recycled or Reused Construction Materials Information

Sometimes construction materials consist of waste materials that have either been recycled, or are reused from another project. If any such materials are used for the ground improvement construction, they are entered in this section instead of the "*Construction Materials Information*" section. The SEEAM Spreadsheet Calculator allows for entry of up to three recycled or reused materials in construction. To enter recycled or reused material information for each recycled or reused material, follow these steps:

1. Enter a description of the recycled or reused material, such as "Deep mixing spoil used as fill."

2. Select the appropriate units for the recycled or reused material from the *Unit* drop down list. In general, the appropriate units are kilograms (kg) for solids and liters (L) for liquids.

3. Enter the quantity of the material used for construction. Make sure the quantity is entered in the appropriate units.

   Note: If the mode of transportation for the recycled or reused material is rail or water freight, the material quantity must be entered in units of kilograms (kg), or an error will occur in the calculations, and appear on the **Calculations** worksheet.

4. Enter the appropriate EEC, in MJ/Unit. Since recycled and reused materials can be highly variable in type and function, their EECs are not included in the database. Instead they require manual user entry. The EEC for these materials may be determined by conducting a life cycle analysis for the energy consumed by the process involved in making the material useful for construction, or a published life cycle analysis for that process. See Shillaber et al. (2015a) (Ch. 2) for additional information about life cycle analysis.

   For recycled or reused materials that require no processing or input energy other than transportation in order to be used as a construction material, the EEC should be entered as "0." This is the default value and "0" is initially entered in the worksheet. If processing is required before the material can be used in construction, the EEC should reflect the processing energy. If the processing is performed on the construction site of interest using regular site equipment, the EEC may be taken as "0," with the fuel or energy required to process the material included in the "*Construction Site Energy (Fuel Consumed)*" section of the **Input** worksheet (Section B.2.2.6).

5. Enter the appropriate CC, in kg CO_2/Unit. As for energy, since recycled and reused materials can be highly variable in type and function, their CCs are not included in the database. Instead, they require manual user entry. The CC for these materials may be determined by conducting a life cycle analysis for the CO_2 emissions generated by the process involved in making the material useful for construction, or a published life cycle analysis for that process. See Shillaber et al. (2015a) (Ch. 2) for additional information about life cycle analysis.

   For recycled or reused materials that require no processing other than transportation in order to be used as an input material, the CC should be entered as "0." This is the default value and "0" is initially entered in the worksheet. If processing is required before the material can be used in construction, the CC should reflect the processing CO_2 emissions. If the processing is performed on the construction site of interest by regular site equipment, the CC may be taken as "0," with the fuel or energy required to process the material included in the "*Construction Site Energy (Fuel Consumed)*" section of the **Input** worksheet (Section B.2.2.6).

6. Biogenic carbon is associated with biomass materials (e.g., wood) (Puettmann et al. 2010). Biogenic carbon is emitted when biomass is either combusted or decays. Biogenic carbon will not usually be applicable for recycled or reused material considerations, as the biogenic emissions are attributed to the project that originally consumed the biomass material. Therefore, there are typically no additional biogenic emissions associated with recycled or reused biomass materials. As such, this entry cell is left blank by default. In rare circumstances, recycled materials may involve biogenic carbon. In such cases, enter the appropriate biogenic CC, in kg CO_2/Unit. If the

recycled material does not involve biogenic carbon (most common), this may be left blank.

See Figure B.4 for the input of Recycled/Reused Material 1.

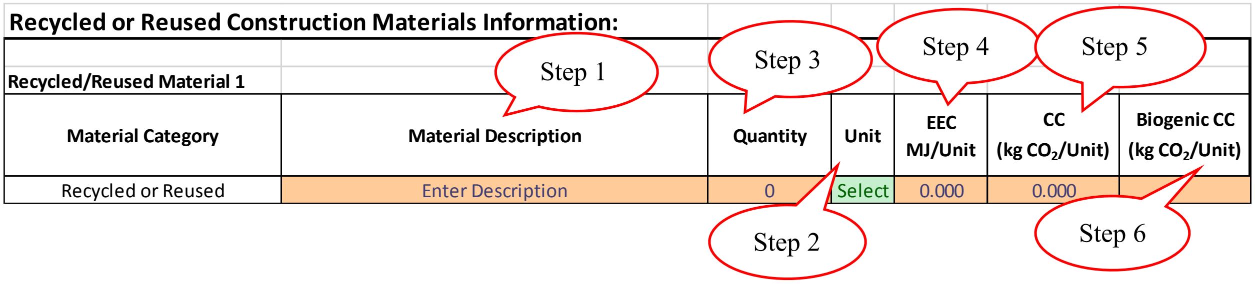

Figure B.4 Input for Recycled or Reused Material 1.

These steps may be repeated for up to three Recycled or Reused Materials, as needed, in the appropriate lines on the **Input** worksheet. If fewer than three recycled or reused materials are used for the construction, leave the remaining "*Recycled or Reused Construction Materials Information*" input lines blank. If more than three Recycled or Reused Materials are used for the construction, additional materials may be added by using the same procedure described for more than 10 construction materials in Section B.2.2.2.

B.2.2.5 Recycled or Reused Construction Materials Transportation

To the right of each recycled or reused material input in the "*Recycled or Reused Construction Materials Information"* section of the worksheet is a corresponding Recycled or Reused Construction Materials Transportation input for the recycled or reused material. As for conventional construction materials transportation, up to two modes of transportation are permitted. Two modes may be necessary for the case of materials transported in bulk by rail or water to a distribution center, and then by truck to the construction site. Most often, only one mode of transportation will be required for recycled or reused input materials. The user may input transportation information for Recycled or Reused Materials by the following steps:

1. Enter a description for the transportation, such as "Transporting deep mixing spoil to site by truck."
2. Enter the one-way travel distance in kilometers (km) for the transportation mode being entered. This will usually be the distance from the recycled or reused material supplier to the construction site.
3. Enter the number of one-way trips made by the vehicle to and/or from the construction site or distribution center. A value must be entered on this line for road transportation of liquids or any other material with a quantity in terms of a unit of volume rather than mass/weight. For road vehicles (trucking), the number of one-way trips may be left at "0" for any solid material with a unit of kilograms (kg). In this situation, the SEEAM Spreadsheet Calculator will estimate the number of trips based on the quantity of material and the selected vehicle payload (in kg) for the computation of total embodied energy and CO_2 emissions; however, the estimated number of trips is not shown on the **Input** worksheet. In this case, the SEEAM Spreadsheet Calculator assumes every vehicle makes a round trip (two one-way trips) to the site. Whenever possible, it is better to estimate the number of one-way trips and enter it into the spreadsheet directly rather than rely on the SEEAM Spreadsheet Calculator to estimate the number of trips. When determining the number of one-way trips, note that in general, vehicles will make round trips (two one-way trips) to the construction site.

   For water and rail freight, a value need not be entered for the number of one-way trips (i.e., it may be left at "0"). The SEEAM Spreadsheet Calculator determines the transport energy and emissions for rail and water freight based on the quantity of material transported (in kg) and the transport distance (in km).

Note: In its present form, the SEEAM Spreadsheet Calculator is unable to account for the transportation of liquids or other materials with a unit of volume (e.g., L, m^3) by rail or water freight because the underlying method is based on the mass of material and the transportation distance. If the recycled or reused material is entered with a unit of volume, the SEEAM Spreadsheet Calculator will return an error on the **Calculations** worksheet when rail or water freight is the selected mode of transportation.

4. Select the *Transportation Mode* from the drop down list. Available transportation modes for selection within the SEEAM Spreadsheet Calculator are as follows:
   - Road Vehicle
   - Water Freight
   - Rail Freight
5. If "Road Vehicle" is the selected Transportation Mode, select the *Vehicle Type* from the drop down list for road vehicles. Vehicle type is not an applicable selection for water freight or rail freight and the only option in the drop down menu for these transportation modes is "N/A." Vehicle Types within the SEEAM Spreadsheet Calculator for road transportation are as follows:
   - Road Vehicle:
     - Minivan or Small Pickup Truck
     - SUV or Full Size Pickup Truck (1/2 ton)
     - SUV or Full Size Pickup Truck (3/4 ton)
     - Full Size Pickup Truck (F350 or GM/Ram 3500 size)
     - Medium Duty Truck (F450 or GM/Ram 4500 size)

- Medium Duty Truck (F550 or GM/Ram 5500 size)
- Medium Duty Truck (F650 or GM/Ram 6500 size)
- Light Heavy Duty Truck
- Heavy Duty Truck

6. If "Road Vehicle" is the selected transportation mode, select the correct *Fuel Type* for the vehicle from the drop down list. For rail or water freight, leave this blank or select N/A from the drop down list. Available Fuel Types for road vehicles are as follows:

- Diesel
- Gasoline

At the completion of Step 6, all of the necessary coefficients will have automatically populated the **Input** worksheet. See Figure B.5 for the input of transportation for Recycled or Reused Material 1.

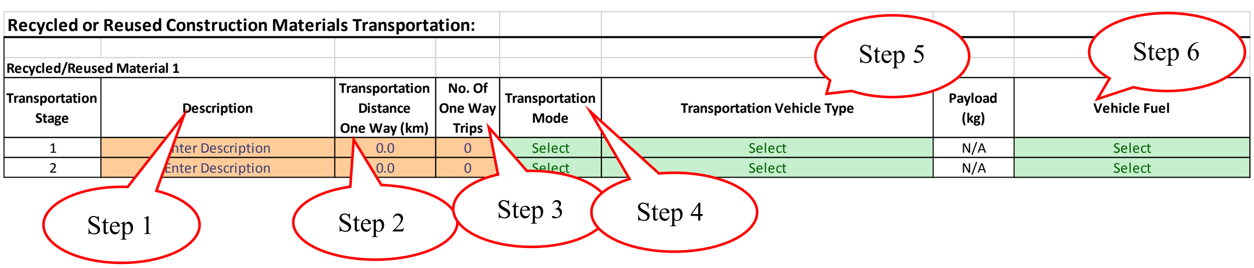

Figure B.5 Input for transportation of Recycled or Reused Material 1.

These steps should be repeated for each recycled or reused construction material transported to the site. There are inputs for up to three materials being transported, corresponding to the three recycled or reused construction materials. If fewer than three recycled or reused materials are transported to the site, leave the remaining "*Recycled or Reused Construction Materials Transportation*" input lines in this section blank. If more than three Recycled or Reused Materials are used for the construction, additional materials transportation may be added by using the same procedure described for more than 10 construction materials in Section B.2.2.2.

Note: Care should be taken when accounting for the transportation of recycled or reused materials in order to avoid double counting. If the waste material is transported to the construction site directly from the site where it is generated, the transportation will be accounted for as "Waste Transportation" for the project that generated the waste. In this case, the transportation energy and emissions for the project of interest are "0," and transportation information may be left blank. More often, the recyclable or reusable waste will be transported from the generating project site to a transfer station or processing facility. Then, it will be transported from that facility to the construction site using the waste as an input material. In this case, the transportation from the generator of the waste to the processing facility is included in the assessment of the project that generated the waste, and transportation from the processing facility to the current construction site is included in the current analysis as recycled or reused material transportation.

B.2.2.6 Construction Site Energy (Fuel Consumed)

Below the "*Recycled or Reused Construction Materials Information*" input section of the worksheet is the input section for "*Construction Site Energy (Fuel Consumed)*". This section allows for the input of up to four different site energy sources (fuels). Site energy information may be input by the following steps:

1. Select the *Fuel Type* from the drop down list. There are four available Fuel Types for selection, including:
    - Diesel
    - Gasoline
    - Compressed Natural Gas (CNG)
    - Electricity (U.S. Avg. Generation Mix)

2. Enter a description for the site energy source (e.g., diesel fuel consumed by site equipment).
3. Enter the quantity of the fuel or energy source used, in the appropriate units. The appropriate units will appear in the "*Unit*" column once a *Fuel Type* selection has been made. Appropriate units include liters (L) for liquids, kilowatt-hours (kW-hr) for electricity, and kilograms (kg) for solids and compressed gases.

If fewer than four fuels or energy sources are used to complete the construction, leave the remaining "*Construction Site Energy (Fuel Consumed)*" input lines blank. See Figure B.6 for the input section for Construction Site Energy Source 1.

Construction Site Energy (Fuel Consumed)					
Energy Source 1					
Step 1	Step 2	Step 3			
Fuel Type	**Description**	**Quantity**	**Unit**	**EEC MJ/Unit**	**CC (kg CO_2/Unit)**
Select	Enter Description	0		0.000	0.000

Figure B.6 Input for Construction Site Energy Source 1.

B.2.2.6.1 Using the Fuel Estimator Worksheet to Determine Fuel Quantities

The **Fuel Estimator** worksheet may be used to assist in estimating the quantity of fuel consumed by equipment for construction operations. On the worksheet, cells that require direct user input via typing are shaded in light orange. Cells that require user input via selection from a drop down list are shaded in green. All other cells in the worksheet are locked and will populate automatically based on the user input. These cells cannot be edited by the user.

The **Fuel Estimator** worksheet requires the user to enter input information about the fuel consumed and the equipment consuming it. It contains a *Basic Information* section (populated by data entered on the **Input** worksheet), followed by four *Energy Source* input tables. These correspond to the four different site energy sources that can be entered on the **Input** worksheet. The tables allow for input of machine type, gross engine power, duration of operation, and average engine load factor. The amount of fuel consumed by each machine combination is computed following the method presented by Shillaber et al. (2014) (Ch. 3). Each table can handle input information for up to 12 different combinations of machine type, gross engine power, duration of operation and load factor. The load factor is the fraction of the maximum/gross engine power being used to perform the work (EPA 2010).

The worksheet may be used to enter information to determine the quantity of fuel for each energy source by the following steps:

1. Select the *Fuel Type* from the drop down list at the top of the table. Available Fuel Types for selection include:
   - Diesel
   - Gasoline
   - Compressed Natural Gas (CNG)
   - Electricity (U.S. Avg. Generation Mix)

      Note: Electricity refers specifically to grid electricity, not electricity produced by an on-site generator which directly consumes another fuel source.

   Once a fuel type has been selected, the *BSFC* and *Consumption Unit* will populate automatically. The *BSFC* is the Brake Specific Fuel Consumption, which is the rate of fuel consumption per unit of power at the engine flywheel (Shillaber et al. 2014). The BSFC values in the SEEAM Spreadsheet Calculator are based on typical engine efficiencies in 2014. In the future, engine efficiencies may improve, therefore reducing fuel consumption for the same applied power.

2. On the first line of the table for each *Energy Source*, select the *Machine Type* from the drop down list. Once the machine type has been selected, the *Average Load Factor* will populate automatically for combustion fuels. For grid electricity, the *Average Load Factor* column will read "*Enter Override!*" and a Load Factor Override must be entered later (see Step 5). Available machine types include:
   - Bulldozer
   - Compressor
   - Crane
   - Drill Rig
   - Excavator
   - Generator
   - Grout/Concrete Pump
   - Front End Loader
   - Plant (concrete, grout, slurry)
   - Roller/Compactor
   - Skid Steer
   - Water Pump
3. Enter the *Gross Engine Power* for the machine, in kilowatts (kW). This is the maximum output power of the machine's engine. Specifications for machines can often be found on equipment manufacturer websites. In addition, the latest version of the Caterpillar

Performance Handbook is helpful in providing specifications for the range of Caterpillar machines.

4. Enter the estimated *Duration of Operation* for the machine, in hours. Many machines will operate for the full duration of each work day for the whole project. However, some specialized machines may have more limited usage.
5. If desired or required, enter a *Load Factor Override*. For combustion fuels (e.g., diesel, gasoline), a load factor entered here will override the *Average Load Factor* from the EPA (2010). If grid electricity is the fuel source, a value must be entered here because average load factors are not available from the EPA; however, the load factors will generally be similar for electric motors and internal combustion engines. Thus, the user may find guidance in selecting load factors for electric motors by examining the average load factor values from the EPA on the **Load Factor Table** worksheet.

   Note: If electricity to power construction equipment is generated on-site by a generator that consumes another fuel (e.g., diesel, gasoline, compressed natural gas) rather than being sourced from the electric grid, then the load on the generator (and the resulting fuel consumed) is all that is required for determining embodied energy and CO_2 emissions associated with the use of electric machinery. Electric motors that rely on the generator are not responsible for any other embodied energy and CO_2 emissions. When electric motors are powered by grid electricity, the energy and CO_2 emissions associated with generating the electricity consumed by the electric motors must be attributed to the project, and the load on the electric motors is relevant for determining the quantity of electricity consumed.

The user may find alternative load factors for specific machine tasks from a resource like the Caterpillar Performance Handbook. In general, for ground engaging equipment (e.g., bulldozers, excavators, loaders), load factors may be classified as low, medium or high if they fall within the following general ranges (Caterpillar 2012):

Low: 0.35 – 0.50

Medium: 0.50 – 0.65

High: 0.65 – 0.80

For other machinery, load factors may be classified as low, medium or high if they fall within the following ranges (Caterpillar 2012):

Low: 0.20 – 0.40

Medium: 0.40 – 0.60

High: 0.60 – 0.80

6. Enter the total number of machines that will operate with the specified combination of machine type, gross engine power, duration of operation and load factor in the *Number of Machines* column. Often the number will be 1, however, on large projects there may be multiple machines performing the same task for the duration of each working shift. In such instances, the number of machines matching a specified combination of machine type, gross engine power, duration of operation and load factor may be greater than 1. If "0" or no number is entered, the worksheet will not compute a quantity of fuel for the machine combination.
7. Use Steps 1 through 6 to enter each different combination of machine type, gross engine power, duration of operation and load factor associated with the fuel source specified at the top of the *Energy Source* table.

8. The total quantity of the specified fuel consumed by all listed machines is determined at the bottom of the *Energy Source* table. This value may be entered as the quantity for one *Energy Source* on the **Input** worksheet.

The Energy Source 1 table for input on the **Fuel Estimator** worksheet is shown in Figure B.7.

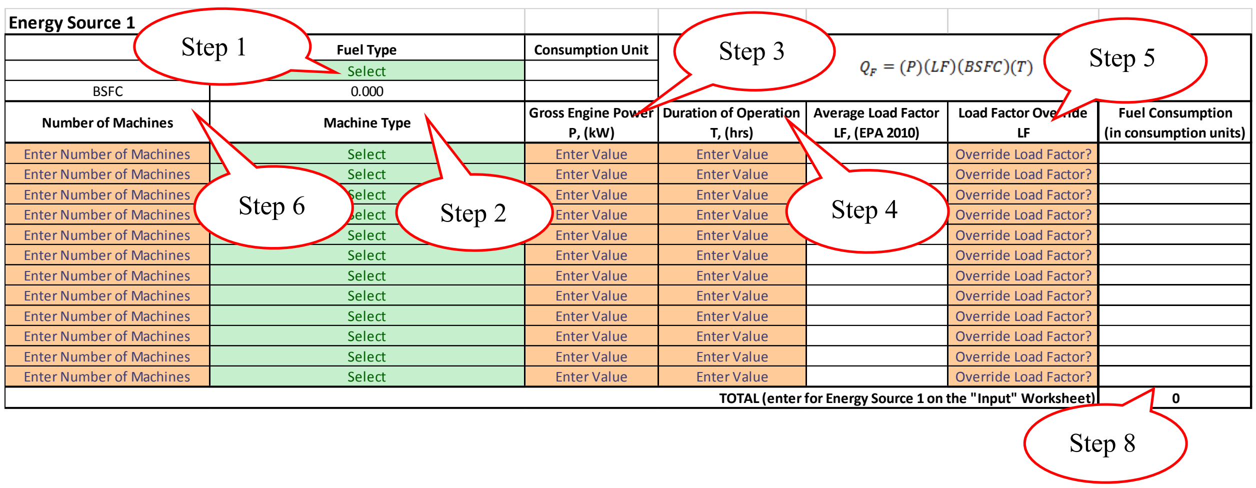

Figure B.7 Energy Source 1 input table from the "Fuel Estimator" worksheet.

The preceding steps may be followed for each energy source (up to four) being consumed on the construction site using the four available *Energy Source* tables in the **Fuel Estimator** worksheet.

B.2.2.7 Waste Materials Transportation

Waste materials transportation follows the same type of input as the construction materials transportation. The major difference is that the waste materials transportation input can only accept one mode of transportation for each waste stream. In addition, the SEEAM Spreadsheet Calculator only allows for up to four waste materials or waste streams. These may include (but are not limited to) trucking to a municipal solid waste landfill, a hazardous waste landfill, an incinerator, or a transfer station/recycling center. Waste material transportation information may be input by the following steps:

1. Enter a description for the waste transportation, such as "Trucking jet grout spoils to landfill."
2. Enter the one-way travel distance, in kilometers (km). This will be the distance from the construction site to the waste disposal or recycling facility.
3. If known, enter the mass, in kilograms (kg), of the solid waste material to be hauled off-site to a disposal or recycling facility in the "*Quantity of Solid Waste*" column. A value must be entered here if the waste is transported by water or rail freight. If the waste is transported by truck, the SEEAM Spreadsheet Calculator can use the entered mass to estimate the number of truckloads of waste material hauled off-site.

   If trucks are the mode of transportation and the mass of solid waste is unknown, or the user does not want the SEEAM Spreadsheet Calculator to estimate the number of trips, the "*Quantity of Solid Waste*" may be left as "0." However, in this case the number of one-way trips cannot be estimated by the SEEAM Spreadsheet Calculator, and must be input manually, as described in Step 4.

   > **Note:** Many waste materials (especially earth materials) are in a loose or bulky state when they are loaded into a truck and hauled off-site for disposal. As such, truck cargo volume may limit capacity instead of payload. In these instances, it is best to estimate the typical volume of material in a truckload, and compute the number of truckloads based on the total volume of waste and the average truckload volume. The number of truckloads then informs the number of one-way trips to enter in the spreadsheet (Step 4).

4. Enter the number of one-way trips made by the vehicle from and/or to the construction site. For road vehicles (trucking), this may be left as "0" if there is a mass of solid waste

materials entered in Step 3. In this situation, the SEEAM Spreadsheet Calculator will estimate the number of trips based on the quantity of waste material and the selected vehicle payload (in kg) for the computation of total embodied energy and CO_2 emissions; however, the estimated number of trips is not shown on the **Input** worksheet. In this case, the SEEAM Spreadsheet Calculator assumes every vehicle makes a round trip (two one-way trips) to the site.

If a non-zero value is entered in this step, the SEEAM Spreadsheet Calculator will not use the mass of waste entered in Step 3 to determine the number of truckloads of waste.

Whenever possible, it is better to estimate the number of one-way trips and enter it into the spreadsheet directly rather than rely on the SEEAM Spreadsheet Calculator to estimate the number of trips (see the note at the end of Step 3). When determining the number of one-way trips, note that in general, vehicles will make round trips (two one-way trips) to the construction site.

For water and rail freight, a value need not be entered for the number of one-way trips. The SEEAM Spreadsheet Calculator determines the transport energy and emissions for rail and water freight based on the quantity of waste transported (in kg) and the transport distance (in km).

> **Note:** In its present form, the SEEAM Spreadsheet Calculator is unable to account for the transportation of liquids or other waste materials with a unit of volume (e.g., L, m^3) by rail or water freight.

5. Select the *Transportation Mode* from the drop down list. As for construction materials transportation, available transportation modes for selection within the SEEAM Spreadsheet Calculator are as follows:
   - Road Vehicle
   - Water Freight
   - Rail Freight
6. If "Road Vehicle" is the selected Transportation Mode, select the *Vehicle Type* from the drop down list. Vehicle type is not an applicable selection for water freight or rail freight and the only option in the drop down menu for these transportation modes is "N/A."

   As for construction materials, the vehicle types within the SEEAM Spreadsheet Calculator for road vehicle transportation of waste are as follows:
   - Road Vehicle:
     - Minivan or Small Pickup Truck
     - SUV or Full Size Pickup Truck (1/2 ton)
     - SUV or Full Size Pickup Truck (3/4 ton)
     - Full Size Pickup Truck (F350 or GM/Ram 3500 size)
     - Medium Duty Truck (F450 or GM/Ram 4500 size)
     - Medium Duty Truck (F550 or GM/Ram 5500 size)
     - Medium Duty Truck (F650 or GM/Ram 6500 size)
     - Light Heavy Duty Truck
     - Heavy Duty Truck

7. If “Road Vehicle” is the selected Transportation Mode, select the *Fuel Type* from the drop down list. For rail or water freight, leave this blank or select N/A from the drop down list. Available Fuel Types for selection include:

- Diesel
- Gasoline

Figure B.8 shows the portion of the **Input** worksheet associated with transportation of Waste Material/Stream 1.

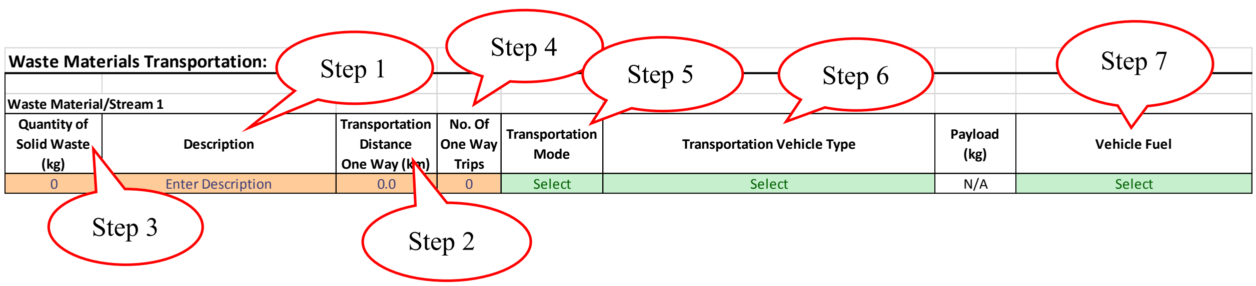

Figure B.8 Input for transportation of Waste Material/Stream 1.

This process may be repeated for each waste material or waste stream leaving the construction site (up to four). For the case of waste material transported off-site that is to be recycled, pay special attention to the note at the end of Section B.2.2.5, Recycled or Reused Construction Materials Transportation. If there are fewer than four waste materials or waste streams leaving the site, leave the remaining “*Waste Materials Transportation*” input lines blank.

B.2.2.8 Other Transportation

The input worksheet does not include a section for transportation associated with mobilization, demobilization or worker commuting because the energy and CO_2 emissions from these sources are generally small compared to those from other aspects of the construction. The energy and emissions associated with these aspects of the project may also be comparable for different alternatives.

If users wish to consider the energy and CO_2 emissions associated with mobilization, demobilization and/or worker commuting, additional transportation may be entered on any unused input lines in the "*Construction Materials Transportation*" or "*Recycled or Reused Construction Materials Transportation*" sections of the **Input** worksheet. When using extra "*Construction Materials Transportation*" or "*Recycled or Reused Construction Materials Transportation*" input lines for this purpose, the user should enter a clear and succinct description (Step 1 in Section B.2.2.3) for any additional transportation entered. Examples of possible descriptions include: "Worker commuting by small pickup truck," or "Hauling drill rig to/from site by heavy duty truck." Users must also enter the number of one-way trips (Step 3 in Section B.2.2.3) because the SEEAM Spreadsheet Calculator cannot estimate the number of trips like it can for construction materials. All other aspects of additional transportation can be input following the steps in Section B.2.2.3.

Once all input information is entered by following the steps in Sections B.2.2.1 through B.2.2.8, the SEEAM Spreadsheet Calculator automatically performs all required calculations and the user may check the calculations for errors and view the results for total embodied energy and CO_2 emissions.

B.2.3 Viewing the Results

Prior to viewing the results, the user should view the **Calculations** worksheet to check that the SEEAM Spreadsheet Calculator is not returning an error in the embodied energy or CO_2 emissions calculations for any of the entered input information. The **Calculations** worksheet is laid out with distinct sections for Materials, Materials Transportation, Construction Site Operations and Waste Transportation. The calculation results for each line of input information on the **Input** worksheet are clearly laid out and labeled on the **Calculations** worksheet with the "Descriptions" entered on the **Input** worksheet. Check to make sure that the word "ERROR" does not appear in any of the cells for mean embodied energy or CO_2 emissions for any entered input. If an error appears, the user should return to the corresponding line on the **Input** worksheet and make sure that all information has been entered correctly and in accordance with the limitations of the SEEAM Spreadsheet Calculator as outlined in this manual. Once all errors have been addressed, the results may be viewed.

To view the results of the SEEAM analysis for all entered input information, click on the **Results** worksheet tab at the bottom of the open SEEAM Spreadsheet Calculator file. The **Results** worksheet presents the results of the embodied energy and CO_2 emissions calculations in three sections:

B.2.3.1 Basic Information

The "*Basic Information*" section of the **Results** worksheet is a copy of the basic information entered on the **Input** worksheet.

B.2.3.2 Overall Totals – Analytically Calculated

The "*Overall Totals – Analytically Calculated*" section of the **Results** worksheet shows the mean and standard deviation of total embodied energy and CO_2 emissions for the proposed ground improvement technique and design, as determined analytically. In addition, it shows the contribution of Materials, Materials Transportation, Site Operations, and Waste Transportation to the overall project embodied energy and CO_2 emissions. See Figure B.9. Note that "0," "N/A" and "#DIV/0!" appear in Figure B.9 because no input data is entered into the SEEAM Spreadsheet Calculator.

Overall Totals - Analytically Calculated										
	Embodied Energy (GJ)					CO_2 Emissions (tonnes)				
	Mean	St Dev	Maximum	Minimum	% of Total	Mean	St Dev	Maximum	Minimum	% of Total
Materials	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
Materials Transportation	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
Site Operations	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
Waste Transportation	0	0	N/A	N/A	#DIV/0!	0	0	N/A	N/A	#DIV/0!
TOTAL	**0**	**0**			**#DIV/0!**	**0**	**0**			**#DIV/0!**

Figure B.9 SEEAM results: analytically calculated total mean and standard deviation of embodied energy and CO_2 emissions. "0," "N/A" and "#DIV/0!" appear because no input data is entered into the SEEAM Spreadsheet Calculator.

Pie graphs to the right of the table on the **Results** worksheet show the proportion of total embodied energy and CO_2 emissions associated with Materials, Materials Transportation, Site Operations and Waste Transportation for the analytically calculated results.

B.2.3.3 Overall Totals – Monte Carlo Simulation for n = 1,000 Values

The "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" section of the **Results** worksheet shows the mean, standard deviation and 90% confidence interval of total embodied energy and CO_2 emissions for the proposed ground improvement technique and design, as determined from Monte Carlo simulated data sets of n = 1,000 values for total embodied energy and CO_2 emissions. In addition, it shows the contribution of Materials, Materials Transportation, Site Operations, and Waste Transportation to the overall project embodied energy and CO_2 emissions as determined from the Monte Carlo simulation. See Figure B.10. Note that "0," "#NUM!" and "#DIV/0!" appear in Figure B.10 because no input data is entered into the SEEAM Spreadsheet Calculator.

Overall Totals - Monte Carlo Simulation for n = 1,000 Values										
	Embodied Energy (GJ)					CO_2 Emissions (tonnes)				
	Mean	St Dev	Maximum	Minimum	% of Total	Mean	St Dev	Maximum	Minimum	% of Total
Materials	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
Materials Transportation	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
Site Operations	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
Waste Transportation	0	0	0	0	#DIV/0!	0	0	0	0	#DIV/0!
TOTAL	**0**	**0**	**0**	**0**	**#DIV/0!**	**0**	**0**	**0**	**0**	**#DIV/0!**
Mean Error (%)	**#DIV/0!**					**#DIV/0!**				
% Different from Calculated	**#DIV/0!**	**#DIV/0!**				**#DIV/0!**	**#DIV/0!**			
Total Embodied Energy and CO_2 Emissions 90% Confidence Interval - Generated from Querying the 1,000 Monte Carlo Simulation Points										
	EE (GJ)					**CO_2 (tonnes)**				
5% < Value	#NUM!				5% < Value	#NUM!				
Mean	0				Mean	0				
95% < Value	#NUM!				95% < Value	#NUM!				

	90% Confidence Interval	
	Low	High
Embodied Energy (GJ)	#NUM!	#NUM!
CO_2 Emissions (tonnes)	#NUM!	#NUM!

Figure B.10 SEEAM results: Monte Carlo simulation for mean, standard deviation and 90% confidence intervals of total embodied energy and CO_2 emissions. "0," "#NUM!" and "#DIV/0!" appear because no input data is entered into the SEEAM Spreadsheet Calculator.

Pie graphs to the right of the table on the **Results** worksheet show the proportion of total embodied energy and CO_2 emissions associated with Materials, Materials Transportation, Site Operations and Waste Transportation. Below the table are histograms of total embodied energy and CO_2 emissions based on the Monte Carlo simulation.

In the center of the table, the line labeled *Mean Error (%)* shows the estimated error (+/-) in the mean values from the Monte Carlo simulated data sets (n = 1,000), with 90% confidence. For the SEEAM, the target mean error is less than +/- 2.5% of the mean value, which was selected because it can be achieved with a moderate number of values in the Monte Carlo simulated data set and generally reflects the degree of accuracy in known information. The calculation of estimated mean error assumes the results are approximately normally distributed, regardless of whether or not that is actually the case for total embodied energy and CO_2 emissions.

> **Note:** if the Mean Error is > 2.5%, then the number of values in the Monte Carlo simulated data set (n = 1,000 in the SEEAM Spreadsheet Calculator) is insufficient to achieve this maximum recommended level of mean error. To reduce the mean error, the number of values in the simulated data set should be increased such that

the mean error is reduced to < 2.5%. This may be accomplished by running the SEEAM Spreadsheet Calculator multiple times, copying and compiling the values from rows 62-1061 of columns CJ and CK on the **Monte Carlo** worksheet for each analysis into a separate Microsoft Excel workbook, then querying the combined data set (n = 2,000 values) to obtain results. The SEEAM analysis can be re-run by clicking the "Save" button, or by clicking the "Calculate Now" button on the "Formulas" menu in Microsoft Excel. The mean, standard deviation, maximum and minimum values of total embodied energy and CO_2 emissions from the combined data may be determined using Microsoft Excel formulas. Whether or not the mean error is < 2.5% may be checked by Eq. B.2, derived using information from Fenton and Griffiths (2008):

$$0.025\hat{\mu}_g \geq t_{\frac{\alpha}{2},n-1}\frac{\hat{\sigma}_g}{\sqrt{n}} \tag{B.2}$$

where n is the number of values in the combined data set, $\hat{\mu}_g$ and $\hat{\sigma}_g$ are the mean and standard deviation of the combined data set, t is the statistic from the t-distribution and α is the desired significance level. For 90% confidence, α = 0.1. The t-distribution is built into Microsoft Excel for obtaining the appropriated test statistic.

The line in the table labeled *% Different from Calculated* shows the percent difference between the means and standard deviations generated from Monte Carlo simulation and those determined from the analytical calculations. This is a second indicator of the amount of error in the Monte Carlo simulation, as the analytical means and standard deviations were generated from mathematical operations on random variables directly. Therefore, they represent the theoretically "correct" values for the total embodied energy and CO_2 emissions data sets.

The bounds of the 90% confidence intervals for total embodied energy and CO_2 emissions derived from the Monte Carlo simulation (n = 1,000) are shown at the bottom of the table.

B.3 USING THE SEEAM RESULTS

B.3.1 Comparing Design Alternatives

Use of the analytical SEEAM results is the fastest and simplest method of evaluating the mean environmental impact of a single construction alternative or multiple alternatives. However, the analytical analysis does not provide detailed information regarding the confidence interval and possible distribution for the estimated total embodied energy and CO_2 emissions. Where the user is not concerned with these details, or for a quick preliminary analysis, the analytical method works well.

The Monte Carlo simulation in the SEEAM Spreadsheet Calculator is particularly useful for statistically comparing the embodied energy and CO_2 emissions of different design alternatives, which is important because design alternatives that have different mean values of embodied energy and CO_2 emissions may not actually be different from each other in the presence of uncertainty. Statistical comparison methods allow the engineer to determine whether or not two design alternatives have significantly different total embodied energy and/or CO_2 emissions, or if one results in more embodied energy and/or CO_2 emissions than another. Therefore, statistical comparison methods can be an important aid in the engineering decision process, particularly for alternatives that have significantly different costs and/or performance characteristics.

Two statistical methods for comparing alternatives using the Monte Carlo simulated data from the SEEAM Spreadsheet Calculator are presented in the following sections (also see Ch. 6 and Appendix P). The first is a simple method of comparing two alternatives that can be readily implemented in Microsoft Excel. The second requires more advanced statistical hypothesis testing.

B.3.1.1 Method 1: Comparison by Taking the Difference Between two Alternatives

The first statistical comparison method is a simple method of comparing two alternatives that does not involve statistical hypothesis testing. It is accomplished by determining the difference between the Monte Carlo generated embodied energy and CO_2 emissions from each alternative, as described by Shillaber et al. (2016, In Review) (Ch. 6) based on a method presented by de Koning et al. (2010). The differences between each Monte Carlo simulated value of total embodied energy and total CO_2 emissions for each project alternative must be taken, such that there are 1,000 difference values comprising a "Difference Data Set" for each environmental impact factor. This may be accomplished by copying the values in the n = 1,000 Monte Carlo simulated data sets (found in rows 62-1061 of columns CJ and CK on the **Monte Carlo** worksheet) from each alternative and pasting them side-by-side in a second spreadsheet file, and then taking the difference between corresponding values for each alternative to generate the "Difference Data Sets" for total embodied energy and CO_2 emissions.

The mean, standard deviation, maximum and minimum of the "Difference Data Sets" for total embodied energy and CO_2 emissions may then be determined using formulas. The "Difference Data Sets" are also plotted in histograms. Bin size should be selected such that the histograms clearly show the shape of the distribution of values in the "Difference Data Sets" (i.e., the histograms should not contain all of the values from the "Difference Data Sets" in a few bins; the number of values in each bin should generally be about 150 or fewer when the simulated data set consists of n = 1,000 values). If a difference histogram centers around zero, then the alternatives are not different (i.e., the difference between them is zero on average). If zero does not fall within a difference histogram, then one of the alternatives involves more embodied energy and/or CO_2 emissions than the other. The farther the center of the difference histogram is away from zero, the more likely one alternative is greater than the other. The greater of the two alternatives may be determined based on the sign of the difference.

When the histogram of the difference values overlaps zero in one of the distribution tails, it is also useful to determine the proportion of the difference values that are greater than or less than zero by querying the "Difference Data Set." In Microsoft Excel, this can be accomplished using the COUNTIF function, setting the criteria to "< 0" or "> 0" and then dividing the result by $n = 1{,}000$.

The proportion of values greater than or less than zero provides an indication of the strength of any conclusions regarding the difference between alternatives. For example, if 2% of the difference values are less than zero, then there is a 98% chance that one alternative is greater than the other; therefore, the two alternatives are most likely significantly different. If 20% of the values are less than zero, then it is only 80% likely that one alternative is greater than another; therefore, the alternatives are most likely not significantly different. Note that statistical hypothesis testing generally uses a significance level between 1% and 10% to determine differences.

Examples using this type of comparison are provided in Sections B.4.4 and B.5.4.

B.3.1.2 Method 2: Nonparametric Statistical Tests

The use of nonparametric statistical hypothesis testing is a more advanced method of analysis applicable when the data does not follow the normal distribution, or the distribution is unknown. Advantages of nonparametric tests are that they do not rely on a theoretical distribution to draw conclusions and can compare more than two alternatives at once.

Nonparametric statistical testing can be performed using the $n = 1{,}000$ Monte Carlo simulated data sets for total embodied energy and CO_2 emissions (found in rows 62-1061 of columns CJ and CK of the **Monte Carlo** worksheet) to infer whether different project alternatives have significantly different total embodied energy and CO_2 emissions. The best way to do this is to copy the simulated data sets (values only) for total embodied energy and CO_2 emissions into a separate spreadsheet file, placing the data for each of the alternatives to be compared side-by-side. Then, statistical tests may be conducted by writing the appropriate formulas in Microsoft Excel, or by exporting the data to separate statistical analysis software such as JMP (SAS Institute), SAS (SAS Institute), SPSS (IBM), or R (The R Foundation). Using specialized statistical analysis software is recommended.

Statistical tests are conducted using the null hypothesis that the alternatives have the same total embodied energy and CO_2 emissions. The alternative hypothesis may either be that the alternatives do not have the same total embodied energy and CO_2 emissions, or that one alternative is greater than or less than another. Statistical tests are conducted by comparing the *p*-value generated by the test method with the desired significance level, α (such as 0.01, 0.05 or 0.1). The *p*-value is defined as the probability of obtaining a result equal to or more extreme than the observed value, assuming the null hypothesis is true (Ott and Longnecker 2010). When the *p*-value is less than α, the statistical test indicates there is significant evidence to suggest the null hypothesis is false.

The most appropriate nonparametric statistical tests to use include the Wilcoxon Rank Sum test described by Wilcoxon (1945) and Mann and Whitney (1947) for comparing two alternatives, and the Kruskal-Wallis test (Kruskal and Wallis 1952) for comparing more than two alternatives. The Wilcoxon Rank Sum test is analogous to the parametric *t*-test and the Kruskal-Wallis test is analogous to the parametric ANOVA test.

When comparing more than two alternatives with the Kruskal-Wallis test, if the test rejects the null hypothesis, then the Steel-Dwass method of multiple comparisons may be used to explore differences between all possible pairs of alternatives. The Steel-Dwass method was originally proposed independently by Steel (1960) and Dwass (1960), and was further elaborated on by Critchlow and Fligner (1991).

B.3.2 Reducing Environmental Impacts for a Ground Improvement Design

The SEEAM Spreadsheet Calculator can also be used after a final design option is selected to determine which aspects of the design cause the most environmental impact and could potentially be targeted for reduction. Reductions in embodied energy and CO_2 emissions for a given design may be achieved by replacing a high energy and emissions virgin material with a recycled one, recycling some waste material on-site rather than disposing it, reducing the machine size and power used on-site for construction, or reducing transportation distances by selecting closer suppliers. For an example of the influence of different decisions on the embodied energy and CO_2 emissions of a ground improvement alternative, see Shillaber et al. (2015c) (Ch. 5).

When seeking target areas for reductions, it is recommended to first observe the proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation. When the biggest contributor/key area for reduction has been identified (e.g., materials, site operations), it is helpful to view the **Calculations** worksheet to see the embodied energy and CO_2 emissions associated with every input entered on the **Input** worksheet. This allows for identification of the biggest specific contributors, which may be targeted for reduction by design modification or selection of alternative materials or methods.

The following two Sections (B.4 and B.5) present case history examples demonstrating the application of the SEEAM Spreadsheet Calculator. Based on the information included in this manual and the case history data provided in Sections B.4 and B.5, a first time user of the SEEAM Spreadsheet Calculator was able to repeat these analyses and obtain comparable results.

B.4 CASE HISTORY EXAMPLE: LPV 111 IN NEW ORLEANS, LA

B.4.1 Project Overview

LPV 111 is an 8.5 km long levee section in New Orleans, LA that serves to protect the city from flooding. During hurricane Katrina in 2005, the levee was overtopped and damaged (Cali et al. 2012). Upgrades to LPV 111 involved raising the levee crest elevation about 3 m to reach the 100 year flood protection level. Two viable design alternatives included Deep Soil Mixing (DSM) to support an earthen embankment composed of DSM spoil and borrow soil, and the use of Prefabricated Vertical Drains (PVDs) to improve the foundation soils for embankment support (Cali et al. 2012). Additional details about the project are available in literature (Bertero et al. 2012; Bertoni et al. 2015; Cali et al. 2012; Cooling et al. 2012; Druss et al. 2012; Schmutzler et al. 2012; Shillaber et al. 2015b; Shillaber et al. 2015c).

The required quantities for each alternative, the results of SEEAM analyses completed using the SEEAM Spreadsheet Calculator for each alternative, and a comparison of the alternatives using the difference method (Section B.3.1.1) are included in the following sections. The reader may use the quantities presented here to gain experience using the SEEAM Spreadsheet Calculator by duplicating the example analysis presented here.

B.4.2 LPV 111 Deep Soil Mixing Alternative

B.4.2.1 Deep Soil Mixing Quantities

Table B.1 contains a summary of all quantities of materials, fuel, haul distances and number of trips for the SEEAM analysis of DSM at LPV 111, including embankment construction. Note that the embankment was constructed using 400,000 m^3 of DSM spoil and 441,000 m^3 of borrow soil. Since the DSM spoil was recycled as embankment fill, there is no waste transportation and disposal with this alternative.

In this case, water (as a construction material) may be assumed to have no transportation in the SEEAM analysis. Assume potable water delivery will occur via existing water distribution infrastructure with no additional transportation energy and emissions.

All transportation of materials by truck is performed by heavy duty trucks consuming diesel fuel. Note that "round trips" is the unit of truck trips in the table; the SEEAM Spreadsheet Calculator requires input of one-way trips. A single round trip is equal to two one-way trips.

Table B.1 Construction quantities for LPV 111 deep soil mixing and embankment construction.

Material	Quantity	Unit
Cement (in binder)	104,250,000	kg
Cement shipping distance by barge to local plant	1,130	km
Slag (in binder)	312,750,000	kg
Slag shipping distance by barge to local plant	1,610	km
Number of 23 tonne truckloads to deliver blended binder from the local plant to the site (mixed 25% cement, 75% slag)	18,131	round trip
Blended slag/cement binder transportation distance to the site from local plant by truck	3.2	km
Water	454,000,000	L
Geogrid (general plastic, in other cases a specific material should be selected if known and available in the coefficient database)	395,325	kg
Geogrid transportation distance	1,127	km
Number of truck trips to deliver geogrid to the site	17	round trip
Average transportation distance for clay borrow	37	km
Total number of truckloads for clay borrow	38,500	round trip
Diesel fuel consumed (DSM rigs, backhoes, pumps)	3,902,000	L
Total diesel fuel consumed for clay borrow extraction	210,000	L
Diesel fuel consumed for embankment placement and compaction	1,960,000	L

B.4.2.2 Deep Soil Mixing SEEAM Analysis Results

Tables B.2 and B.3 together constitute the "*Overall Totals – Analytically Calculated*" table from the **Results** worksheet. The embodied energy and CO_2 emissions from the "*Overall Totals –*

Analytically Calculated" table from the SEEAM Spreadsheet Calculator have been separated into two tables here to fit the page width and maintain readability.

When the quantities from Table B.1 are entered correctly into the SEEAM Spreadsheet Calculator, the values shown in Tables B.2 and B.3 should exactly match the values shown in the "*Overall Totals – Analytically Calculated*" table on the **Results** worksheet.

Table B.2 "*Overall Totals – Analytically Calculated*," Embodied energy results from the SEEAM Spreadsheet Calculator for the deep mixing alternative for LPV 111.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	762,256	122,364	N/A	N/A	65%
Materials Transportation	150,843	1,683	N/A	N/A	13%
Site Operations	261,096	6,251	N/A	N/A	22%
Waste Transportation	0	0	N/A	N/A	0%
TOTAL	**1,174,195**	**122,535**			**100%**

Table B.3 "*Overall Totals – Analytically Calculated*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the deep mixing alternative for LPV 111.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	104,741	11,485	N/A	N/A	71%
Materials Transportation	22,047	129	N/A	N/A	15%
Site Operations	19,734	481	N/A	N/A	13%
Waste Transportation	0	0	N/A	N/A	0%
TOTAL	**146,521**	**11,496**			**100%**

Tables B.4 and B.5 together constitute the upper portion of the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table on the **Results** worksheet. The embodied energy and CO_2 emissions from the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table from the SEEAM Spreadsheet Calculator have been separated into two tables here to fit the page width and maintain readability.

Note that these results are for one Monte Carlo realization (i.e., simulated data set) of n = 1,000 values; every time the SEEAM Spreadsheet Calculator is run, a different realization is generated (see Section B.1.2). Therefore, the values in the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table on the **Results** worksheet may differ from those shown here even when the exact same input data (Table B.1) is entered on the **Input** worksheet. Also, note the Mean Error is < 2.5%, so no additional values are needed in the Monte Carlo simulation.

Table B.4 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," Embodied energy results from the SEEAM Spreadsheet Calculator for the deep mixing alternative for LPV 111.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	762,069	121,171	1,229,532	422,064	65%
Materials Transportation	150,887	1,745	156,000	146,184	13%
Site Operations	261,311	8,547	286,361	238,269	22%
Waste Transportation	0	0	0	0	0%
TOTAL	**1,174,267**	**121,394**	**1,654,580**	**827,596**	**100%**
Mean Error (%)	**0.54%**				
% Different from Calculated	**0.01%**	**0.93%**			

Table B.5 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the deep mixing alternative for LPV 111.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	105,275	11,751	142,816	65,018	72%
Materials Transportation	22,054	135	22,513	21,659	15%
Site Operations	19,769	663	22,019	17,836	13%
Waste Transportation	0	0	0	0	0%
TOTAL	**147,098**	**11,796**	**184,881**	**107,463**	**100%**
Mean Error (%)	**0.42%**				
% Different from Calculated	**0.39%**	**2.61%**			

Table B.6 shows the 90% confidence interval from the bottom of the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table on the **Results** worksheet. Again, these results are for one Monte Carlo realization (i.e., simulated data set) of n = 1,000 values; every time the SEEAM Spreadsheet Calculator is run, a different realization is generated (see Section B.1.2). Therefore, the values for the 90% confidence interval on the **Results** worksheet may differ from those shown here even when the exact same input data (Table B.1) is entered on the **Input** worksheet.

Table B.6 90% confidence interval results from the SEEAM Spreadsheet Calculator for the deep mixing alternative for LPV 111.

	90% Confidence Interval	
	Low	**High**
Embodied Energy (GJ)	994,778	1,391,436
CO_2 Emissions (tonnes)	129,584	167,314

The plots on the **Results** worksheet (pie graphs, histograms) are not shown here. The user can verify that they have entered the input information correctly based on matching the values in Tables B.2 and B.3 to those appearing in the "*Overall Totals – Analytically Calculated*" table on the **Results** worksheet in the SEEAM Spreadsheet Calculator. If they match, the correct/matching figures will be displayed in the SEEAM Spreadsheet Calculator.

B.4.3 LPV 111 Prefabricated Vertical Drains Alternative

B.4.3.1 Prefabricated Vertical Drains Quantities

Table B.7 contains a summary of all quantities of materials, fuel, haul distances and number of trips for the SEEAM analysis of the PVD alternative for LPV 111, including embankment construction. Unlike the DSM alternative, which did not involve any waste disposal, this alternative involves hauling waste from the cement/bentonite wall construction to a disposal facility.

In this case, water (as a construction material) may be assumed to have no transportation in the SEEAM analysis. Assume potable water delivery will occur via existing water distribution infrastructure with no additional transportation energy and emissions.

All transportation of materials by truck is performed by heavy duty trucks consuming diesel fuel. Note that "round trips" is the unit of truck trips in the table; the SEEAM Spreadsheet Calculator requires input of one-way trips. A single round trip is equal to two one-way trips.

Table B.7 Construction quantities for LPV 111 prefabricated vertical drains and embankment construction.

Material	Quantity	Unit
Polypropylene PVDs (molded)	580,100	kg
PVDs transportation distance	1,175	km
PVDs total number of truckloads	24	round trip
Geonet drainage media (general polyethylene)	714,600	kg
Geonet transportation distance	604	km
Geonet total number of truckloads	30	round trip
Geogrid (3 layers), (general plastic, in other cases a specific material should be selected if known and available in the coefficient database)	1,534,200	kg
Geogrid transportation distance	1,130	km
Geogrid total number of truckloads	63	round trip
Geotextile separator fabric, (polypropylene film)	191,300	kg
Geotextile transportation distance	604	km
Geotextile total number of truckloads	8	round trip
Cement	24,816,000	kg
Distance from local cement batch plant to the site	3.2	km
Number of 23 tonne truckloads of cement delivered to the site	1,079	round trip
Cement shipping distance to local plant by barge	1,130	km
Bentonite	6,895,000	kg
Distance from bentonite supplier to the site	3,058	km
Number of truckloads of bentonite delivered	282	round trip
Water	137,841,000	L
Cement/Bentonite cutoff wall waste material (for disposal)	148,589	m^3
Excavated C/B wall material for disposal - transport distance	40	km
Excavated C/B wall material for disposal - number of truckloads	12,960	round trip
Average transportation distance for clay borrow	37	km
Total number of truckloads for clay borrow	115,333	round trip
Diesel fuel consumed to install PVDs	430,500	L
Diesel fuel consumed to extract clay borrow	622,000	L
Diesel fuel consumed to excavate the C/B wall	263,600	L
Diesel fuel consumed for degrading the levee	15,000	L
Diesel fuel consumed to construct the embankment	3,312,000	L

B.4.3.2 Prefabricated Vertical Drains SEEAM Analysis Results

Tables B.8 through B.12 present the results of the SEEAM analysis for the PVDs alternative for LPV 111, as shown on the **Results** worksheet in the SEEAM Spreadsheet Calculator. These results follow the same format as those presented in Section B.4.2.2 for the DSM design alternative for LPV 111.

When the quantities from Table B.7 are entered correctly into the SEEAM Spreadsheet Calculator, the values shown in Tables B.8 and B.9 should exactly match the values shown in the "*Overall Totals – Analytically Calculated*" table on the **Results** worksheet.

Table B.8 "*Overall Totals – Analytically Calculated*," Embodied energy results from the SEEAM Spreadsheet Calculator for the prefabricated vertical drains alternative for LPV 111.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	400,505	66,932	N/A	N/A	49%
Materials Transportation	190,912	5,139	N/A	N/A	24%
Site Operations	199,653	4,894	N/A	N/A	25%
Waste Transportation	18,397	612	N/A	N/A	2%
TOTAL	**809,467**	**67,310**			**100%**

Table B.9 "*Overall Totals – Analytically Calculated*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the prefabricated vertical drains alternative for LPV 111.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	32,333	3,313	N/A	N/A	51%
Materials Transportation	14,910	395	N/A	N/A	23%
Site Operations	15,090	376	N/A	N/A	24%
Waste Transportation	1,390	47	N/A	N/A	2%
TOTAL	**63,723**	**3,358**			**100%**

As described in Section B.4.2.2, the results presented in Tables B.10 through B.12 are for one Monte Carlo realization of n = 1,000 values; every time the SEEAM Spreadsheet Calculator is run, a different realization is generated (see Section B.1.2). Therefore, the values in the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table on the **Results** worksheet may differ from those shown here even when the exact same input data (Table B.7) is entered on the **Input** worksheet. Also, note the Mean Error is < 2.5%, so no additional values are needed in the Monte Carlo simulation.

Table B.10 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," Embodied energy results from the SEEAM Spreadsheet Calculator for the prefabricated vertical drains alternative for LPV 111.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	400,631	66,988	711,721	250,623	49%
Materials Transportation	191,076	6,241	210,108	172,498	24%
Site Operations	199,829	6,681	220,203	179,941	25%
Waste Transportation	18,413	616	20,291	16,581	2%
TOTAL	**809,950**	**68,777**	**1,132,006**	**643,567**	**100%**
Mean Error (%)	**0.44%**				
% Different from Calculated	**0.06%**	**2.18%**			

Table B.11 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the prefabricated vertical drains alternative for LPV 111.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	32,178	3,368	45,013	22,619	51%
Materials Transportation	14,910	481	16,717	13,182	23%
Site Operations	15,090	515	17,024	13,240	24%
Waste Transportation	1,390	47	1,569	1,220	2%
TOTAL	**63,568**	**3,535**	**75,845**	**53,231**	**100%**
Mean Error (%)	**0.29%**				
% Different from Calculated	**0.24%**	**5.28%**			

Table B.12 90% confidence interval results from the SEEAM Spreadsheet Calculator for the prefabricated vertical drains alternative for LPV 111.

	90% Confidence Interval	
	Low	**High**
Embodied Energy (GJ)	718,342	940,906
CO_2 Emissions (tonnes)	58,201	69,698

As with the results for the DSM alternative for LPV 111 described in Section B.4.2.2, the plots on the **Results** worksheet (pie graphs, histograms) are not shown here. The user can verify that they have entered the input information correctly based on matching the values in Tables B.8 and B.9 to those appearing in the "*Overall Totals – Analytically Calculated*" table on the **Results** worksheet in the SEEAM Spreadsheet Calculator. If they match, the correct/matching figures will be displayed in the SEEAM Spreadsheet Calculator.

B.4.4 Comparing LPV 111 Alternatives

Table B.13 shows rounded values of total embodied energy and CO_2 emissions from the SEEAM analyses for the DSM and PVD alternatives for LPV 111, including the results from both the analytical calculations and the Monte Carlo simulation.

Table B.13 Rounded values of total embodied energy and CO_2 emissions from the deep soil mixing and prefabricated vertical drains design alternatives for LPV 111.

Method of Analysis	Descriptive Statistic	Deep Soil Mixing		Prefabricated Vertical Drains	
		Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Analytical	Mean	1,174,000	147,000	809,000	64,000
	St. Dev	122,500	11,500	67,300	3,360
Monte Carlo Simulation	Mean	1,174,000	147,000	810,000	64,000
	St. Dev.	121,400	11,800	68,800	3,540
	90% CI Low	995,000	129,600	718,000	58,200
	90% CI High	1,391,000	167,300	941,000	69,700

Based on inspection of the values in Table B.13, it appears the DSM alternative is responsible for more total embodied energy and CO_2 emissions than the PVD alternative. This conclusion may be confirmed by comparing the two alternatives using the difference method (Section B.3.1.1), or nonparametric statistical hypothesis tests (Section B.3.1.2). The difference method is used and illustrated here. The results from both methods are presented by Shillaber et al. (2016, In Review) (Ch. 6, also see Appendix P).

To conduct the difference method, the $n = 1{,}000$ Monte Carlo simulated data sets for total embodied energy and CO_2 emissions for each alternative are copied into a separate Microsoft Excel workbook. Then, the difference between the alternatives is taken to form "Difference Data Sets," as described in Section B.3.1.1. The first five Monte Carlo simulated values of total embodied energy and CO_2 emissions, with the computed difference are shown in Table B.14. Note that these values will be different for each Monte Carlo simulation, as the coefficients that lead to the computed total embodied energy and CO_2 emissions are randomly generated for each line.

Table B.14 Example using the first five lines in the Monte Carlo simulated data sets for the deep soil mixing and prefabricated vertical drains alternatives for LPV 111, with the computed difference. An actual comparison requires that the differences for all 1,000 rows be computed.

MC Calc	LPV 111 Deep Mixing		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	1,160,107	144,560	800,263	69,038	359,844	75,522
2	1,335,429	158,057	778,298	60,709	557,131	97,348
3	996,205	135,127	787,031	58,363	209,174	76,764
4	1,334,384	143,153	798,508	64,389	535,875	78,764
5	1,427,064	170,021	783,363	63,301	643,701	106,720

Descriptive statistics for the complete "Difference Data Sets" are shown in Table B.15. Note that these will be different for every analysis, as the Monte Carlo simulations involve random generation of the embodied energy and CO_2 emissions coefficients.

Table B.15 Descriptive statistics of the difference in total embodied energy and CO_2 emissions between Monte Carlo simulations for the deep soil mixing and prefabricated vertical drains design alternatives for LPV 111 (DSM – PVDs).

Descriptive Statistic	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Mean	363,747	83,167
Std. Dev.	137,838	12,209
Minimum	-99,596	49,054
Maximum	954,405	134,999
% < 0	0.4%	0.0%

The descriptive statistics indicate that there are some differences in embodied energy between alternatives that are less than zero (i.e., the minimum embodied energy difference is less than zero). However, the mean embodied energy difference is greater than zero, at nearly 364,000 GJ. None of the CO_2 emissions difference data are less than zero (i.e., the minimum difference is greater than zero). This clearly indicates that the CO_2 emissions for the DSM alternative are larger than those from the PVD alternative, since the difference taken was DSM – PVDs.

The "% < 0" in Table B.15 represents the proportion of values in the "Difference Data Set" that are less than zero, determined as described in Section B.3.1.1.

Figures B.11 and B.12 are histograms of the total embodied energy and CO_2 emissions difference data, respectively. Note that based on the size of the bins, there is sufficient resolution in the histograms to see the shape of the distributions of the "Difference Data Sets" (bin frequency is generally less than 100 out of n = 1,000 values in the data sets).

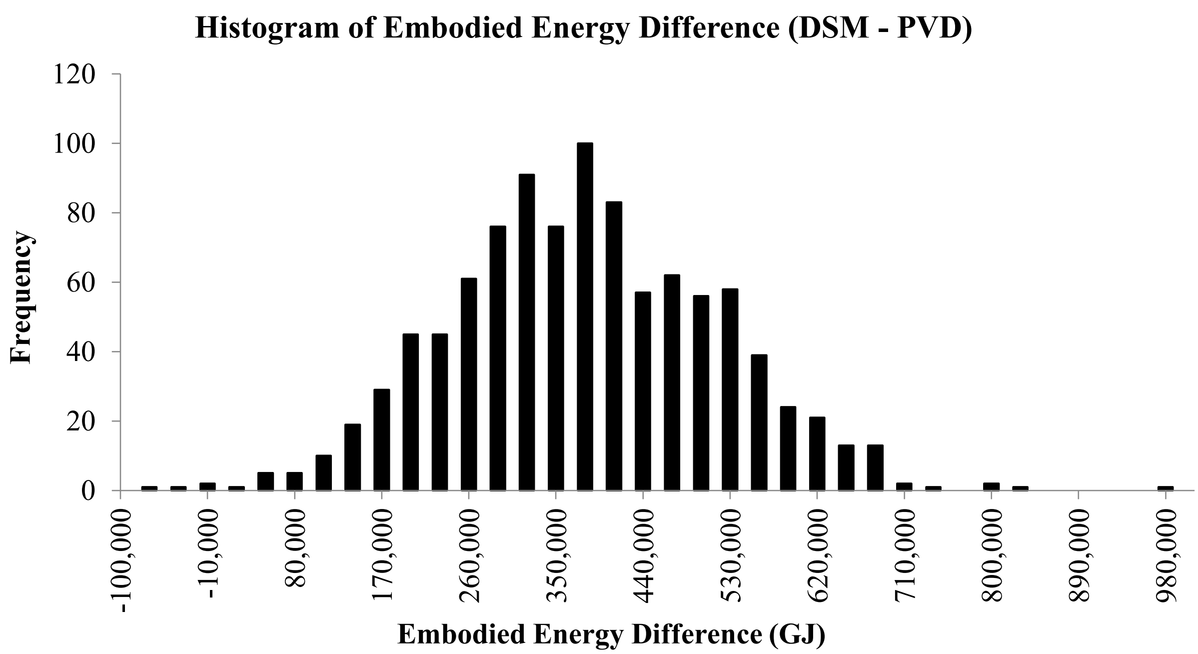

Figure B.11 Histogram of the embodied energy difference data set comparing the deep soil mixing and prefabricated vertical drains design alternatives for LPV 111.

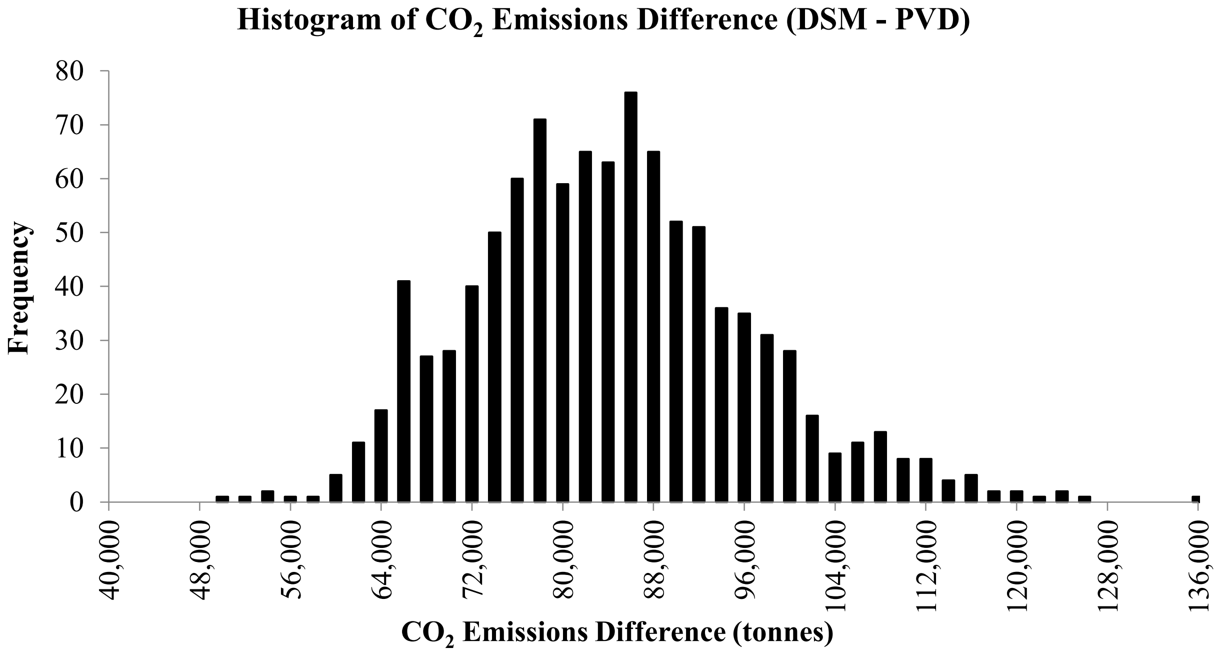

Figure B.12 Histogram of the CO_2 emissions difference data set comparing the deep soil mixing and prefabricated vertical drains design alternatives for LPV 111.

The histogram for the embodied energy difference (Figure B.11) shows that only the extreme left tail extends below zero. The histogram for the CO_2 emissions difference (Figure B.12) lies completely in the positive range. Again, a positive difference indicates that the DSM alternative has greater total embodied energy and CO_2 emissions than the PVDs alternative based on the subtraction that was performed (DSM – PVDs).

Note that slightly different "Difference" histograms will be generated for each comparison of SEEAM analyses conducted using the quantities in Tables B.1 and B.7 because the Monte Carlo simulations from each SEEAM analysis are different due to the random generation of embodied energy and CO_2 emissions coefficients (see Section B.1.2).

In summary, based on the difference method, it is clear that the DSM alternative for LPV 111 results in more total embodied energy and CO_2 emissions than the PVDs alternative. Discussion regarding which LPV 111 alternative is more sustainable is presented by Shillaber et al. (2015b) (Ch. 4).

B.5 CASE HISTORY EXAMPLE: REPLACEMENT BRIDGE IN DUPUYER, MT

B.5.1 Project Overview

As part of a 5.5 mile reconstruction effort along US Highway 89, Southeast of Dupuyer, MT, an existing triple culvert bridge was to be replaced. The bridge owner is the Montana Department of Transportation (MDT) and the lead geotechnical specialist on the project for the state was John Sharkey. Mr. Sharkey provided the design details presented in this manual.

Two design alternatives were considered for the bridge. These included a cast-in-place reinforced concrete flat slab supported by reinforced concrete pile caps founded on driven steel pipe piles, and a Geosynthetic Reinforced Soil Integrated Bridge System (GRS-IBS). The GRS-IBS system utilizes woven geotextile reinforcement to provide lateral restraint for a zone of compacted soil that directly supports the bridge deck beam. The system involves closely spaced reinforcement (typically 12 inches), frictionally connected non-structural concrete masonry unit (CMU) facing elements, and the use of select granular backfill (Adams et al. 2011).

Approximate construction costs for the pile supported and GRS-IBS bridge abutments are $235,000 and $138,000, respectively. Additional details about this project are provided by Phillips et al. (2016).

The reader may use the details presented in this section to gain experience using the SEEAM Spreadsheet Calculator by duplicating the presented example analyses.

B.5.2 Geosynthetic Reinforced Soil Integrated Bridge System (GRS-IBS)

B.5.2.1 GRS-IBS Construction Quantities

Table B.16 contains required material quantities, Table B.17 contains information regarding construction transportation and Table B.18 contains information regarding the activity of equipment operating on-site during construction for the GRS-IBS bridge support alternative.

Unlike the LPV 111 example, note that the data provided in these tables is not ready for input into the SEEAM Spreadsheet Calculator. The reader must determine the appropriate values to input by either converting the quantities in these tables into the appropriate units, or using the given information to calculate the correct quantity to input.

The "Note" column in each table provides details about where the presented quantity or information comes from. In some cases, it indicates that normally, the engineer would be responsible for tracking down the presented quantity, as it will not necessarily come directly from the design.

Table B.16 Construction material quantities for the GRS-IBS bridge alternative.

Item	Quantity	Unit	Note
Geotextile, Mirafi HP570; 14 oz/yd^2 (TenCate 2012) (GRS-IBS reinforcement)	6,895	yd^2	Woven polypropylene geotextile, not molded. Quantity determined by the design. Type of reinforcement and Mass/Unit Area need to be determined by the engineer.
CMU block (GRS-IBS facing)	313	yd^2	1.13 blocks/ft^2 of wall, 25 bags of cement and 5 tons of sand per 1,000 CMU (Allied Concrete Co. 2015). This information would normally need to be located by the engineer.
Special backfill, in-place volume (GRS-IBS, an aggregate)	1,203	yd^3	Determined based on the design. Assume in place (compacted) unit weight of 130 pcf. The most reasonable value would normally need to be determined by the engineer.
Foundation material, in-place volume (aggregate)	124	yd^3	Determine based on the design. Assume in place (compacted) unit weight of 130 pcf. The most reasonable value would normally need to be determined by the engineer.
Excavation	1,480	yd^3	Determined based on the design. Excavated material is disposed off-site.

Table B.17 Construction transportation information for the GRS-IBS bridge alternative.

Item	Haul Distance	Unit	Note
Geotextile	2,175	mile	Assume typical heavy duty truck payload capacity. Distance is from the manufacturer in Georgia to the site in Montana; distance is normally determined by the engineer using a tool such as Google Maps.
CMU Block	385	mile	Assume typical heavy duty truck payload capacity. CMU blocks were known to come from Washington State; 385 miles was assumed based on a Google search for CMU suppliers. The distance could be as large as 665 miles. This distance must normally be determined by the engineer.
Special backfill	50	mile	Assume 18 tons per truckload (needs to be determined by the engineer). Distance known to be >40 miles from the site. 50 miles assumed. This distance normally needs to be determined by the engineer.
Foundation material	50	mile	Assume 18 tons per truckload (needs to be determined by the engineer). Distance known to be >40 miles from the site. 50 miles assumed. This distance normally needs to be determined by the engineer.
Excavated Waste (for disposal)	18.6	mile	Assume 12 yd^3 of excavated material per truckload and a reasonable distance to a disposal facility. In this case it is best not use truck payload capacity. These quantities normally need to be estimated by the engineer.

Table B.18 Equipment and site operations information for the GRS-IBS bridge alternative.

Task	Equipment	No. of Machines	Total Time (hrs)	Note
Excavation	CAT 320D Excavator (Diesel)	1	119	Assumed equipment, 110 kW engine (Caterpillar 2012). Engine load factor = 0.5. Equipment selection, operating time and engine load factor must normally be determined by the engineer. Given time is based on production rate information from RSMeans (2011).
Backfill and Foundation Material Placement	CAT 320D Excavator (Diesel)	1	89	Assumed equipment, 110 kW engine (Caterpillar 2012). Engine load factor = 0.2. Equipment selection, operating time and engine load factor must normally be determined by the engineer. Given time is based on production rate information from RSMeans (2011).
	Walk Behind Compactor (Gas)	2	89	Assumed equipment, 5.2 kW engine. Engine load factor = 0.2. Equipment selection, operating time and engine load factor must normally be determined by the engineer. Given time is based on production rate information from RSMeans (2011).

B.5.2.2 GRS-IBS SEEAM Analysis Results

Tables B.19 through B.23 present the results of the SEEAM analysis for the GRS-IBS bridge alternative, as shown on the **Results** worksheet in the SEEAM Spreadsheet Calculator. These results follow the same format as the results for the LPV 111 alternatives presented in Sections B.4.2.2 and B.4.3.2.

When the quantities from Tables B.16, B.17 and B.18 are used to enter the correct/appropriate required input information into the SEEAM Spreadsheet Calculator, the values shown in Tables B.19 and B.20 should be very close (if not an exact match) to the values shown in the "*Overall Totals – Analytically Calculated*" table on the **Results** worksheet.

Table B.19 "*Overall Totals – Analytically Calculated*," Embodied energy results from the SEEAM Spreadsheet Calculator for the GRS-IBS bridge alternative.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	464	231	N/A	N/A	38%
Materials Transportation	518	12	N/A	N/A	43%
Site Operations	104	3	N/A	N/A	9%
Waste Transportation	132	4	N/A	N/A	11%
TOTAL	**1,218**	**231**			**100%**

Table B.20 "*Overall Totals – Analytically Calculated*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the GRS-IBS bridge alternative.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	21	13	N/A	N/A	27%
Materials Transportation	39	1	N/A	N/A	50%
Site Operations	8	0	N/A	N/A	10%
Waste Transportation	10	0	N/A	N/A	13%
TOTAL	**78**	**13**			**100%**

As for the LPV 111 results, note that the results in Tables B.21 through B.23 are for one Monte Carlo realization (i.e., simulated data set) of n = 1,000 values; every time the SEEAM Spreadsheet Calculator is run, a different realization is generated (see Section B.1.2). Therefore, the values in the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table on the **Results** worksheet may differ from those shown here even when the exact same input data is entered on the **Input** worksheet. Also, note the Mean Error is < 2.5%, so no additional values are needed in the Monte Carlo simulation.

Table B.21 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," Embodied energy results from the SEEAM Spreadsheet Calculator for the GRS-IBS bridge alternative.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	466	220	2,304	298	38%
Materials Transportation	518	17	572	467	42%
Site Operations	104	3	114	94	9%
Waste Transportation	132	4	146	119	11%
TOTAL	**1,220**	**221**	**3,017**	**1,018**	**100%**
Mean Error (%)	**0.94%**				
% Different from Calculated	**0.13%**	**4.43%**			

Table B.22 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the GRS-IBS bridge alternative.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	21	12	152	12	27%
Materials Transportation	39	1	43	35	50%
Site Operations	8	0	9	7	10%
Waste Transportation	10	0	11	9	13%
TOTAL	**78**	**12**	**207**	**65**	**100%**
Mean Error (%)	**0.83%**				
% Different from Calculated	**0.31%**	**6.81%**			

Table B.23 90% confidence interval results from the SEEAM Spreadsheet Calculator for the GRS-IBS bridge alternative.

	90% Confidence Interval	
	Low	**High**
Embodied Energy (GJ)	1,056	1,610
CO_2 Emissions (tonnes)	69	100

B.5.3 Pile Supported Reinforced Concrete Bridge Structure

B.5.3.1 Pile Supported Bridge Construction Quantities

Table B.24 contains required material quantities, Table B.25 contains information regarding construction transportation and Table B.26 contains information regarding the activity of equipment operating on-site during construction for the pile supported bridge alternative. In working through this analysis, the engineer must determine the appropriate required input quantities for analysis with the SEEAM Spreadsheet Calculator by either converting the quantities in Tables B.24 through B.26 into the appropriate units, or using the given information to calculate the correct quantity to input.

The "Note" column in each table provides details about where the presented quantity or information comes from. In some cases, it indicates that normally, the engineer would be responsible for tracking down the presented quantity, as it will not necessarily come directly from the design.

Table B.24 Construction material quantities for the pile supported bridge alternative.

Item	Quantity	Unit	Note
Concrete	235	yd^3	Determined based on the design. Assume typical 25 MPa (3,600 psi) concrete mix. Correct mix must normally be selected by the engineer.
Reinforcing Steel (bar)	38,770	lb	Determined based on the design. Assume the steel includes the world average recycled content.
12" Diameter by 0.5" wall thickness steel pipe piles.	26	pile	Piles are 16 ft long, extending to rock. Quantities determined based on the design. Assume the steel includes the world average recycled content. 12" pipe piles are 65.5 lb/ft (American Institute of Steel Construction 2006).
Excavation	400	yd^3	Determined based on the design. Excavated material is reused on-site.

Table B.25 Construction transportation information for the pile supported bridge alternative.

Item	Haul Distance	Unit	Note
Concrete	50	mile	Assume 10 yd^3 per truckload (needs to be determined by the engineer). Do not use truck payload capacity in this case. Distance known to be >40 miles from the site. 50 miles assumed. This distance normally needs to be determined by the engineer.
Reinforcing Steel (bar)	497	mile	Assume typical heavy duty truck payload capacity. Steel could either come from Utah or Washington State; 497 miles was assumed based on a Google search for steel suppliers. The distance could be as large as 671 miles. This distance must normally be determined by the engineer.
12” Diameter by 0.5” wall thickness steel pipe piles.	497	mile	Assume typical heavy duty truck payload capacity. Steel could either come from Utah or Washington State; 497 miles was assumed based on a Google search for steel suppliers. The distance could be as large as 671 miles. This distance must normally be determined by the engineer.
Excavated Waste	0	mile	Excavated material is reused on-site, therefore there is no haul to a disposal facility.

Table B.26 Equipment and site operations information for the pile supported bridge alternative.

Task	Equipment	No. of Machines	Total Time (hrs)	Note
Excavation	CAT 320D Excavator (Diesel)	1	32	Assumed equipment, 110 kW engine (Caterpillar 2012). Engine load factor = 0.5. Equipment selection, operating time and engine load factor must normally be determined by the engineer. Given time is based on production rate information from RSMeans (2011).
Pile Driving	Liebherr HS825 Crane (Diesel)	1	40	Assumed equipment, 270 kW engine (Liebherr 2010). Engine load factor = 0.4. Equipment selection, operating time and engine load factor must normally be determined by the engineer.
	APE D12-42 Diesel Hammer	1	40	Assumed equipment. Fuel consumption = 4.4 L/hr based on hammer specifications from the manufacturer (American Piledriving Equipment 2012). Equipment selection and operating time must normally be determined by the engineer.

B.5.3.2 Pile Supported Bridge SEEAM Results

Tables B.27 through B.31 present the results of the SEEAM analysis for the pile supported bridge alternative, as shown on the **Results** worksheet in the SEEAM Spreadsheet Calculator. These results follow the same format as the results for the GRS-IBS alternative presented in Section B.5.2.2 and the results for the LPV 111 alternatives presented in Sections B.4.2.2 and B.4.3.2.

When the quantities from Tables B.24, B.25 and B.26 are used to enter the correct/appropriate required input information into the SEEAM Spreadsheet Calculator, the values shown in Tables B.27 and B.28 should be very close (if not an exact match) to the values shown in the "*Overall Totals – Analytically Calculated*" table on the **Results** worksheet.

Table B.27 "*Overall Totals – Analytically Calculated*," Embodied energy results from the SEEAM Spreadsheet Calculator for the pile supported bridge alternative.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	938	0	N/A	N/A	82%
Materials Transportation	125	3	N/A	N/A	11%
Site Operations	79	2	N/A	N/A	7%
Waste Transportation	0	0	N/A	N/A	0%
TOTAL	**1,142**	**4**			**100%**

Table B.28 "*Overall Totals – Analytically Calculated*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the pile supported bridge alternative.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	100	0	N/A	N/A	87%
Materials Transportation	9	0	N/A	N/A	8%
Site Operations	6	0	N/A	N/A	5%
Waste Transportation	0	0	N/A	N/A	0%
TOTAL	**116**	**0**			**100%**

As for the GRS-IBS bridge alternative results, note that the results presented in Tables B.29 through B.31 are for one Monte Carlo realization (i.e., simulated data set) of n = 1,000 values; every time the SEEAM Spreadsheet Calculator is run, a different realization is generated (see Section B.1.2). Therefore, the values in the "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*" table on the **Results** worksheet may differ from those shown here even when the exact same input data is entered on the **Input** worksheet. Also, note the Mean Error is < 2.5%, so no additional values are needed in the Monte Carlo simulation.

Table B.29 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," Embodied energy results from the SEEAM Spreadsheet Calculator for the pile supported bridge alternative.

	Embodied Energy (GJ)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	938	0	938	938	82%
Materials Transportation	125	4	138	109	11%
Site Operations	79	3	88	70	7%
Waste Transportation	0	0	0	0	0%
TOTAL	**1,142**	**7**	**1,164**	**1,117**	**100%**
Mean Error (%)	**0.03%**				
% Different from Calculated	**0.02%**	**83.95%**			

Table B.30 "*Overall Totals – Monte Carlo Simulation for n = 1,000 Values*," CO_2 emissions results from the SEEAM Spreadsheet Calculator for the pile supported bridge alternative.

	CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Maximum**	**Minimum**	**% of Total**
Materials	100	0	100	100	87%
Materials Transportation	9	0	10	9	8%
Site Operations	6	0	7	5	5%
Waste Transportation	0	0	0	0	0%
TOTAL	**116**	**0**	**118**	**114**	**100%**
Mean Error (%)	**0.02%**				
% Different from Calculated	**0.03%**	**81.33%**			

Table B.31 90% confidence interval results from the SEEAM Spreadsheet Calculator for the pile supported bridge alternative.

	90% Confidence Interval	
	Low	**High**
Embodied Energy (GJ)	1,131	1,153
CO_2 Emissions (tonnes)	115	117

In this analysis, the reason the standard deviation is small and significantly different between the "Analytically Calculated" results and the Monte Carlo Simulation is that the specific steel coefficients (e.g., 'steel bar and rod,' 'steel pipe') and concrete coefficient do not have a standard deviation accompanying the mean to define a lognormal distribution. Therefore, their application leads to deterministic results for those materials in the overall SEEAM analysis. Users will get a higher standard deviation of project embodied energy and CO_2 emissions if general coefficients (e.g., 'general steel') with a mean and standard deviation to define a lognormal distribution are used in place of the specific coefficients.

Users are cautioned that when many predominant construction inputs use coefficients without both lognormal distribution parameters (i.e., mean and standard deviation), the reported confidence intervals become narrow because the analysis is unable to reflect any actual uncertainty in those coefficients that may exist. Users will get a wider confidence interval for project embodied energy and CO_2 emissions if general coefficients with complete lognormal distribution parameters are used in place of the specific coefficients.

B.5.4 Comparing Alternatives for the Dupuyer Bridge

The same process described for the comparison of LPV 111 alternatives in Section B.4.4 has been used to compare the MDT Dupuyer bridge alternatives. Table B.32 shows rounded values of total embodied energy and CO_2 emissions from the SEEAM analyses for the GRS-IBS and pile supported bridge alternatives, including the results from both the analytical calculations and the Monte Carlo simulation.

Table B.32 Rounded values of total embodied energy and CO_2 emissions from the GRS-IBS and pile supported bridge alternatives.

Method of Analysis	Descriptive Statistic	GRS-IBS		Steel Piles	
		Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Analytical	Mean	1,220	78	1,140	116
	St. Dev	230	13	4	0
Monte Carlo Simulation	Mean	1,220	78	1,140	116
	St. Dev.	220	12	7	0
	90% CI Low	1,060	69	1,130	115
	90% CI High	1,610	100	1,150	117

Based on the values in Table B.32, it appears the GRS-IBS bridge alternative is responsible for less CO_2 emissions than the pile supported bridge alternative. It is less apparent which alternative involves more embodied energy; the GRS-IBS alternative has a higher mean embodied energy, but it also has a larger standard deviation. Conclusions may be confirmed by comparing the two alternatives using the difference method (Section B.3.1.1).

Note that the comparison may lead to different results (and potentially different conclusions) if the general steel coefficient (with complete lognormal distribution parameters) was used instead of the specific coefficients. Therefore, in circumstances where a SEEAM assessment is conducted for a project alternative having many construction inputs with specific coefficients that do not have both lognormal distribution parameters, it is good practice to conduct the analysis and compare project alternatives using both specific coefficients and general coefficients. Details of the comparison of bridge alternatives when the general steel coefficient is used in place of the specific coefficients are not included in this manual, but descriptive statistics of the difference data for this comparison are included in Table B.35 at the end of this section.

The first five Monte Carlo simulated values of total embodied energy and CO_2 emissions, with the computed difference are shown in Table B.33. Note that these values will be different for each Monte Carlo simulation, as the coefficients that lead to the computed total embodied energy and CO_2 emissions are randomly generated for each line.

Table B.33 Example using the first five lines in the Monte Carlo simulated data sets for the GRS-IBS and pile supported bridge alternatives, with the computed difference. An actual comparison requires that the difference for all 1,000 rows be computed.

MC Calc	GRS-IBS		Steel Piles		Difference (GRS-IBS - Piles)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	1,121	77	1,137	116	-16	-39
2	1,109	72	1,136	117	-27	-45
3	1,081	71	1,135	116	-54	-45
4	1,136	73	1,136	116	0	-43
5	1,061	80	1,141	116	-80	-36

Descriptive statistics for the complete "Difference Data Sets" are shown in Table B.34. Like Table B.33, note that these values will be different for every analysis due to random generation of the coefficients in the Monte Carlo simulation.

Table B.34 Descriptive statistics of the difference in total embodied energy and CO_2 emissions between Monte Carlo simulations for the GRS-IBS and pile supported bridge design alternatives (GRS-IBS – Piles).

Descriptive Statistic	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Mean	75	-38
Std. Dev.	196	12
Minimum	-160	-50
Maximum	2,182	127
% < 0	43%	98%

The descriptive statistics indicate that there are some differences in embodied energy between alternatives that are less than zero (i.e., the minimum embodied energy difference is less than zero). However, the mean embodied energy difference is greater than zero, at 75 GJ. The mean of the CO_2 emissions difference data is less than zero at -38 tonnes, but the maximum difference is greater than zero.

Since the "Difference Data Sets" for both embodied energy and CO_2 emissions cross zero, additional evaluation is needed to determine if the alternatives are significantly different. This may be accomplished by determining the proportion of values in the "Difference Data Sets" that are either greater than zero or less than zero, in addition to plotting histograms of the "Difference Data Sets."

In this case, the proportion of values in the "Difference Data Sets" that are less than zero was determined; 43% of the values in the "Difference Data Set" for embodied energy are less than zero and 98% of the values in the "Difference Data Set" for CO_2 emissions are less than zero. These proportions indicate that the embodied energy is comparable for both bridge alternatives, while it appears the alternatives involve significantly different CO_2 emissions. This is further illustrated by the histograms in Figures B.13 and B.14.

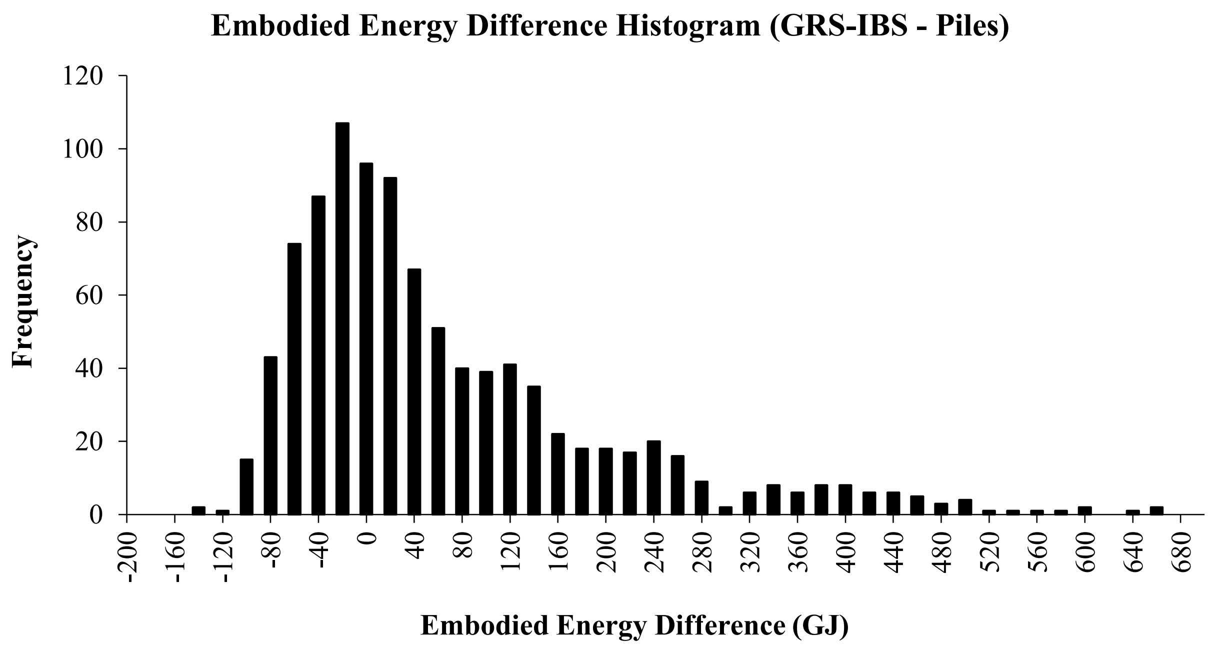

Figure B.13 Histogram of the embodied energy difference data set comparing the GRS-IBS and pile supported bridge design alternatives.

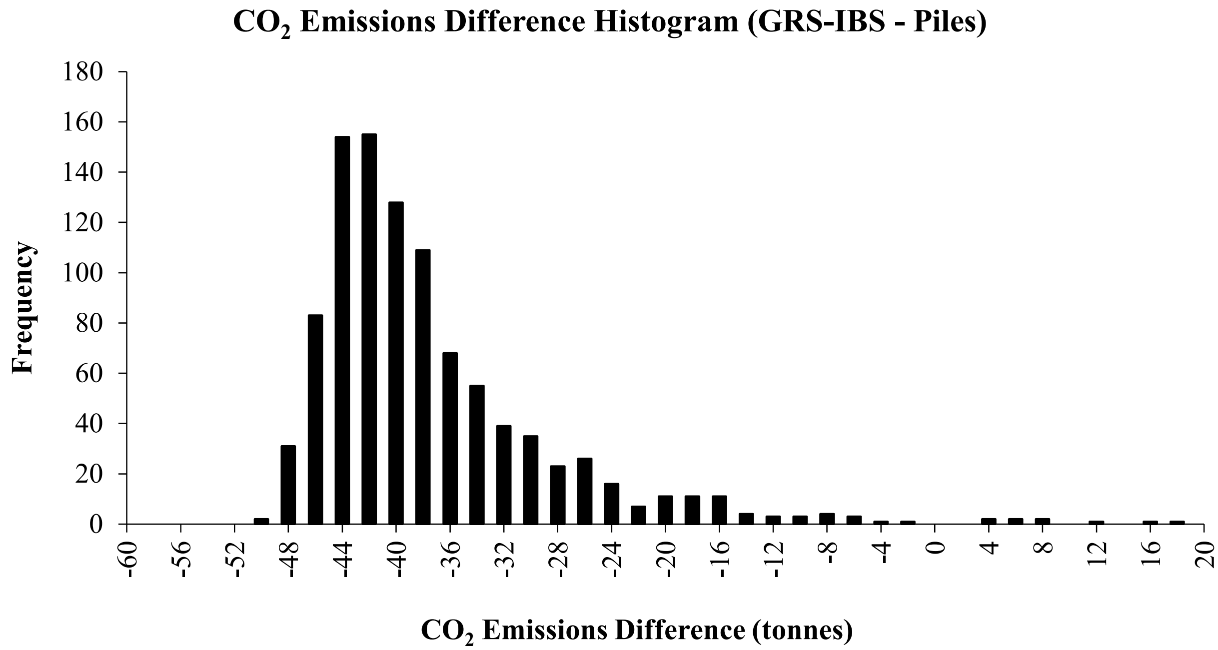

Figure B.14 Histogram of the CO_2 emissions difference data set comparing the GRS-IBS and pile supported bridge design alternatives.

The histogram for the embodied energy difference (Figure B.13) shows that zero is close to the mode, and there is a significant amount of difference data on either side of zero. Therefore, the embodied energy between alternatives is not significantly different. The histogram for the CO_2 emissions difference (Figure B.14) lies predominantly in the negative range, with the extreme right tail extending greater than zero. Since the difference taken was GRS-IBS – Piles, a negative difference indicates that the pile supported bridge alternative has greater total CO_2 emissions than the GRS-IBS bridge alternative.

Note that slightly different "Difference" histograms will be generated for each comparison of SEEAM analyses conducted using the same quantities. Different "Difference" histograms are generated because the Monte Carlo simulations from each SEEAM analysis differ due to the random generation of embodied energy and CO_2 emissions coefficients.

In summary, based on the difference method, it is clear that the two bridge alternatives result in comparable total embodied energy, while the GRS-IBS alternative results in less CO_2 emissions than the pile supported alternative. Discussion regarding which alternative is more sustainable is presented by Phillips et al. (2016).

If the specific ‘steel bar and rod’ and ‘steel pipe’ coefficients were changed to ‘general steel’ (with complete lognormal distribution parameters), the resulting descriptive statistics of the “Difference Data Sets” for total embodied energy and CO_2 emissions between project alternatives are shown in Table B.35. Note that the proportions of difference values less than zero are similar to those in Table B.34, and point to the same conclusions.

Table B.35. Descriptive statistics of the difference in total embodied energy and CO_2 emissions between Monte Carlo simulations for the GRS-IBS and pile supported bridge design alternatives, using the general steel coefficient instead of specific coefficients.

Descriptive Statistic	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Mean	13	-39
Std. Dev.	233	15
Minimum	-491	-73
Maximum	2,301	116
% < 0	**54%**	**98%**

B.6 SELECTING MORE SUSTAINABLE GEOTECHNICAL ALTERNATIVES

An introduction to sustainability as applicable in geotechnical engineering and ground improvement is presented by Shillaber et al. (2015a) (Ch. 2). While sustainability involves many considerations impacting the environment, society and the economy, some important factors to consider for geotechnical ground improvement solutions include the ability of the proposed solution to meet project performance criteria, its monetary cost, and its environmental impacts.

The most sustainable solution will meet or exceed project performance criteria with minimum monetary costs and environmental impacts.

Since meeting minimum performance criteria is not negotiable, monetary cost and environmental impacts are key competing factors affecting the sustainability of geotechnical ground improvement solutions with comparable performance. Additional research needs to be conducted on how to best weight all competing factors; however, the following questions may serve as a starting point, or guide to comparing geotechnical ground improvement solutions and selecting the most sustainable option:

- Are the design alternatives projected to meet or exceed project performance criteria?
    - Is one alternative more reliable than another?
- Which alternative has lower lifetime monetary costs?
- Which alternative involves less environmental impact (e.g., embodied energy, CO_2 emissions)?
- Are there any other important factors for the project of interest (e.g., construction time, site accessibility, etc.) that require careful consideration?

Best performance with least monetary cost and least environmental impact is generally most sustainable. Engineers should seek to develop geotechnical designs that efficiently address all three of these factors. To that end, the SEEAM Spreadsheet Calculator is a useful tool that can provide relevant information regarding embodied energy and CO_2 emissions that can be considered in the larger decision process.

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The efforts of Megan Hamilton working through the examples presented in this manual as a first time user of the SEEAM Spreadsheet Calculator are also very much appreciated.

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Appendix C: Fuel Cycle Analysis using GREET 1, Version 2012 rev.2

C.1 GREET INPUT

Petroleum

Federal Reformulated Gasoline	
Vehicle Technology	
Spark Ignition Engine	
Pathway Options	
FRFG O2 Content (%):	2.3
FRFG Sulfur Level (ppm):	25.5
Conventional Gasoline Oxygenate:	Ethanol
FRFG Ethanol Feedstock: Corn (%):	100
FRFG Ethanol Feedstock: Woody Biomass (%):	0
FRFG Ethanol Feedstock: Herbaceous Biomass (%):	0

Conventional Gasoline	
Vehicle Technology	
Spark Ignition Engine	
Pathway Options	
Conventional Gasoline Sulfur Level (ppm):	25.5

Low Sulfur Diesel	
Vehicle Technology	
Compression-Ignition, Direct Injection	
Pathway Options	
Low-Sulfur Diesel: Sulfur Level (ppm):	11
Low-Sulfur Diesel Location for Use:	United States

Natural Gas

Compressed Natural Gas	
Vehicle Technology	
Dedicated Spark Ignition engine	
Pathway Options	
CNG Feedstock Source:	North America Natural Gas

Figure C.1 Petroleum and natural gas pathways for year 2010 from GREET.

Electricity	
Vehicle Technology	
Electric Vehicle	
Pathway Options	
NG turbine combined cycle share of total NG power plant capacity (%):	80.5
Simple-cycle NG turbine share of total NG power plant capacity (%):	5.9
Advanced coal technology share of total coal power plant capacity (%):	0
Advanced biomass technology share of total biomass power plant capacity (%):	0
LWR Plant Technology Shares for Electricity Production: Gas Diffusion (%):	25
LWR Plant Technology Shares for Electricity Production: Centrifuge (%):	75
HTGR Plant Technology Shares for Electricity Production: Gas Diffusion (%):	25
HTGR Plant Technology Shares for Electricity Production: Centrifuge (%):	75
Woody Biomass Plant Technology Shares for Electricity Production (%):	0
Herbaceous Biomass Plant Technology Shares for Electricity Production (%):	100
Type of Electricity Displaced by Cogeneration of Electricity in NG-Based Fuel Production Plants:	Average Electricity Generation Mix
Type of Electricity Displaced by Electricity cogenerated in Biomass-Based Fuel Production Plants	Average Electricity Generation Mix
Type of Electricity Displaced by Cogeneration of Electricity in Biomass-Based Fuel Production Plants:	Average Electricity Generation Mix

Marginal Generation Mix	
Residual Oil (%):	0.87
Natural Gas (%):	22.71
Coal (%):	46.04
Nuclear Power (%):	20.33
Biomass Electricity (%):	0.3
Others (%):	9.75

Average Generation Mix	
Residual Oil (%):	0.87
Natural Gas (%):	22.71
Coal (%):	46.04
Nuclear Power (%):	20.33
Biomass Electricity (%):	0.3
Others (%):	9.75

Figure C.2 Electricity pathways for year 2010 from GREET.

Reformulated/Conventional Gasoline Market Shares

Year	RFG %	CG %
2010	50.0%	50.0%

Low-Sulfur/Conventional Diesel Market Shares

Year	LSD %	CD %
2010	100.0%	0.0%

Figure C.3 Fuel market shares for gasoline and diesel from GREET.

Petroleum	
Items	Assumptions
Share of Oil Sands Products in Crude Oil Feed	8.0%
Share of Surface Mining in Oil Sands Recovery Methods	50.0%
Crude Recovery Efficiency	98.0%
Surface Mining: Bitumen Recovery Efficiency	94.8%
Surface Mining: Bitumen Upgrading Efficiency	98.6%
In Situ Production: Bitumen Recovery Efficiency	84.3%
In Situ Production: Bitumen Upgrading Efficiency	98.6%
CG Refining Efficiency	90.6%
RFG Refining Efficiency	90.6%
LSD Refining Efficiency	90.60%

Natural Gas	
Items	Assumptions
Share of Shale Gas in Natural Gas Supply	23.0%
NA NG Recovery Efficiency	95.7%
NA Shale Gas Recovery Efficiency	96.5%
NA NG Processing Efficiency	97.2%
CNG Assumptions	
NG Compression Efficiency: NG Compressors	92.8%
NG Compression Efficiency: Electric Compressors	97.10%

Ethanol	
Items	Assumptions
CO2 Emissions from Domestic Land Use Change by Corn Farming (g/bushel)	447
CO2 Emissions from Foreign Land Use Change by Corn Farming (g/bushel)	285
Corn Farming Energy Use (Btu/bushel)	9,608
Ethanol Production Energy Use:Dry Mill (Btu/gallon)	26,856
Ethanol Production Energy Use:Wet Mill (Btu/gallon)	47,409

Electricity	
Items	Assumptions
Residual Oil Utility Boiler Efficiency	32.8%
NG Utility Boiler Efficiency	31.9%
NG Simple Cycle Turbine Efficiency	32.6%
NG Combined Cycle Turbine Efficiency	49.8%
Coal Utility Boiler Efficiency	34.5%
Electricity Transmission and Distribution Loss	6.5%
Energy intensity in HTGR reactors (MWh/g of U-235)	8.704
Energy intensity in LWR reactors (MWh/g of U-235)	6.926
Electricity Use of Uranium Enrichment (kWh/SWU): Gaseous Diffusion Plants for LWR electricity generation	2,400
Electricity Use of Uranium Enrichment (kWh/SWU): Centrifuge Plants for LWR electricity generation	50.0
Electricity Use of Uranium Enrichment (kWh/SWU): Gaseous Diffusion Plants for HTGR electricity generation	2,400
Electricity Use of Uranium Enrichment (kWh/SWU): Centrifuge Plants for HTGR electricity generation	50

Figure C.4 Production assumptions for fuels in GREET, for year 2010.

Baseline Vehicles (Model Year 2005)		
Items	SI Vehicle: CG and RFG	CIDI Vehicle: CD and LSD
Gasoline Equivalent MPG	23.4	28.08
Exhaust VOC	0.122	0.088
Evaporative VOC	0.058	0
CO	3.745	0.539
NOx	0.141	0.141
Exhaust PM10	0.008	0.009
Brake and Tire Wear PM10	0.021	0.021
Exhaust PM2.5	0.008	0.008
Brake and Tire Wear PM2.5	0.007	0.007
CH4	0.015	0.003
N2O	0.012	0.012

MPG and Emission Ratios: AFV/GV (Model Year 2005)			
Items	CIDI Vehicle: CD and LSD	SI Vehicle: Dedicated CNGV	Electric Vehicle
Gasoline Equivalent MPG	120.0%	95.0%	400.0%
Exhaust VOC		90.0%	0.0%
Evaporative VOC		50.0%	0.0%
CO		100.0%	0.0%
NOx		100.0%	0.0%
Exhaust PM10		100.0%	0.0%
Brake and Tire Wear PM10		100.0%	100.0%
Exhaust PM2.5		100.0%	0.0%
Brake and Tire Wear PM2.5		100.0%	100.0%
CH4		1000.0%	0.0%
N2O		100.00%	0.00%

Figure C.5 Vehicle assumptions for GREET analysis.

C.2 GREET OUTPUT

Vehicle Technologies, Passenger Cars: Well-to-Pump Energy Consumption and Emissions
(Btu or grams per mmBtu of Fuel Available at Fuel Station Pumps)

Year: 2010	Baseline CG and RFG	Compressed Natural Gas, NA NG	Baseline Conventional and LS Diesel	Electricity (U.S. Mix)	Electricity (NE U.S. Mix)	Electricity (CA Mix)
Total Energy	225,677	176,460	200,148	1,426,827	1,017,535	1,037,754
WTP Efficiency	81.6%	85.0%	83.3%	41.2%	49.6%	49.1%
Fossil Fuels	205,371	165,744	196,890	1,227,167	730,642	769,315
Coal	15,929	45,398	14,362	845,808	167,403	124,665
Natural Gas	117,267	114,608	110,904	350,273	538,083	629,377
Petroleum	72,175	5,739	71,624	31,086	25,156	15,274
CO2 (w/ C in VOC & CO)	15,482	11,133	16,304	183,760	100,459	102,705
CH4	144.175	601.050	142.346	476.727	522.155	581.168
N2O	1.256	0.181	0.220	2.626	1.109	0.958
GHGs	19,460	26,213	19,928	196,460	113,843	117,520
VOC: Total	27.363	6.666	8.107	16.820	10.373	10.399
CO: Total	12.231	9.919	11.797	36.998	47.597	47.861
NOx: Total	47.564	32.747	46.136	252.318	113.317	103.232
PM10: Total	7.461	9.178	6.827	274.586	75.567	58.299
PM2.5: Total	4.027	3.083	3.824	82.627	30.159	24.620
SOx: Total	26.675	29.770	25.488	596.823	157.173	117.713
VOC: Urban	15.897	0.218	3.439	1.535	1.374	1.692
CO: Urban	3.502	0.825	3.552	16.109	24.328	28.248
NOx: Urban	9.683	4.179	9.731	105.536	48.062	68.676
PM10: Urban	1.903	0.402	1.927	12.005	9.975	10.069
PM2.5: Urban	1.160	0.327	1.171	9.697	8.781	8.751
SOx: Urban	9.231	8.460	9.176	263.878	68.845	103.077

Figure C.6 Well to pump results from GREET analysis for select fuel/energy sources.

C.3 PROCESSED GREET OUTPUT

		Conversion Factors	Units
	Btu to MJ	0.00105506	MJ/btu
	Gal to L	3.78541	L/gal
	lb to kg	2.20462	lb/kg
	kWh to MJ	0.27778	kWh/MJ

	Converstion Factors	Units
Diesel	7.7851	gal/mmbtu
Gasoline	8.6140	gal/mmbtu
CNG	49.3389	lb/mmbtu
Electricity	293.0832	kWh/mmbtu

LHV	Diesel	128,450	btu/gal
	Gasoline	116,090	btu/gal
	CNG	20,268	btu/lb
	Electricity	3,412	btu/kWh

LHV	Diesel	35.8011	MJ/L
	Gasoline	32.3562	MJ/L
	CNG	47.1433	MJ/kg
	Electricity	3.6000	MJ/kWh

Figure C.7 Conversion factors for determining energy and emissions per sold unit (e.g., L, kg, kW-hr) of a fuel or energy source.

LHV Reference: Alternative Fuels Data Center (2013).

Well-to-Pump Energy Consumption and Emissions

(MJ or grams per unit of Fuel (Liter for Diesel & Gasoline, kg for CNG, kWh for Electricity)

Year: 2010	Baseline CG and RFG	Units	Compressed Natural Gas, NA NG	Units	Baseline Conventional and LS Diesel	Units	Electricity (U.S. Mix)	Units	Electricity (NE U.S. Mix)	Units	Electricity (CA Mix)	Units
Total Energy	7.3021	MJ/L	8.3189	MJ/kg	7.1655	MJ/L	5.1364	MJ/kWh	3.6630	MJ/kWh	3.7358	MJ/kWh
Total Energy							1.4268	MJ/MJ	1.0175	MJ/MJ	1.0377	MJ/MJ
WTP Efficiency	81.6%		85.0%		83.3%		41.2%		49.6%		49.1%	
Fossil Fuels	6.6450	MJ/L	7.8137	MJ/kg	7.0489	MJ/L	4.4176	MJ/kWh	2.6302	MJ/kWh	2.7694	MJ/kWh
Coal	0.5154	MJ/L	2.1402	MJ/kg	0.5142	MJ/L	3.0448	MJ/kWh	0.6026	MJ/kWh	0.4488	MJ/kWh
Natural Gas	3.7943	MJ/L	5.4030	MJ/kg	3.9705	MJ/L	1.2609	MJ/kWh	1.9370	MJ/kWh	2.2657	MJ/kWh
Petroleum	2.3353	MJ/L	0.2705	MJ/kg	2.5642	MJ/L	0.1119	MJ/kWh	0.0906	MJ/kWh	0.0550	MJ/kWh
CO2 (w/ C in VOC & CO)	474.7956	g/L	497.4566	g/kg	553.2276	g/L	626.9884	g/kWh	342.7645	g/kWh	350.4296	g/kWh
CH4	4.4215	g/L	26.8569	g/kg	4.8302	g/L	1.6266	g/kWh	1.7816	g/kWh	1.9829	g/kWh
N2O	0.0385	g/L	0.0081	g/kg	0.0075	g/L	0.0090	g/kWh	0.0038	g/kWh	0.0033	g/kWh
GHGs	596.8093	g/L	1,171.2880	g/kg	676.2054	g/L	670.3229	g/kWh	388.4317	g/kWh	400.9777	g/kWh
VOC: Total	0.8392	g/L	0.2979	g/kg	0.2751	g/L	0.0574	g/kWh	0.0354	g/kWh	0.0355	g/kWh
CO: Total	0.3751	g/L	0.4432	g/kg	0.4003	g/L	0.1262	g/kWh	0.1624	g/kWh	0.1633	g/kWh
NOx: Total	1.4587	g/L	1.4633	g/kg	1.5655	g/L	0.8609	g/kWh	0.3866	g/kWh	0.3522	g/kWh
PM10: Total	0.2288	g/L	0.4101	g/kg	0.2317	g/L	0.9369	g/kWh	0.2578	g/kWh	0.1989	g/kWh
PM2.5: Total	0.1235	g/L	0.1378	g/kg	0.1298	g/L	0.2819	g/kWh	0.1029	g/kWh	0.0840	g/kWh
SOx: Total	0.8181	g/L	1.3302	g/kg	0.8649	g/L	2.0364	g/kWh	0.5363	g/kWh	0.4016	g/kWh
VOC: Urban	0.4875	g/L	0.0097	g/kg	0.1167	g/L	0.0052	g/kWh	0.0047	g/kWh	0.0058	g/kWh
CO: Urban	0.1074	g/L	0.0368	g/kg	0.1205	g/L	0.0550	g/kWh	0.0830	g/kWh	0.0964	g/kWh
NOx: Urban	0.2970	g/L	0.1867	g/kg	0.3302	g/L	0.3601	g/kWh	0.1640	g/kWh	0.2343	g/kWh
PM10: Urban	0.0584	g/L	0.0180	g/kg	0.0654	g/L	0.0410	g/kWh	0.0340	g/kWh	0.0344	g/kWh
PM2.5: Urban	0.0356	g/L	0.0146	g/kg	0.0398	g/L	0.0331	g/kWh	0.0300	g/kWh	0.0299	g/kWh
SOx: Urban	0.2831	g/L	0.3780	g/kg	0.3114	g/L	0.9004	g/kWh	0.2349	g/kWh	0.3517	g/kWh

Figure C.8 Well to pump energy consumption and emissions for each fuel source, per unit of fuel, determined by applying the conversion factors to the GREET output.

C.4 REFERENCES

Alternative Fuels Data Center (2013). “Alternative fuels data center - fuel properties comparison.” <http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf>. (March 29, 2013).

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Appendix D: Fuel Cycle Supporting Calculations

D.1 BRAKE SPECIFIC FUEL CONSUMPTION

D.1.1 Diesel

- Lower Heating Value (LHV) = 35.801 MJ/L (Alternative Fuels Data Center 2013)
- Efficiency = 36.5% [Middle of range suggested by Heywood (1988)]

Rearranging Eq. 3.3:

$$BSFC = \frac{1}{(Efficiency)(LHV)}$$

$$BSFC = \frac{1}{(0.365)\left(35.801\,\frac{MJ}{L}\right)}\left(3.6\,\frac{MJ}{kW * hr}\right) = 0.275\,\frac{L}{kW * hr}$$

Typical Diesel BSFC = 0.275 L/kW-hr.

D.1.2 Gasoline

- Lower Heating Value (LHV) = 32.356 MJ/L (Alternative Fuels Data Center 2013)
- Efficiency = 25% [Middle of range suggested by Heywood (1988)]

Rearranging Eq. 3.3:

$$BSFC = \frac{1}{(Efficiency)(LHV)}$$

$$BSFC = \frac{1}{(0.25)\left(32.356\,\frac{MJ}{L}\right)}\left(3.6\,\frac{MJ}{kW * hr}\right) = 0.445\,\frac{L}{kW * hr}$$

Typical Gasoline BSFC = 0.445 L/kW-hr.

D.2 SPREADSHEET COMPUTATIONS OF ENERGY AND EMISSIONS PER 100 MJ OF USEABLE ENERGY

Quantity of fuel to produce 100 MJ of useable energy (at the engine flywheel):

$$Q_{100MJ} = \frac{\dfrac{100\ MJ}{LHV \dfrac{MJ}{unit\ of\ fuel}}}{Efficiency}$$

Useable energy per unit of fuel:

$$Useful\ Energy = (Efficiency)\left(LHV \frac{MJ}{unit\ of\ fuel}\right)$$

Ratio of useable energy to embodied energy to produce the fuel:

$$Ratio = \left(\frac{Useful\ Energy}{Embodied\ Energy}\right)$$

Determine embodied energy and CO_2 emissions per 100 MJ of useable energy based on the computed Q_{100MJ} and Eq. 3.1 and Eq. 3.2. Complete calculations were performed using a spreadsheet, and are shown in Figure D.1.

Fuel	Engine Efficiency	Fuel Energy Content (LHV)	Unit	Quantity of Fuel to Produce 100 MJ Useable On-Site Energy	Unit	On Site CO_2 Emissions per Unit of Fuel	Unit	Fuel Production CO_2 Emissions Per Unit of Fuel	Unit	EE per unit of Fuel	Unit	Useable Energy per Unit of Fuel	Unit	Ratio Useable Energy to EE	EE per 100 MJ useable Energy (MJ)	On-Site CO_2 Emissions for 100 MJ of Useable Energy On-Site (kg)	Fuel Production CO_2 Emissions for 100 MJ of Useable Energy On-Site (kg)	Total CO_2 Emissions for 100 MJ of Useable Energy On-Site (kg)
Diesel	0.43	35.801	MJ/L	6.496	L	2.695	kg/L	0.553	kg/L	7.166	MJ/L	15.4	MJ/L	2.15	46.5	17.5	3.6	21.1
	0.365	35.801		7.653		2.695		0.553		7.166		13.1		1.82	54.8	20.6	4.2	24.9
	0.3	35.801		9.311		2.695		0.553		7.166		10.7		1.50	66.7	25.1	5.1	30.2
Gasoline	0.3	32.356	MJ/L	10.302	L	2.351	kg/L	0.475	kg/L	7.302	MJ/L	9.7	MJ/L	1.33	75.2	24.2	4.9	29.1
	0.25	32.356		12.362		2.351		0.475		7.302		8.1		1.11	90.3	29.1	5.9	34.9
	0.2	32.356		15.453		2.351		0.475		7.302		6.5		0.89	112.8	36.3	7.3	43.7
CNG	0.3	47.143	MJ/kg	7.071	kg	2.373	kg/kg	0.497	kg/kg	8.319	MJ/kg	14.1	MJ/kg	1.70	58.8	16.8	3.5	20.3
	0.25	47.143		8.485		2.373		0.497		8.319		11.8		1.42	70.6	20.1	4.2	24.4
	0.2	47.143		10.606		2.373		0.497		8.319		9.4		1.13	88.2	25.2	5.3	30.4
Electricity	0.95	3.600	MJ/kW-h	29.240	kW-h	0	kg/kW-h	0.627	kg/kW-h	5.136	MJ/kWh	3.4	MJ/kWh	0.67	150.2	0.0	18.3	18.3
	0.9	3.600		30.864		0		0.627		5.136		3.2		0.63	158.5	0.0	19.4	19.4
	0.85	3.600		32.680		0		0.627		5.136		3.1		0.60	167.8	0.0	20.5	20.5

Fuel	Engine Efficiency	Fuel Energy Content (LHV)	Unit	Quantity of Fuel to Produce 100 MJ Useable On-Site Energy	Unit	On Site CO_2 Emissions per Unit of Fuel	Unit	Fuel Production CO_2 Emissions Per Unit of Fuel	Unit	EE per unit of Fuel	Unit	Useable Energy per Unit of Fuel	Unit	Ratio Useable Energy to EE	EE per 100 MJ useable Energy (MJ)	On-Site CO_2 Emissions for 100 MJ of Useable Energy On-Site (kg)	Fuel Production CO_2 Emissions for 100 MJ of Useable Energy On-Site (kg)	Total CO_2 Emissions for 100 MJ of Useable Energy On-Site (kg)
Diesel	1	35.801	MJ/L	2.793	L	2.695	kg/L	0.553	kg/L	7.166	MJ/L	35.8	MJ/L	5.00	20.0	7.5	1.5	9.1
Gasoline	1	32.356	MJ/L	3.091	L	2.351	kg/L	0.475	kg/L	7.302	MJ/L	32.4	MJ/L	4.43	22.6	7.3	1.5	8.7
CNG	1	47.143	MJ/kg	2.121	kg	2.373	kg/kg	0.497	kg/kg	8.319	MJ/kg	47.1	MJ/kg	5.67	17.6	5.0	1.1	6.1
Electricity	1	3.600	MJ/kW-h	27.778	kW-h	0	kg/kW-h	0.627	kg/kW-h	5.136	MJ/kWh	3.6	MJ/kWh	0.70	142.7	0.0	17.4	17.4

Figure D.1 Spreadsheet calculations of embodied energy and CO_2 emission per 100 MJ of useable energy from fuel.

D.3 GEOTECHNICAL EXAMPLE

As an example of determining the embodied energy and CO_2 emissions associated with construction fuels used for ground improvement, an assumed site with loose sands (D_r = 30%) extending to a depth of 10 m below the ground surface was considered. These sands must be densified to D_r = 70% to provide adequate bearing capacity and mitigate liquefaction risk over a 50 m by 50 m area, for a total treated volume of 25,000 m^3. Two ground improvement alternatives to achieve this densification include deep dynamic compaction, and vibrocompaction. The embodied energy and CO_2 emissions from fuel for each alternative are computed in the following subsections.

D.3.1 Deep Dynamic Compaction

Given:

- Loose sand from surface to 10 m deep; D_r = 30%
- 50 m x 50 m area
- Assumed minimum groundwater depth below ground surface = 2 m
- Needed D_r = 70%

Procedure from Lukas (1995), also see guidance at www.GeotechTools.org (Transportation Research Board 2014):

1) Determine required weight and drop height:

$$D = n(WH)^{0.5}$$

n = empirical coefficient = 0.5

D = 10 m (depth of treatment)

Rearranging and solving for WH:

$$WH = \left(\frac{10m}{0.5}\right)^2 = 400Mg * m$$

Therefore, use a 15 Mg weight falling from a height of 27 m.

$$15Mg(27m) = 405Mg * m$$

2) Determine applied energy from Table 8 in FHWA-SA-95-037 (Lukas 1995).

Applied energy = 250 kJ/m^3

Determine applied energy (*AE*) per unit area:

$$AE = 250\frac{kJ}{m^3}(10m) = 2{,}500\frac{kJ}{m^2}$$

3) Determine number of drops, *N* and spacing.

$$AE = \frac{N(WH)(P)}{(Spacing)^2}$$

where *P* = number of passes, assumed to be 1

Rearranging and solving for *N*:

$$N = \frac{AE(Spacing)^2}{WH(1)} = \frac{2{,}500\frac{kJ}{m^2}(Spacing)^2}{405Mg * m\left(10\frac{kN}{Mg}\right)(1)} = 0.617(Spacing)^2$$

Assume *N* = 10 drops and solving for spacing:

$$Spacing = \sqrt{\frac{10}{0.617}} = 4m$$

4) Determine total number of drops:

50 m by 50 m = a grid of 13 x 13 drop points (169 drop locations)

Total drops = (169 locations)(10 drops/location) = 1,690 drops

5) Determine operational time to conduct the compaction:

Assume cranes can complete 60 drops per hour per machine.

$$\frac{1{,}690\ drops}{60\,\frac{drops}{hr}} = 28.2\ hours \approx 29\ hours$$

Time to improve ground = 29 machine hours.

6) Select equipment and determine fuel consumption:

   Selected crane: Liebherr HS855, 105 ft boom, 603 hp (450 kW) diesel V8 engine

   - Engine Load factor: 0.43 (EPA 2010)
   - BSFC = 0.275 L/kW-hr (Section D.1)

Use Eq. 3.4 to solve for fuel consumption:

$$450kW(0.43)\left(0.275\frac{L}{kW * hr}\right)(29hrs) = 1{,}543L$$

Total fuel consumed for Deep Dynamic Compaction = 1,543 L Diesel.

7) Determine the embodied energy and CO_2 emissions associated with the fuel using Eq. 3.1 and Eq. 3.2:

   Embodied Energy in the fuel (ignores fuel energy content released during combustion):

$$7.17\frac{MJ}{L}(1{,}543L) = 11{,}100MJ$$

   Embodied Energy in the improved ground from fuel (includes fuel production and combustion energy):

$$43.0\frac{MJ}{L}(1{,}543L) = 66{,}300MJ$$

   CO_2 emissions from the fuel:

$$3.25\frac{kg\ CO_2}{L}(1{,}543L) = 5{,}000\ kg\ CO_2$$

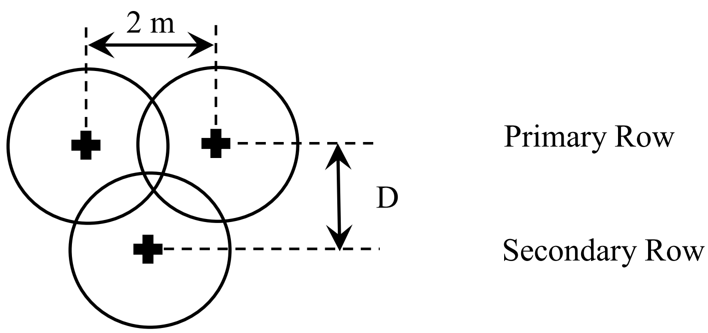
D.3.2 Vibrocompaction

Spacing per compaction point = 2 m [based on Figure 7b from Elias (2006)].

- Assume triangular arrangement (most common).
- Vibroflot must be 100 kW or more. (V23 = 130 kW)

1) Determine number of treatment locations:

   Treatment Locations Layout:



- Solve for D to determine the spacing between primary and secondary rows, to determine the number of rows.

$$D = \sqrt{(2m)^2 - \left(\frac{2m}{2}\right)^2} = 1.7m$$

- 30 total rows required to make up 50 m
  - o 15 primary rows, 27 treatment locations per row
  - o 15 secondary rows, 25 treatment locations per row

$$Total\ Treatment\ Locations = 15(27) + 15(25) = 780$$

2) Determine the time to complete the densification:

   Assume:

  - o Vibroflot retrieved in 0.5m increments

- Assume 1 minute per step during withdrawal
- Assume 10 minutes for initial penetration

Time for 1 location:

$$\frac{10m}{0.5\frac{m}{step}}\left(\frac{1min}{step}\right) + 10min = 30\ minutes\ per\ location = 0.5hrs$$

Total time:

$$780\ locations\left(0.5\frac{hrs}{location}\right) = 390hrs$$

Time to improve ground = 390 machine hours.

3) Select equipment and determine fuel consumption:

Selected crane: Liebherr HS855, 105 ft boom, 603 hp (450 kW) diesel V8 engine

- Engine Load factor: 0.43 (EPA 2010)
- BSFC = 0.275 L/kW-hr (Section D.1)

Electric vibroflot V23, 130kW (Requires 213 kW Diesel generator)

- Engine Load factor: 0.43 (EPA 2010)
- BSFC = 0.275 L/kW-hr (Section D.1)

Crane Fuel Consumption (using Eq. 3.4):

$$450kW(0.43)\left(0.275\frac{L}{kW * hr}\right)(390hrs) = 20{,}753L$$

Generator Fuel Consumption (using Eq. 3.4):

$$213kW(0.43)\left(0.275\frac{L}{kW * hr}\right)(390hrs) = 9{,}823L$$

Total Fuel Consumption:

$$20{,}753L + 9{,}823L = 30{,}576L$$

Total fuel consumed for Vibrocompaction = 30,576 L Diesel.

4) Determine the embodied energy and CO_2 emissions associated with fuel using Eq. 3.1 and Eq. 3.2:

Embodied Energy in the fuel (ignores fuel energy content released during combustion):

$$7.17\frac{MJ}{L}(30{,}576L) = 220{,}500MJ$$

Embodied Energy in the improved ground from fuel (includes fuel production and combustion energy):

$$43.0\frac{MJ}{L}(30{,}756L) = 1{,}322{,}500MJ$$

CO_2 emissions from the fuel:

$$3.25\frac{kg\ CO_2}{L}(30{,}756L) = 100{,}000\ kg\ CO_2$$

5) Consider if grid electricity were used to power the 130 kW vibroflot and a 50 kW pump (each with a load factor of 100%):

Embodied Energy in the fuel (ignores fuel energy content released during combustion):

$$180kW(390hrs)\left(5.14\frac{MJ}{kW*hr}\right) + 7.17\frac{MJ}{L}(20{,}753L) = 509{,}600MJ$$

Embodied Energy in the improved ground from fuel (includes fuel production and combustion energy):

$$180kW(390hrs)\left(5.14\frac{MJ}{kW*hr}\right) + 43.0\frac{MJ}{L}(20{,}753) = 1{,}253{,}200MJ$$

CO_2 emissions from the fuel:

$$180kW(390hrs)\left(0.63\frac{kg\ CO_2}{kW*hr}\right) + 3.25\frac{kg\ CO_2}{L}(20{,}753L) = 111{,}700\ kg\ CO_2$$

Applying a load factor of 0.43 to both the vibroflot and pump:

Embodied Energy in the fuel (ignores fuel energy content released during combustion):

$$180kW(390hrs)(0.43)\left(5.14\frac{MJ}{kW*hr}\right)+7.17\frac{MJ}{L}(20{,}753L)=304{,}000MJ$$

Embodied Energy in the improved ground from fuel (includes fuel production and combustion energy):

$$180kW(390hrs)(0.43)\left(5.14\frac{MJ}{kW*hr}\right)+43.0\frac{MJ}{L}(20{,}753)=1{,}047{,}500MJ$$

CO_2 emissions from the fuel:

$$180kW(390hrs)(0.43)\left(0.63\frac{kg\ CO_2}{kW*hr}\right)+3.25\frac{kg\ CO_2}{L}(20{,}753L)=86{,}500\ kg\ CO_2$$

D.4 COMPARING ENERGY: DEEP DYNAMIC COMPACTION ENERGY TO PROCTOR COMPACTION ENERGY AND INPUT FUEL ENERGY

Standard Proctor Compaction:

3 layers, 25 blows/layer from a 5.5 lb hammer dropping 12 inches.

Standard Proctor Energy = 12,400 ft-lb/ft^3

Modified Proctor Compaction:

5 layers, 25 blows/layer, 10 lb hammer dropping 18 inches.

Modified Proctor Energy = 56,250 ft-lb/ft^3

1) Convert energy to kJ/m^3

Standard Proctor:

$$12{,}400\frac{ft*lb}{ft^3}\left(\frac{4.4482N}{lb}\right)\left(\frac{1m}{3.28084ft}\right)\left(\frac{35.3147ft^3}{m^3}\right)=593{,}700\frac{N*m}{m^3}\approx 594\frac{kJ}{m^3}$$

Modified Proctor:

$$56{,}250\frac{ft*lb}{ft^3}\left(\frac{4.4482N}{lb}\right)\left(\frac{1m}{3.28084ft}\right)\left(\frac{35.3147ft^3}{m^3}\right) = 2{,}693{,}250\frac{N*m}{m^3} \approx 2{,}693\frac{kJ}{m^3}$$

2) Compute Deep Dynamic Compaction (DDC) energy:

169 locations, 10 drops per location, 15 Mg weight, 27 m drop height

$$\frac{1{,}690\ drops(15{,}000kg)\left(9.81\frac{m}{s^2}\right)(27m)\left(\frac{1kJ}{1{,}000J}\right)}{25{,}000m^3} = 269\frac{kJ}{m^3}$$

DDC/Std. Proctor:

$$\frac{269\frac{kJ}{m^3}}{594\frac{kJ}{m^3}} = 0.452 = 45.2\%$$

DDC energy is less than standard proctor energy per unit.

3) Compare DDC energy to input fuel energy:

DDC energy:

$$1{,}690\ drops(15{,}000kg)\left(9.81\frac{m}{s^2}\right)(27m)\left(\frac{1MJ}{1{,}000{,}000J}\right) = 6{,}714MJ$$

Input fuel energy:

$$43.0\frac{MJ}{L}(1{,}543L) = 66{,}300MJ$$

Ratio DDC Energy/Input Fuel Energy:

$$\frac{6{,}714MJ}{66{,}300MJ} = 0.101 = 10.1\%$$

Conclusion:

There is nearly 10 times as much energy in the diesel fuel than is imparted to the ground for deep dynamic compaction. The efficiency with which energy from fuel is delivered to the ground is approximately 10%.

D.5 COMPARING CO_2 AND CO_{2EQ} INCLUDING METHANE AND NITROUS OXIDE FROM FUEL COMBUSTION

Comparison for Diesel and Gasoline

Diesel combustion CO_2 emissions = 2.70 kg CO_2/L.

Gasoline combustion CO_2 emissions = 2.35 kg CO_2/L.

Nitrous Oxide (N_2O) emissions coefficients:

Gasoline = 0.08 g N_2O/kg of fuel (EPA 2015).

Diesel = 0.08 g N_2O/kg of fuel (EPA 2015).

Methane (CH_4) emissions coefficients:

Gasoline = 0.18 g CH_4/kg of fuel (EPA 2015).

Diesel = 0.18 g CH_4/kg of fuel (EPA 2015).

Density of fuels:

Gasoline = 0.74 kg/L (Chevron 2009).

Diesel = 0.85 kg/L (Chevron 2007).

100 year Global Warming Potential (GWP) of N_2O and CH_4:

N_2O GWP = 265 (IPCC 2013).

CH_4 GWP = 28 (IPCC 2013).

Combustion Emissions of N_2O per L of fuel:

Gasoline:

$$0.08 \frac{g}{kg\ Fuel}\left(0.74 \frac{kg}{L}\right) = 0.059 \frac{g}{L}$$

Diesel:

$$0.08 \frac{g}{kg\ Fuel}\left(0.85 \frac{kg}{L}\right) = 0.068 \frac{g}{L}$$

Combustion Emissions of CH_4 per L of fuel:

Gasoline:

$$0.18 \frac{g}{kg\ Fuel}\left(0.74 \frac{kg}{L}\right) = 0.133 \frac{g}{L}$$

Diesel:

$$0.18 \frac{g}{kg\ Fuel}\left(0.85 \frac{kg}{L}\right) = 0.153 \frac{g}{L}$$

Total CO_{2eq} Emissions from combusting 1 L of fuel:

Gasoline:

$$2.35 \frac{kg\ CO_2}{L}(1) + 0.059 \frac{g\ N_2O}{L}(265)\left(\frac{1kg}{1{,}000g}\right) + 0.133 \frac{g\ CH_4}{L}(28)\left(\frac{1kg}{1{,}000g}\right)$$

$$= 2.37 \frac{kg\ CO_{2eq}}{L}$$

Diesel:

$$2.70 \frac{kg\ CO_2}{L}(1) + 0.068 \frac{g\ N_2O}{L}(265)\left(\frac{1kg}{1{,}000g}\right) + 0.153 \frac{g\ CH_4}{L}(28)\left(\frac{1kg}{1{,}000g}\right)$$

$$= 2.72 \frac{kg\ CO_{2eq}}{L}$$

Difference between CO_2 and CO_{2eq} combustion emissions:

Gasoline:

$$2.37 \frac{kg\ CO_{2eq}}{L} - 2.35 \frac{kg\ CO_2}{L} = 0.02 \frac{kg}{L} = 0.85\%\ different$$

Diesel:

$$2.72 \frac{kg\ CO_{2eq}}{L} - 2.70 \frac{kg\ CO_2}{L} = 0.02 \frac{kg}{L} = 0.74\%\ different$$

The difference between the CO_2 emissions and CO_{2eq} emissions including N_2O and CH_4 due to the combustion of diesel and gasoline is less than 1%. Therefore, it is reasonable to use the simpler CO_2 emissions result when estimating the carbon emissions from fuel combustion in construction operations.

D.6 REFERENCES

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Appendix E: SEEAM Results for Analyses of LPV 111 Design Alternatives

This Appendix contains tables and figures that present the results of SEEAM analyses conducted for the various design options for upgrading levee LPV 111 in New Orleans, LA. These analyses are pertinent for the discussion presented in Chs. 4 – 5. Note that the calculations tables included in this Appendix show an analytically computed mean and standard deviation for embodied energy and CO_2 emissions. In Chs. 4 – 5, the mean values of total embodied energy and CO_2 emissions as shown in this Appendix are considered to be deterministic results (i.e., the mean value is the amount of embodied energy or CO_2 emissions resulting from the construction for a particular scenario). Uncertainty in the SEEAM analysis is addressed in Chs. 6 – 7 and Appendices J, K, O, P and Q.

E.1 LPV 111 DEEP MIXING WITH SPOIL RECYCLING AS EMBANKMENT FILL

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Slag (U.S.)	225,493	65,678	6,568	3,440
2	Cementitious Materials	Portland Cement (U.S.)	500,400	102,165	96,640	10,946
3	Other	Water	4,540	0	454	0
4	Plastics	General Plastics (Average)	31,824	14,892	1,079	505
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	**762,256**	**122,364**	**104,741**	**11,485**
RM 1	Recycled or Reused	Deep Mix Spoil, Recycled Embankment Material	0		0	
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TOTAL	**762,256**	**122,364**	**104,741**	**11,485**

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1		Ship slag from Chicago to batch plant	79,054	0	14,602	0
	Heavy Duty Truck	Ship mixed binder from plant to site	2,059	68	156	5
2		Ship cement to batch plant	18,495	0	3,416	0
3						
4	Heavy Duty Truck	Shipping geogrid - supplier to site	682	23	52	2
5	Heavy Duty Truck	Ship clay from borrow area to site	50,553	1,681	3,821	129
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**150,843**	**1,683**	**22,047**	**129**
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TRANSPORTATION TOTAL	**150,843**	**1,683**	**22,047**	**129**

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Fuel consumed for deep mixing, including plants	167,786	5,580	12,682	429
2	Diesel	Fuel Consumed for extracting Clay Borrow	9,030	300	683	23
3	Diesel	Fuel consumed for placing and compacting levee	84,280	2,803	6,370	216
4						
		SITE OPERATIONS TOTAL	**261,096**	**6,251**	**19,734**	**481**

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Figure E.1 Line by line SEEAM calculations for Deep Soil Mixing with spoil recycling as embankment fill at LPV 111.

Table E.1 SEEAM results for Deep Soil Mixing with spoil recycling as embankment fill at LPV 111.

	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	762,256	65%	104,741	71%
Materials Transportation	150,843	13%	22,047	15%
Site Operations	261,096	22%	19,734	13%
Waste Transportation	0	0%	0	0%
TOTAL	**1,174,195**	**100%**	**146,521**	**100%**

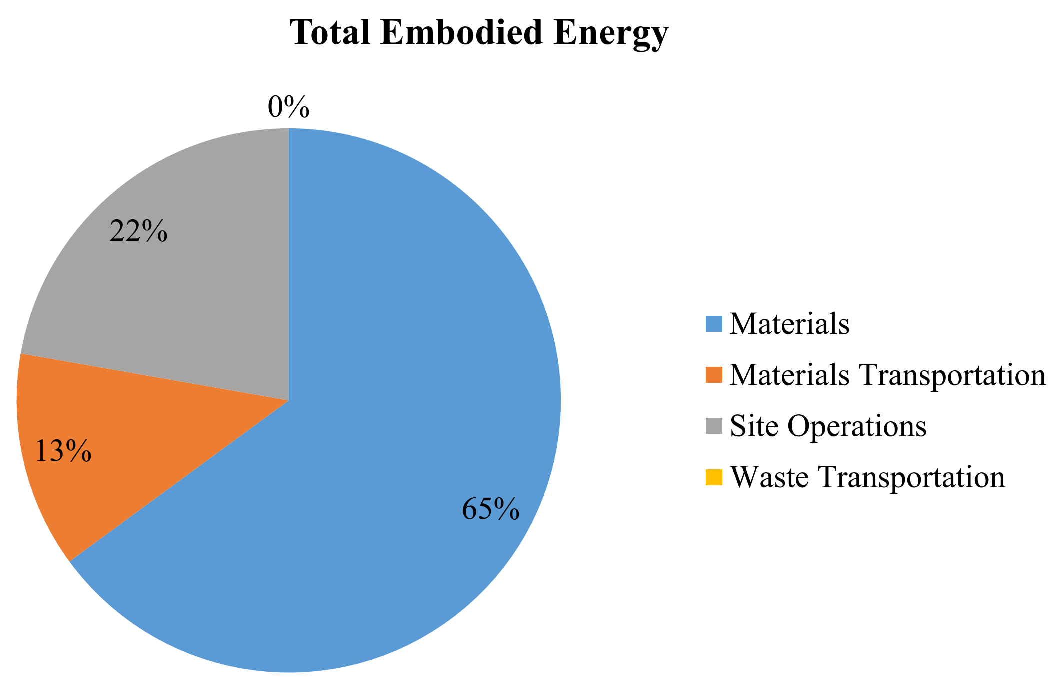

Figure E.2 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing with spoil recycling as embankment fill for LPV 111.

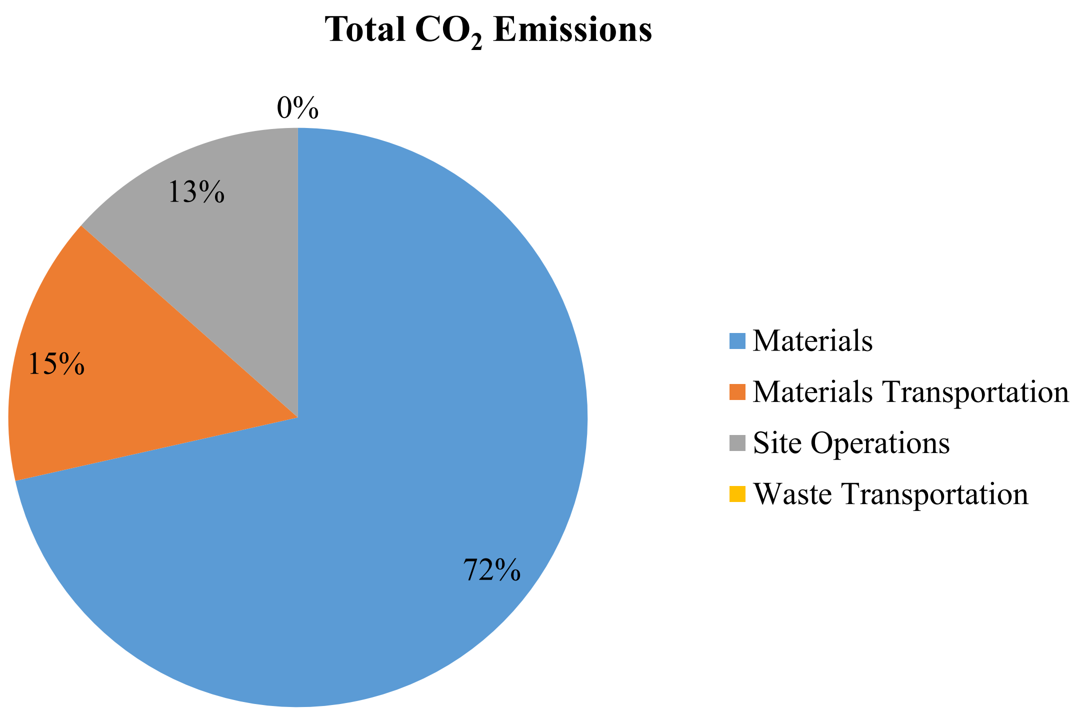

Figure E.3 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing with spoil recycling as embankment fill for LPV 111.

E.2 LPV 111 DEEP MIXING WITHOUT SPOIL RECYCLING AS EMBANKMENT FILL

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Slag (U.S.)	225,493	65,678	6,568	3,440
2	Cementitious Materials	Portland Cement (U.S.)	500,400	102,165	96,640	10,946
3	Other	Water	4,540	0	454	0
4	Plastics	General Plastics (Average)	31,824	14,892	1,079	505
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	762,256	122,364	104,741	11,485
RM 1	Recycled or Reused	Deep Mix Spoil, Recycled Embankment Material	0		0	
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	0	0	0	0
		MATERIALS TOTAL	762,256	122,364	104,741	11,485

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1		Ship slag from Chicago to batch plant	79,054	0	14,602	0
	Heavy Duty Truck	Ship mixed binder from plant to site	2,059	68	156	5
2		Ship cement to batch plant	18,495	0	3,416	0
3						
4	Heavy Duty Truck	Shipping geogrid - supplier to site	682	23	52	2
5	Heavy Duty Truck	Ship clay from borrow area to site	96,380	3,205	7,285	247
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	196,669	3,206	25,510	247
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	0	0	0	0
		MATERIALS TRANSPORTATION TOTAL	196,669	3,206	25,510	247

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Fuel consumed for deep mixing, including plants	167,786	5,580	12,682	429
2	Diesel	Fuel Consumed for extracting Clay Borrow	17,200	572	1,300	44
3	Diesel	Fuel consumed for placing and compacting levee	84,280	2,803	6,370	216
4						
		SITE OPERATIONS TOTAL	269,266	6,270	20,352	482

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	DSM Return material	49,542	1,648	3,744	127
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	49,542	1,648	3,744	127

Figure E.4 Line by line SEEAM calculations for Deep Soil Mixing without spoil recycling as embankment fill at LPV 111.

Table E.2 SEEAM results for Deep Soil Mixing without spoil recycling as embankment fill at LPV 111.

	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	762,256	60%	104,741	68%
Materials Transportation	196,669	15%	25,510	17%
Site Operations	269,266	21%	20,352	13%
Waste Transportation	49,542	4%	3,744	2%
TOTAL	**1,277,734**	**100%**	**154,347**	**100%**

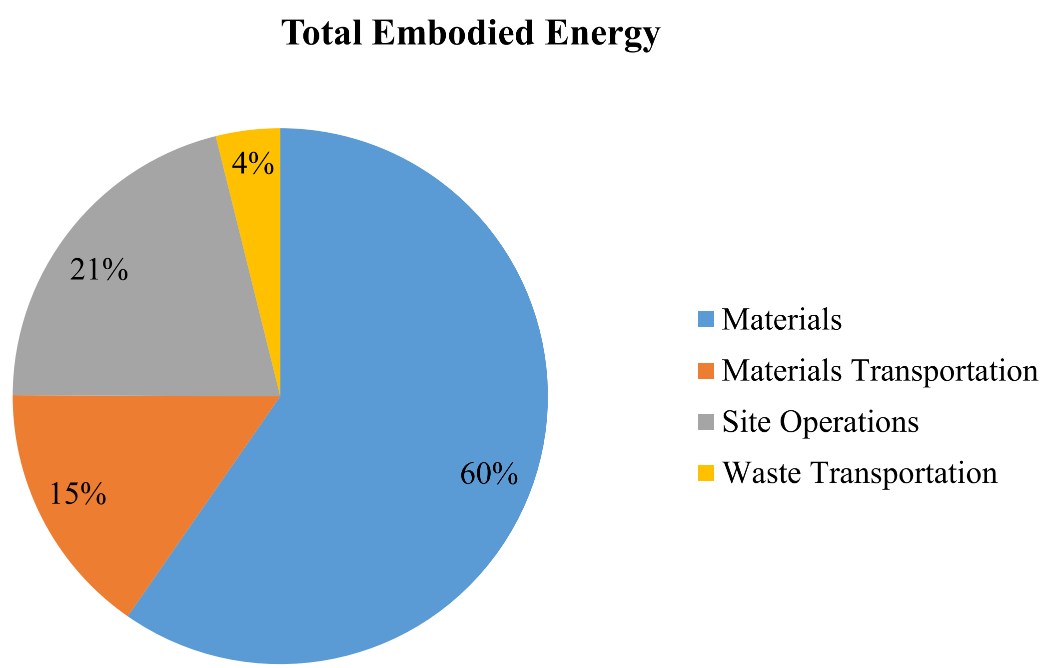

Figure E.5 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing without spoil recycling as embankment fill for LPV 111.

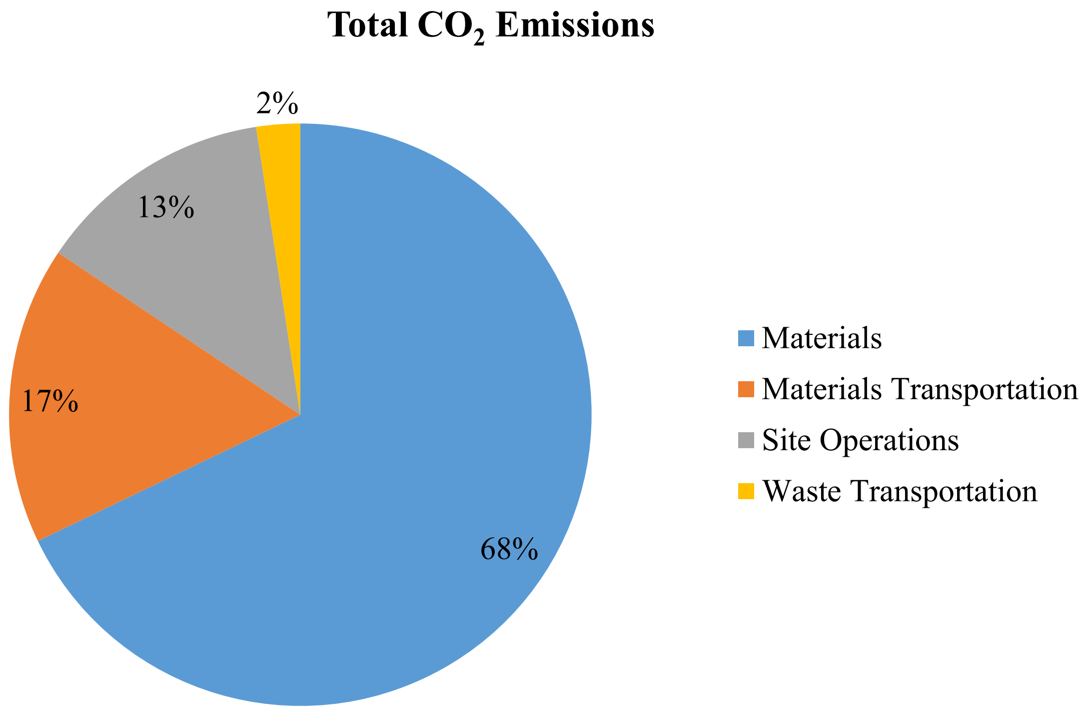

Figure E.6 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing without spoil recycling as embankment fill for LPV 111.

E.3 LPV 111 DEEP MIXING WITH SPOIL RECYCLING AS EMBANKMENT FILL, EXCLUDING BARGE TRANPORT

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Slag (U.S.)	225,493	65,678	6,568	3,440
2	Cementitious Materials	Portland Cement (U.S.)	500,400	102,165	96,640	10,946
3	Other	Water	4,540	0	454	0
4	Plastics	General Plastics (Average)	31,824	14,892	1,079	505
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	762,256	122,364	104,741	11,485
RM 1	Recycled or Reused	Deep Mix Spoil, Recycled Embankment Material	0		0	
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	0	0	0	0
		MATERIALS TOTAL	762,256	122,364	104,741	11,485

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1		Ship slag from Chicago to batch plant	0	0	0	0
	Heavy Duty Truck	Ship mixed binder from plant to site	2,059	68	156	5
2		Ship cement to batch plant	0	0	0	0
3						
4	Heavy Duty Truck	Shipping geogrid - supplier to site	682	23	52	2
5	Heavy Duty Truck	Ship clay from borrow area to site	50,553	1,681	3,821	129
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	53,294	1,683	4,028	129
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	0	0	0	0
		MATERIALS TRANSPORTATION TOTAL	53,294	1,683	4,028	129

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Fuel consumed for deep mixing, including plants	167,786	5,580	12,682	429
2	Diesel	Fuel Consumed for extracting Clay Borrow	9,030	300	683	23
3	Diesel	Fuel consumed for placing and compacting levee	84,280	2,803	6,370	216
4						
		SITE OPERATIONS TOTAL	261,096	6,251	19,734	481

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	0	0	0	0

Figure E.7 Line by line SEEAM calculations for Deep Soil Mixing with spoil recycling as embankment fill at LPV 111, excluding barge transport.

Table E.3 SEEAM results for Deep Soil Mixing with spoil recycling as embankment fill at LPV 111, excluding barge transport.

	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	762,256	71%	104,741	82%
Materials Transportation	53,294	5%	4,028	3%
Site Operations	261,096	24%	19,734	15%
Waste Transportation	0	0%	0	0%
TOTAL	**1,076,647**	**100%**	**128,503**	**100%**

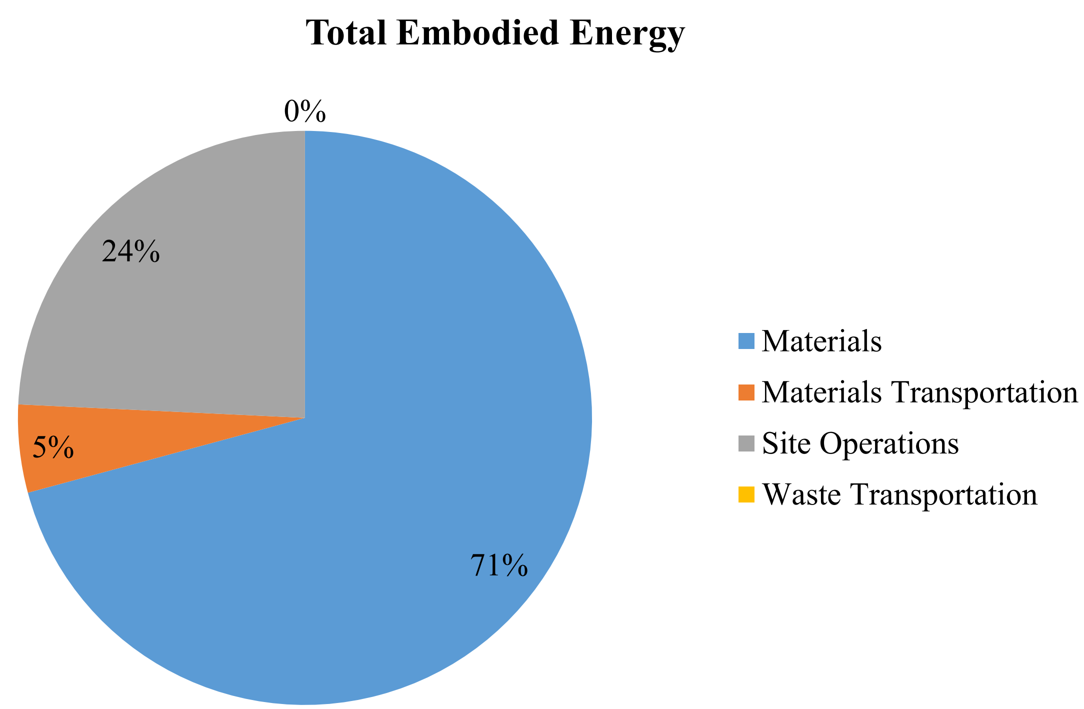

Figure E.8 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing with spoil recycling as embankment fill for LPV 111, excluding barge transport.

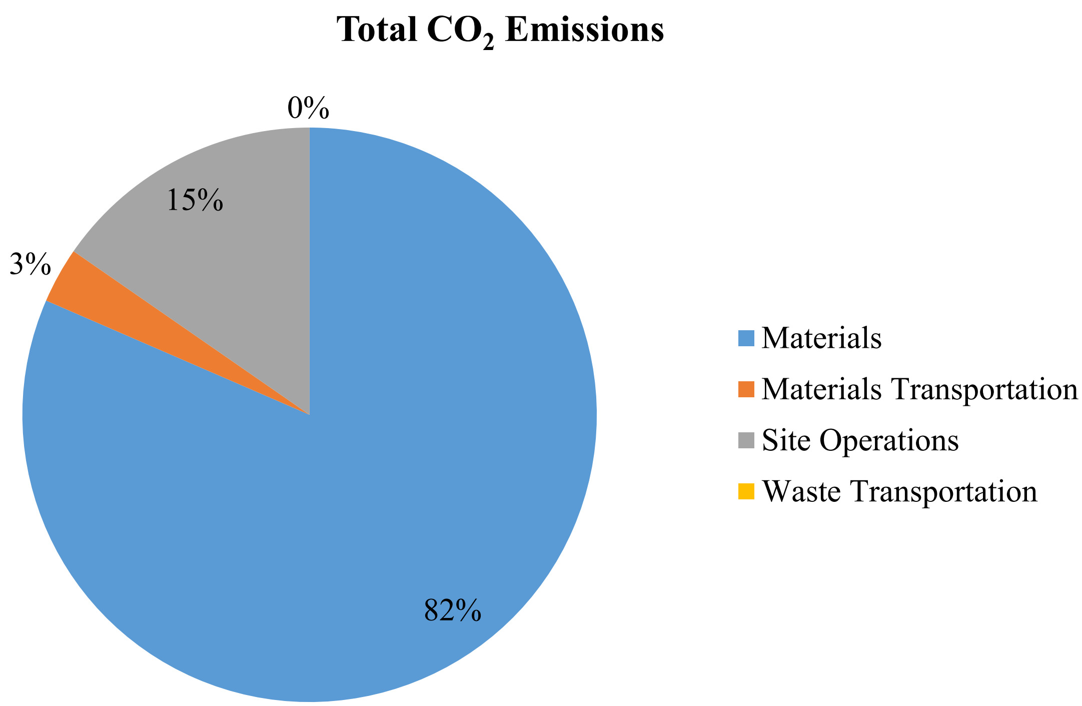

Figure E.9 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing with spoil recycling as embankment fill for LPV 111, excluding barge transport.

E.4 LPV 111 DEEP MIXING WITH SPOIL RECYCLING AS EMBANKMENT FILL, 100% PORTLAND CEMENT BINDER

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ) Mean	Embodied Energy (GJ) St Dev	CO_2 Emissions (tonnes) Mean	CO_2 Emissions (tonnes) St Dev
1						
2	Cementitious Materials	Portland Cement (U.S.)	2,001,600	408,660	386,559	43,785
3	Other	Water	4,540	0	454	0
4	Plastics	General Plastics (Average)	31,824	14,892	1,079	505
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	**2,037,964**	**408,931**	**388,092**	**43,788**
RM 1	Recycled or Reused	Deep Mix Spoil, Recycled Embankment Material	0		0	
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TOTAL	**2,037,964**	**408,931**	**388,092**	**43,788**

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ) Mean	Embodied Energy (GJ) St Dev	CO_2 Emissions (tonnes) Mean	CO_2 Emissions (tonnes) St Dev
1						
2		Ship cement to batch plant	73,980	0	13,665	0
	Heavy Duty Truck	Ship mixed binder from plant to site	2,059	68	156	5
3						
4	Heavy Duty Truck	Shipping geogrid - supplier to site	682	23	52	2
5	Heavy Duty Truck	Ship clay from borrow area to site	50,553	1,681	3,821	129
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**127,274**	**1,683**	**17,693**	**129**
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TRANSPORTATION TOTAL	**127,274**	**1,683**	**17,693**	**129**

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ) Mean	Embodied Energy (GJ) St Dev	CO_2 Emissions (tonnes) Mean	CO_2 Emissions (tonnes) St Dev
1	Diesel	Fuel consumed for deep mixing, including plants	167,786	5,580	12,682	429
2	Diesel	Fuel Consumed for extracting Clay Borrow	9,030	300	683	23
3	Diesel	Fuel consumed for placing and compacting levee	84,280	2,803	6,370	216
4						
		SITE OPERATIONS TOTAL	**261,096**	**6,251**	**19,734**	**481**

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ) Mean	Embodied Energy (GJ) St Dev	CO_2 Emissions (tonnes) Mean	CO_2 Emissions (tonnes) St Dev
1						
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Figure E.10 Line by line SEEAM calculations for Deep Soil Mixing with spoil recycling as embankment fill at LPV 111, 100% Portland cement binder.

Table E.4 SEEAM results for Deep Soil Mixing with spoil recycling as embankment fill at LPV 111, with 100% Portland cement binder.

	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	2,037,964	84%	388,092	91%
Materials Transportation	127,274	5%	17,693	4%
Site Operations	261,096	11%	19,734	5%
Waste Transportation	0	0%	0	0%
TOTAL	**2,426,334**	**100%**	**425,519**	**100%**

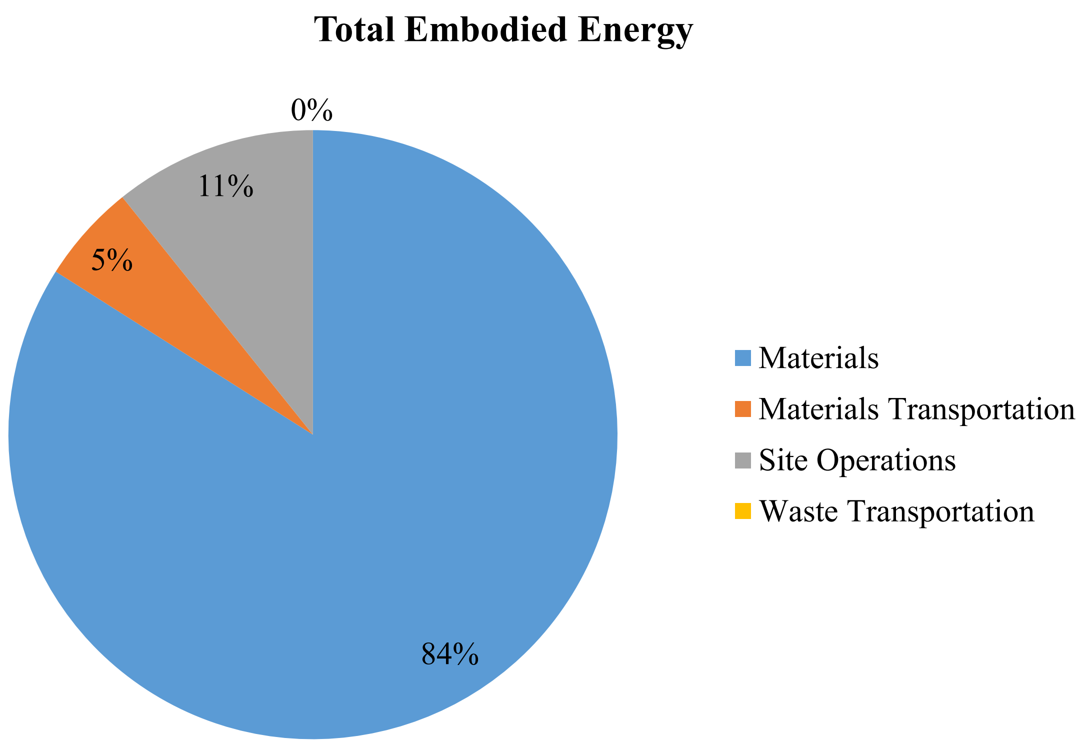

Figure E.11 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing with spoil recycling as embankment fill for LPV 111, with 100% Portland cement binder.

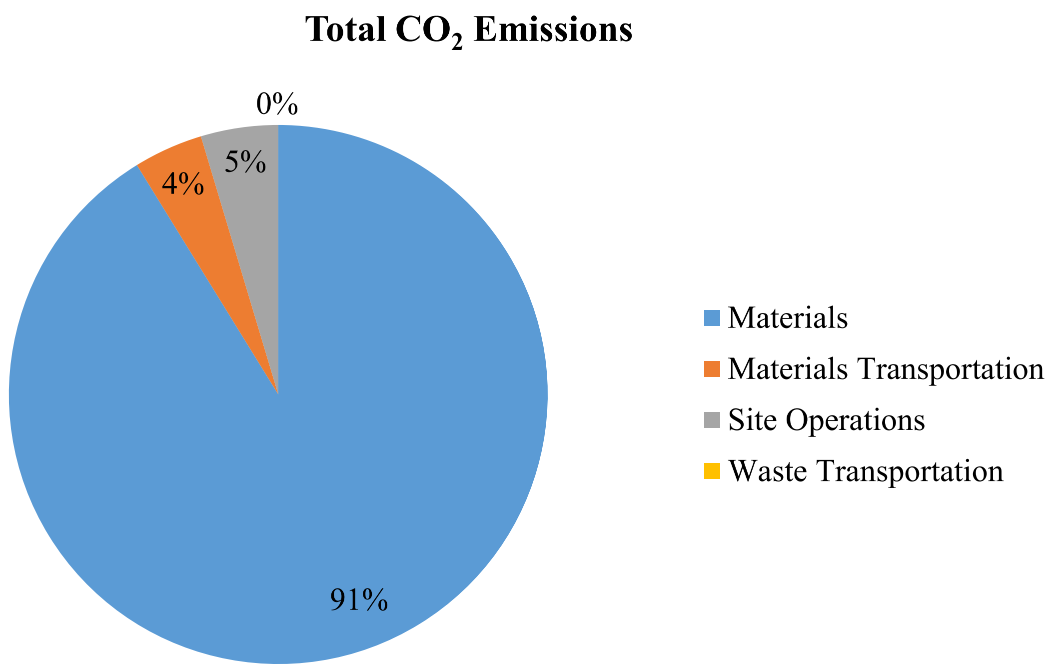

Figure E.12 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing with spoil recycling as embankment fill for LPV 111, with 100% Portland cement binder.

E.5 LPV 111 DEEP MIXING, EXCLUDING EMBANKMENT CONSTRUCTION

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Slag (U.S.)	225,493	65,678	6,568	3,440
2	Cementitious Materials	Portland Cement (U.S.)	500,400	102,165	96,640	10,946
3	Other	Water	4,540	0	454	0
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	**730,433**	**121,455**	**103,662**	**11,474**
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TOTAL	**730,433**	**121,455**	**103,662**	**11,474**

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1		Ship slag from Chicago to batch plant	79,054	0	14,602	0
	Heavy Duty Truck	Ship mixed binder from plant to site	2,059	68	156	5
2		Ship cement to batch plant	18,495	0	3,416	0
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**99,608**	**68**	**18,174**	**5**
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TRANSPORTATION TOTAL	**99,608**	**68**	**18,174**	**5**

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Fuel consumed for deep mixing, including plants	167,786	5,580	12,682	429
2						
3						
4						
		SITE OPERATIONS TOTAL	**167,786**	**5,580**	**12,682**	**429**

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Figure E.13 Line by line SEEAM calculations for Deep Soil Mixing at LPV 111, excluding embankment construction.

Table E.5 SEEAM results for Deep Soil Mixing at LPV 111, excluding embankment construction.

	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	730,433	73%	103,662	77%
Materials Transportation	99,608	10%	18,174	14%
Site Operations	167,786	17%	12,682	9%
Waste Transportation	0	0%	0	0%
TOTAL	**997,827**	**100%**	**134,517**	**100%**

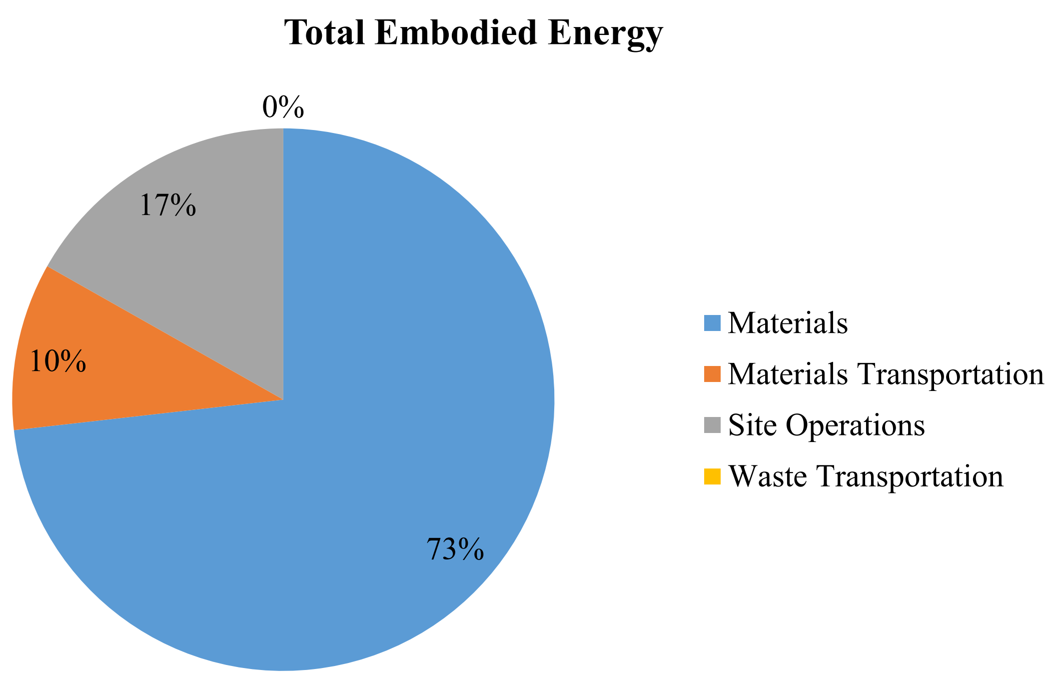

Figure E.14 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing at LPV 111, excluding embankment construction.

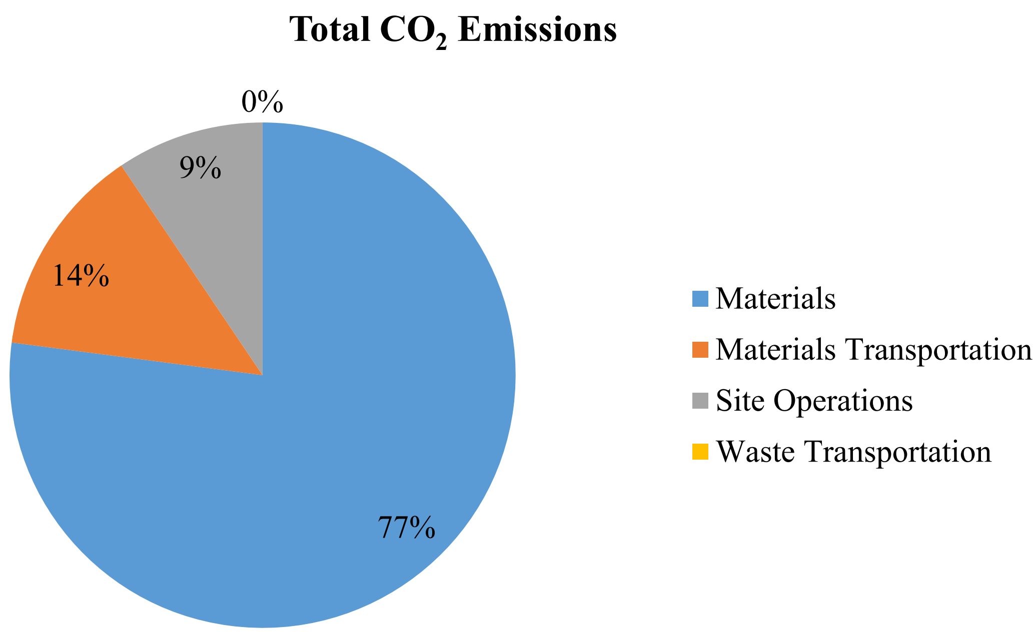

Figure E.15 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Deep Soil Mixing at LPV 111, excluding embankment construction.

E.6 LPV 111 PREFABRICATED VERTICAL DRAINS

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Plastics	Polypropylene (Injection Molding)	66,770	0	2,280	0
2	Plastics	Polyethylene (General)	59,383	23,417	1,458	575
3	Plastics	General Plastics (Average)	123,503	57,793	4,188	1,961
4	Plastics	Polypropylene (Oriented Film)	18,977	0	568	0
5	Cementitious Materials	Portland Cement (U.S.)	119,117	24,320	23,004	2,606
6	Other	Bentonite	11,377	0	696	0
7	Other	Water	1,378	0	138	0
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	400,505	66,932	32,333	3,311
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	0	0	0	0
		MATERIALS TOTAL	400,505	66,932	32,333	3,311

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Shipping PVDs from supplier to site	1,001	33	76	3
2	Heavy Duty Truck	Shipping geonet from supplier to site	643	21	49	2
3	Heavy Duty Truck	Shipping geogrid from supplier to site	2,526	84	191	6
4	Heavy Duty Truck	Shipping geotextile supplier to site	171	6	13	0
5	Heavy Duty Truck	Shipping cement to site	123	4	9	0
		Shipping cement to plant	4,403	0	813	0
6	Heavy Duty Truck	Shipping Bentonite to site	30,604	1,018	2,313	78
7		No shipping				
8	Heavy Duty Truck	Shipping clay borrow to site	151,441	5,036	11,446	387
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	190,912	5,139	14,910	395
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	0	0	0	0
		MATERIALS TRANSPORTATION TOTAL	190,912	5,139	14,910	395

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Fuel consumed to install PVDs	18,512	616	1,399	47
2	Diesel	Fuel consumed to extract clay borrow	26,746	889	2,022	68
3	Diesel	Fuel consumed to excavate C/B Wall	11,335	377	857	29
4	Diesel	Fuel to degrade & construct new embankment	143,061	4,758	10,813	366
		SITE OPERATIONS TOTAL	199,653	4,894	15,090	376

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Excavated C/B Wall material	18,397	612	1,390	47
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	18,397	612	1,390	47

Figure E.16 Line by line SEEAM calculations for Prefabricated Vertical Drains at LPV 111.

Table E.6 SEEAM results for Prefabricated Vertical Drains at LPV 111.

	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	400,505	49%	32,333	51%
Materials Transportation	190,912	24%	14,910	23%
Site Operations	199,653	25%	15,090	24%
Waste Transportation	18,397	2%	1,390	2%
TOTAL	**809,467**	**100%**	**63,723**	**100%**

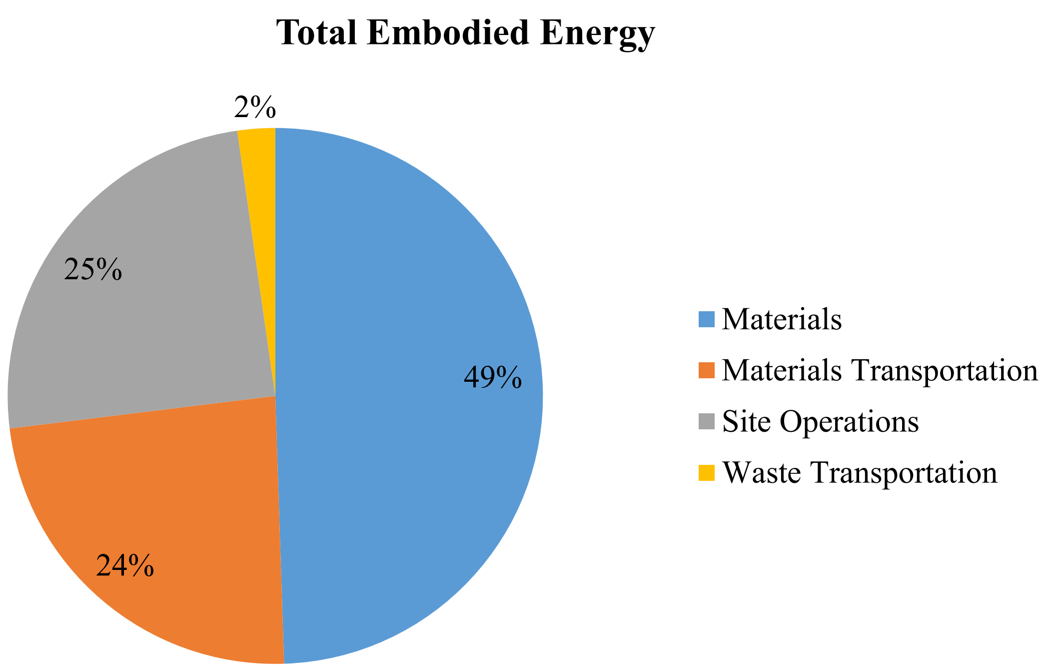

Figure E.17 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Prefabricated Vertical Drains at LPV 111.

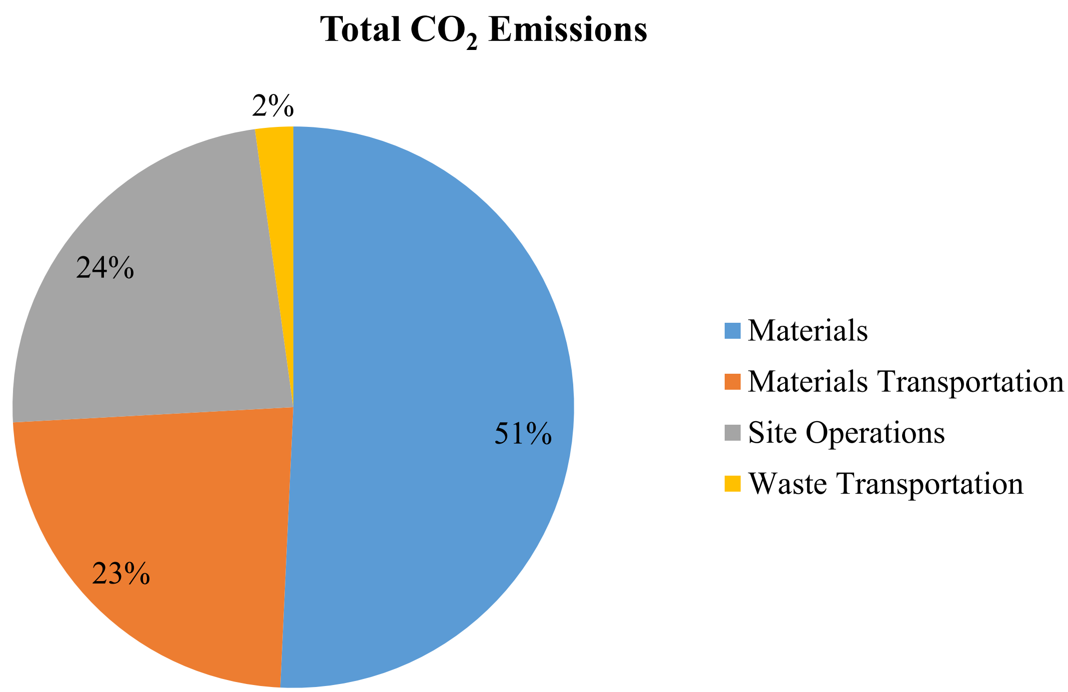

Figure E.18 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Prefabricated Vertical Drains at LPV 111.

E.7 LPV 111 REINFORCED CONCRETE T-WALL, MATERIALS ONLY

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Concrete	25MPA Concrete (Portland Cement Only)	126,977	0	23,934	0
2	Steel	Steel Bar and Rod, World Avg. Recycled Content	316,008	0	25,456	0
3	Steel	Engineered Steel Sections, World Avg. Recycled Content	1,804,860	0	125,874	0
4	Steel	Engineered Steel Sections, World Avg. Recycled Content	507,583	0	35,400	0
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	**2,755,428**	**0**	**210,664**	**0**
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TOTAL	**2,755,428**	**0**	**210,664**	**0**

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		SITE OPERATIONS TOTAL	**0**	**0**	**0**	**0**

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1						
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	**0**	**0**	**0**	**0**

Figure E.19 Line by line SEEAM calculations for a Reinforced Concrete T-wall at LPV 111, including materials only.

Table E.7 SEEAM results for a Reinforced Concrete T-wall at LPV 111, including materials only.

	Embodied Energy (GJ)		**CO_2 Emissions (tonnes)**	
	Mean	**% of Total**	**Mean**	**% of Total**
Materials	2,755,428	100%	210,664	100%
Materials Transportation	0	0%	0	0%
Site Operations	0	0%	0	0%
Waste Transportation	0	0%	0	0%
TOTAL	**2,755,428**	**100%**	**210,664**	**100%**

Appendix F: LPV 111 SEEAM Analysis – Supporting Calculations

F.1 ESTIMATING QUANTITIES FOR THE DEEP SOIL MIXING OPTION

F.1.1 Fuel Consumed to Extract Clay Borrow, with use of Recycled Embankment Material as Fill

Equipment: Cat 340 or Cat 345 excavator

Production Rate: 100 – 144 CY/hr

[above information provided via personal communication by J. Gardner (2014)]

Cat 345 Specifications to be used in calculations (Caterpillar 2012):

Weight: 44,970 kg

Power: 257 kW = 345 hp at the flywheel

Fuel Consumption:

Load	Fuel Consumption (L/hr)
Low (20% - 40%)	14.5 – 30.5
Medium (40% - 60%)	29 – 45.6
High (60% - 80%)	43.3 - 61

For the construction activity of excavating the borrow soil, high medium load is reasonable. Assume an engine load of 60% on average.

1) Determine hourly fuel consumption from Eq. 3.4, using BSFC = 0.275 L/kW-hr:

$$Q_F = (257\ kW)(0.60)\left(0.275\frac{L}{kW * hr}\right)(1hr)$$

$$Q_F = 42.4\frac{L}{hr}$$

2) Compute hours of excavating:

Total levee fill required = 841,000 m^3 (Cali et al. 2012)

Total recycled embankment material = 400,000 m^3 (Druss et al. 2012)

Clay borrow required = 841,000 m^3 – 400,000 m^3 = 441,000 m^3

Production Rates:

100 CY/hr = 76.4 m^3/hr ≈ 76 m^3/hr

144 CY/hr = 110.1 m^3/hr ≈ 110 m^3/hr

Hours of operation for slow production:

$$\frac{441{,}000m^3}{76\,\frac{m^3}{hr}} = 5{,}803\ hrs$$

Hours of operation for fast production:

$$\frac{441{,}000m^3}{110\,\frac{m^3}{hr}} = 4{,}009\ hrs$$

3) Compute total fuel used to excavate borrow soil:

Slow production:

$$5{,}803hrs\left(42.4\frac{L}{hr}\right) = 246{,}047L$$

Fast production:

$$4{,}009\ hrs\left(42.4\frac{L}{hr}\right) = 169{,}982L$$

4) Estimate of average total fuel consumption for extraction of clay borrow soil:

Fuel Estimate = 210,000 L

F.1.2 Fuel Consumed to Extract Clay Borrow without use of Recycled Embankment Material as Fill

Equipment: Cat 340 or Cat 345 excavator

Production Rate: 100 – 144 CY/hr

[above information provided via personal communication by J. Gardner (2014)]

Cat 345 Specifications to be used in calculations (Caterpillar 2012):

Weight: 44,970 kg

Power: 257 kW = 345 hp at the flywheel

Fuel Consumption:

Load	Fuel Consumption (L/hr)
Low (20% - 40%)	14.5 – 30.5
Medium (40% - 60%)	29 – 45.6
High (60% - 80%)	43.3 - 61

For the activity, high medium load is reasonable. Assume an engine load of 60% on average.

1) Determine hourly fuel consumption from Eq. 3.4, using BSFC = 0.275 L/kW-hr:

$$Q_F = (257\ kW)(0.60)\left(0.275 \frac{L}{kW * hr}\right)(1hr)$$

$$Q_F = 42.4 \frac{L}{hr}$$

2) Compute hours of excavating:

Total levee fill required = 841,000 m^3 (Cali et al. 2012)

Clay borrow required = 841,000 m^3

Production Rates:

100 CY/hr = 76.4 m^3/hr ≈ 76 m^3/hr

144 CY/hr = 110.1 m^3/hr ≈ 110 m^3/hr

Hours of operation for slow production:

$$\frac{841{,}000m^3}{76\,\frac{m^3}{hr}} = 11{,}066\ hrs$$

Hours of operation for fast production:

$$\frac{841{,}000m^3}{110\,\frac{m^3}{hr}} = 7{,}645\ hrs$$

3) Compute total fuel used to excavate borrow soil:

Slow production:

$$11{,}066hrs\left(42.4\frac{L}{hr}\right) = 469{,}200L$$

Fast production:

$$7{,}645\ hrs\left(42.4\frac{L}{hr}\right) = 324{,}100L$$

4) Estimate of average total fuel consumption for extraction of clay borrow soil:

Fuel Estimate = 400,000 L

F.1.3 Fuel Consumed to Place and Compact the Embankment

In this section, productivity information was obtained from the 2012 RS Means Heavy Construction Cost data (RSMeans 2011).

Embankment Compaction (RS Means section 31 23 23.23)

- 1 sheep's foot roller, 6 inch lifts, 4 passes = 1,300 CY/day (compacted)
  - Set this as the control value, select other equipment to supply 1 roller as 1 unit of production.

Spreading loose fill, no compaction (RS Means section 31 23 23.17)

- 1 dozer, 300 hp = 600 – 1,000 CY/day
  - Therefore, 2 dozers needed to keep 1 roller busy

Load soil from stockpile – wheel mounted front end loader (RS Means section 31 23 23.15)

- 5 CY bucket = 2,600 CY/day (maximum)
  - Therefore, 1 loader is required to keep dozers and roller busy

Off road haul trucks to move material

- Cat 770 haul truck has a 25 CY capacity. Using a bulking factor of 1.18 to convert from the compacted volume to loose volume:

$$\frac{1{,}300\,\frac{CY}{day}(1.18)}{25CY} = 62\ truckloads/day$$

- Assume truck cycle (load, haul, dump, return) = 25 minutes
  - 5 off-road haul trucks required

Total Equipment (to construct 1,300 CY of embankment – considered to be 1 production unit)

- 1 sheep's foot roller
- 2 bulldozers (about 300 hp each)
- 1 front end loader (5 CY bucket)
- 5 off road haul trucks (25 CY capacity)

Determine the fuel based on 1 production unit doing all work. Multiple production units shorten project duration, but the same fuel will be consumed.

Equipment:

Type	Assumed Model	Gross Power (kW)	Load Factor	Approx. Fuel Consumption (L/hr)
Roller (1)	Cat CP54	97	50%	9.4
Bulldozer (2)	Cat D7E	175	50%	24
Front Loader (1)	Cat 950K	173	40%	17.4
Off Road Truck (5)	Cat 770	381	40%	30.6

References: (Caterpillar 2012; Caterpillar 2014)

Fuel consumption (per 8 hour day) using Eq. 3.4:

Type	No. of Units	Gross Power (kW)	Load Factor	Quantity of Fuel (L)
Roller	1	97	50%	106.7
Bulldozer	2	175	50%	385
Front Loader	1	173	40%	152.2
Off Road Truck	5	381	40%	1,676

Total Fuel = 2,320 L per 8 hour day (production = 1,300 CY of embankment)

Estimated overall total fuel consumed:

$$\frac{2{,}320L}{1{,}300CY}(841{,}000m^3)\left(\frac{1.30795062CY}{m^3}\right) = 1{,}963{,}053L$$

Estimated embankment compaction fuel ≈ 1,960,000 L

F.1.4 Clay Borrow Transportation – Number of Truckloads Required

Assumption: 15 CY of material per truck (semi-trailers ≈ 20 CY, 10 wheelers ≈ 10 CY, both sizes used to haul material [information obtained via personal communication from J. Gardner (2014)].

441,000 m^3 = 577,000 CY of borrow soil

$$\frac{577{,}000CY}{15\,\frac{CY}{truck}} = 38{,}467\ truckloads$$

Total truckloads of borrow soil = 38,500, each truck making a round trip.

F.1.5 Quantity of Geogrid

Type of geogrid: Huesker 400MP, poly-vinyl alcohol

Mass/Area: 1,050 g/m^2

Roll = 5 m wide by 100 m long

Roll Mass: 525 kg

Above data from Huesker (2013).

Total area of geogrid = 450,000 yd^2 ≈ 376,000 m^2 (Kelsey 2012).

Number of rolls required:

$$\frac{376{,}300m^2}{500\,\frac{m^2}{roll}} = 753\ rolls$$

Mass of rolls:

$$753\ rolls\left(525\,\frac{kg}{roll}\right) = 395{,}325kg$$

Total mass of geogrid ≈ 395,000 kg

F.1.6 Number of Truckloads Required to Haul Geogrid

Payload of Class 8 heavy duty truck = 24,494 kg (Davis et al. 2012).

$$395{,}000kg\left(\frac{1\ truck}{24{,}494kg}\right) = 16.1\ truckloads$$

Total number of truckloads for geogrid = 17

F.1.7 Disposal of Deep Mixing Spoil

Distance = 40 km from the site to the disposal facility

Quantity of waste material = 400,000 m^3

Assume:

- 15 CY (11.47 m^3) of waste per truck

$$\frac{400{,}000m^3}{\frac{11.47m^3}{truck}} = 34{,}873\ truckloads$$

Number of waste disposal truckloads = 34,900.

F.2 SUMMARY OF QUANTITIES FOR THE DEEP SOIL MIXING OPTION

Table F.1 contains a summary of all quantities of materials, fuel, haul distances and number of trips for the SEEAM analysis. Data was obtained from Schmutzler et al. (2012), Druss et al. (2012), Cali et al. (2012), and Kelsey (2012). Additional information was also obtained via personal communication from F. Leoni (2013), T. Leffingwell (2014), and J. Gardner (2014). Distances were obtained using Google Maps.

Table F.1 LPV 111 Deep Soil Mixing option: total quantities of materials, fuel, haul distances and number of trips.

Material	Quantity	Unit
Binder (25% Cement, 75% Slag)	417,000,000	kg
Cement (in binder)	104,250,000	kg
Slag (in binder)	312,750,000	kg
Water	454,000,000	L
Treated Foundation Soil Volume	1,400,000	m^3
Diesel Fuel Consumed (mixing rigs, backhoes, pumps)	3,901,948	L
Binder Transportation Distance to Site by Truck (mixed 25%/75% at Buzzi Unicem plant)	3.2	km
Number of cement truck loads (23 tonne) to deliver binder to the site	18,131	round trip
Cement Shipping Distance by Barge to Buzzi Unicem Plant (from Festus, MO)	1,130	km
Slag Shipping Distance by Barge to Buzzi Unicem Plant (from Chicago, IL)	1,610	km
Total Clay Fill Required to Construct the Levee	841,000	m^3
Amount of Recycled Embankment Material (Deep mixing spoil)	400,000	m^3
Actual (Remaining) Quantity of Clay Borrow Required	441,000	m^3
Geogrid (Huesker Fortrac 400MP Geogrid, made of PVA = polyvinyl alcohol)	395,325	kg
Geogrid Transportation Distance	1,127	km
Number of Truck Trips to Deliver Geogrid from Charlotte	17	round trip
Average Transportation Distance for Clay Borrow	37	km
Total Number of Truckloads for Clay borrow	38,500	round trip
Total Diesel Fuel Consumed for Clay Extraction (as built)	210,000	L
Diesel Fuel Consumed for Clay Placement and Compaction	1,960,000	L
Total Diesel Fuel Consumed for Clay Extraction (No Recycled Embankment Material used)	400,000	L
Total Number of Truckloads for Clay borrow with no REM	73,400	round trip
Deep Mixing Return material for Disposal - Travel Distance	40	km
Deep Mixing Return Material for Disposal - Number of Truckloads	34,900	round trip

F.3 ESTIMATING QUANTITES FOR THE PREFABRICATED VERTICAL DRAINS OPTION

F.3.1 Fuel Consumed to Extract Clay Borrow

Equipment: Cat 340 or Cat 345 excavator

Production Rate: 100 – 144 CY/hr

[above information provided via personal communication by J. Gardner (2014)]

Cat 345 Specifications to be used in calculations (Caterpillar 2012):

Weight: 44,970 kg

Power: 257 kW = 345 hp at the flywheel

Fuel Consumption:

Load	Fuel Consumption (L/hr)
Low (20% - 40%)	14.5 – 30.5
Medium (40% - 60%)	29 – 45.6
High (60% - 80%)	43.3 - 61

For the activity, high medium load is reasonable. Assume an engine load of 60% on average.

1) Determine hourly fuel consumption from Eq. 3.4, using BSFC = 0.275 L/kW-hr:

$$Q_F = (257\ kW)(0.60)\left(0.275\frac{L}{kW * hr}\right)(1hr)$$

$$Q_F = 42.4\frac{L}{hr}$$

2) Compute the total hours of excavating, where the total volume of required clay borrow = 1,729,989 CY (URS Group 2008).

Production Rates:

100 CY/hr

144 CY/hr

Hours of operation for slow production:

$$\frac{1{,}729{,}989CY}{100\,\frac{CY}{hr}} = 17{,}300\ hrs$$

Hours of operation for fast production:

$$\frac{1{,}729{,}989CY}{144\,\frac{CY}{hr}} = 12{,}014\ hrs$$

3) Compute total fuel used to excavate borrow soil:

Slow production:

$$17{,}300hrs\left(42.4\frac{L}{hr}\right) = 733{,}520L$$

Fast production:

$$12{,}014\ hrs\left(42.4\frac{L}{hr}\right) = 509{,}394L$$

4) Estimate of average total fuel consumption for extraction of clay borrow soil:

Fuel Estimate = 622,000 L

F.3.2 Fuel Consumed to Construct the Embankment

Fuel Consumed to Degrade the Existing Levee

Information from the 2012 RS Means Heavy Construction Cost Data (RSMeans 2011):

- Soil stripping and stockpiling (RS Means section 31 14 13)
    - 300hp bulldozer can strip 1,650 CY/day

Assume:

- Cat D7E bulldozer (same as for fill spreading)
    - Power = 175 kW
    - Load Factor = 50%

1) Hourly fuel consumption (per Eq. 3.4):

$$Q_F = (175\ kW)(0.50)\left(0.275\frac{L}{kW * hr}\right)(1hr) = 24\frac{L}{hr}$$

2) Daily fuel consumption:

$$24\frac{L}{hr}(8hrs) = 192L$$

3) Estimate total fuel to degrade the levee [total of 125,718 CY of degrading (URS Group 2008)]:

$$\frac{192L}{1{,}650CY}(125{,}718CY) = 15{,}000L$$

Total diesel fuel to degrade the levee = 15,000 L

Fuel Consumed to Place and Compact the Embankment

Based on the same equipment and productivity assumptions described in section A.1.3, fuel consumption is 2,320 L per 1,300 CY of compacted embankment. Total embankment volume = 1,855,707 CY (URS Group 2008).

Estimated overall total fuel consumed:

$$\frac{2{,}320L}{1{,}300CY}(1{,}855{,}707CY) = 3{,}312{,}000L$$

Total fuel consumed to construct the embankment = 3,312,000 L.

F.3.3 Fuel Consumed to Install the Prefabricated Vertical Drains (PVDs)

Assumptions:

- Excavator mounted mast and mandrel.
- Production of 12,000 ft of drain per 10 hours

[Above based on information in a case study by Geo-Technics America (2009)].

- Excavator is a Cat 328D LCR
  - o 204 hp (152 kW) engine (Caterpillar 2012)
  - o Engine load factor = 50%

At LPV 111, total length of installed drains = 24,597,000 linear ft (URS Group 2008).

1) Hourly fuel consumption based on Eq. 3.4:

$$Q_F = (152\ kW)(0.50)\left(0.275\frac{L}{kW * hr}\right)(1hr) = 21\frac{L}{hr}$$

2) Installation time:

$$\frac{10hrs}{12{,}000ft}(24{,}597{,}000ft) = 20{,}500hrs$$

3) Total fuel consumption for installation of PVDs:

$$20{,}500hrs\left(21\frac{L}{hr}\right) = 430{,}500L$$

Total diesel fuel for installation of PVDs = 430,500 L

F.3.4 Fuel Consumed for Cement/Bentonite Slurry Wall Excavation

Assumptions:

- Slurry wall dimensions:
  - 64 ft deep
  - 3 ft wide
  - 27,330 ft long

- Excavation:
  - Method = clamshell bucket
  - Machine power = 450 kW (Liebherr HS855 crane)
  - Bucket capacity = 1 m^3
  - Cycle time (to excavate 1 bucket): 2 minutes
  - Engine load factor = 0.43 [7 cycle average from EPA (2010)]

1) Compute excavated volume:

$$64ft(3ft)(27{,}330ft)\left(\frac{1CY}{27ft^3}\right) = 194{,}347CY = 148{,}589m^3$$

2) Compute total excavation time for 1 machine:

$$148{,}589m^3\left(\frac{1\ bucket}{1m^3}\right)\left(\frac{2\ minutes}{1\ bucket}\right)\left(\frac{1\ hr}{60\ minutes}\right) = 4{,}953hrs$$

3) Compute the total fuel consumed using Eq. 3.4:

$$Q_F = (450\ kW)(0.43)\left(0.275\frac{L}{kW * hr}\right)(4{,}953hrs) = 263{,}600L$$

Total diesel fuel consumed for slurry wall excavation = 263,600 L

F.3.5 Cement/Bentonite Slurry Wall Waste

The excavated material from slurry wall construction was assumed to be disposed as waste. The volume of the slurry wall was assumed equal to the volume of waste disposed. The disposal facility was assumed to be 40 km from the site. Trucks hauling waste material were assumed to have a capacity of 15 CY.

Total number of truckloads of waste:

$$194{,}347CY\left(\frac{1\ truckload}{15CY}\right) = 12{,}960\ truckloads$$

F.3.6 Estimating Cement and Bentonite Quantities for the Slurry Wall

Assumptions:

- Total wall volume = 194,347 CY (no overcut)
- Slurry cement/water ratio by mass = 18%
- Slurry bentonite/water ratio by mass = 5%
- Cement specific gravity = 3.15
- Bentonite specific gravity = 2.35
- Water specific gravity = 1.0; density = ρ = 1,000 kg/m^3

Calculations:

1) Determine the density of cement and bentonite:

$$\rho_{cement} = 3.15(1{,}000kg) = 3{,}150\frac{kg}{m^3}\ (solids)$$

$$\rho_{bentonite} = 2.35(1{,}000kg) = 2{,}350\frac{kg}{m^3}\ (solids)$$

2) Mix design – 1,000 kg water (= 1,000 L water = 1 m^3). Compute the amount of cement and bentonite based on the w/c and w/b ratios:

$$Cement: 0.18(1{,}000kg) = 180\ kg\ Cement$$

$$Bentonite: 0.05(1{,}000kg) = 50\ kg\ Bentonite$$

3) Compute the volume of cement and bentonite solids in the mix with 1,000 kg (1 m^3) of water:

$$Volume\ of\ Cement\ Solids = \frac{180kg}{3{,}150\frac{kg}{m^3}} = 0.057m^3$$

$$Volume\ of\ Bentonite\ Solids = \frac{50kg}{2{,}350\frac{kg}{m^3}} = 0.021m^3$$

4) Compute the total volume, mass and density of slurry for 1,000 kg (1 m^3) of water:

$$Volume\ of\ Slurry = 1m^3 + 0.057m^3 + 0.021m^3 = 1.078m^3$$

$$Mass\ of\ Slurry = 1{,}000kg + 180kg + 50kg = 1{,}230kg$$

$$Density\ of\ Slurry = \frac{1{,}230kg}{1.078m^3} = 1{,}141\frac{kg}{m^3}$$

5) Compute the quantity of each material (water, cement, bentonite) per 1 m^3 of slurry:

$$1m^3\ Slurry = 1{,}141kg = Water + Cement + Bentonite$$

$$1m^3\ Slurry = 1{,}141kg = Water + 0.18(Water) + 0.05(Water)$$

$$1m^3\ Slurry = 1{,}141kg = 1.23(Water)$$

$$Mass\ of\ Water\ per\ 1m^3\ of\ Slurry = 927.6\ kg$$

$$Mass\ of\ Cement\ per\ 1m^3\ of\ Slurry = 0.18(927.6\ kg) = 167kg$$

$$Mass\ of\ Bentonite\ per\ 1m^3\ of\ Slurry = 0.05(927.6\ kg) = 46.4kg$$

6) Compute total material quantities from total required volume of slurry. Total required volume of slurry = 194,347 CY = 148,589 m^3 ≈ 148,600 m^3:

$$Water = 927.6\frac{kg}{m^3}(148{,}600m^3) = 137{,}841{,}360\ kg = 137{,}841{,}360L \approx 137{,}841{,}000L$$

$$Cement = 167\frac{kg}{m^3}(148{,}600m^3) = 24{,}816{,}200\ kg \approx 24{,}816{,}000kg$$

$$Bentonite = 46.4\frac{kg}{m^3}(148{,}600m^3) = 6{,}895{,}040\ kg \approx 6{,}895{,}000kg$$

Overall quantities: 137,841,000 L of water, 24,816,000 kg of cement, and 6,895,000 kg of bentonite.

F.3.7 Cement and Bentonite Transportation

Cement Transportation from Local Plant

Distance = 3.2 km by truck, 1,130 km by barge from Missouri to local plant

Assumptions:

- Cement tanker carries 23 tonnes

$$\frac{24{,}816{,}000kg}{23{,}000\frac{kg}{truckload}} = 1{,}079\ truckloads$$

Number of truckloads to deliver cement to the site = 1,079.

Bentonite Transportation from Wyoming

Distance = 3,058 km by truck

Heavy duty Class 8 truck payload capacity = 24,494 kg (Davis et al. 2012)

$$6{,}895{,}000kg\left(\frac{1\ truck}{24{,}494kg}\right) = 282\ truckloads$$

Number of truckloads to deliver bentonite to the site = 282.

F.3.8 Wick Drains, Geonet, Separator Fabric and Geogrid Quantities

Polypropylene Wick Drains

Wick Drains Mass

Assume:

- Roll = 305 m long; 23.6 kg (similar to Amerdrain)
- Required length = 24,597,000 linear ft (URS Group 2008).

Compute the mass of polypropylene wick drains:

$$24{,}597{,}000ft\left(\frac{1m}{3.28084ft}\right)\left(\frac{1\ roll}{305m}\right)\left(\frac{23.6kg}{roll}\right) = 580{,}109kg$$

Total mass of polypropylene wick drains = 580,100 kg.

Wick Drains Transportation from North Carolina

Distance = 1,175 km

Heavy duty Class 8 truck payload capacity = 24,494 kg (Davis et al. 2012)

$$580{,}100kg\left(\frac{1\ truck}{24{,}494kg}\right) = 24\ truckloads$$

Number of truckloads to deliver wick drains to site = 24.

Geonet

Geonet Mass

Take measurements on a sample of typical high density polyethylene (HDPE) geonet:

- Sample dimensions:
  - Average Mass = 14.05 g
  - Thickness = 6.12 mm
  - Average Width = 102.80 mm
  - Average Length = 126.26 mm

1) Compute area of the sample:

$$(126.26mm)(102.80mm) = 12{,}980mm^2 = 0.01298m^2$$

2) Compute the mass/area:

$$\frac{14.05g}{0.01298m^2} = 1{,}082\frac{g}{m^2} = 1.082\frac{kg}{m^2}$$

3) Compute total mass of geonet based on a required area of 789,837 yd^2 (URS Group 2008):

$$789{,}837SY\left(\frac{1m^2}{1.19599SY}\right)\left(1.082\frac{kg}{m^2}\right) = 714{,}558kg$$

Total mass of HDPE geonet = 714,600 kg.

Geonet Transportation from Texas

Distance = 604 km

Heavy duty Class 8 truck payload capacity = 24,494 kg (Davis et al. 2012)

$$714{,}600kg\left(\frac{1\ truck}{24{,}494kg}\right) = 30\ truckloads$$

Number of truckloads to deliver geonet to the site = 30.

Separator Fabric

Separator Fabric Mass

Assume:

- Fabric is polypropylene, GSE NW8 or equivalent
  - 270 g/m^2 (GSE 2014)
- 847,230 yd^2 of fabric needed (URS Group 2008)

Compute the total mass of separator fabric:

$$847{,}230SY\left(\frac{1m^2}{1.19599SY}\right)\left(0.270\frac{kg}{m^2}\right) = 191{,}265kg$$

Total mass of polypropylene separator fabric = 191,300 kg.

Separator Fabric Transportation from Texas

Distance = 604 km

Heavy duty Class 8 truck payload capacity = 24,494 kg (Davis et al. 2012)

$$191{,}300kg\left(\frac{1\ truck}{24{,}494kg}\right) = 8\ truckloads$$

Number of truckloads to deliver separator fabric to the site = 8.

Geogrid

Geogrid Mass

Assume:

- Huesker Fortrac 200 geogrid, 715 g/m^2 (Huesker 2015)

Compute the total mass of 3 layers of geogrid with a total area of 2,566,287 yd^2 (URS Group 2008):

$$2{,}566{,}287SY\left(\frac{1m^2}{1.19599SY}\right)\left(0.715\frac{kg}{m^2}\right) = 1{,}534{,}206kg$$

Total mass of geogrid (general plastic) = 1,534,200 kg.

Geogrid Transportation from North Carolina

Distance = 1,130 km

Heavy duty Class 8 truck payload capacity = 24,494 kg (Davis et al. 2012)

$$1{,}534{,}200kg\left(\frac{1\ truck}{24{,}494kg}\right) = 63\ truckloads$$

Number of truckloads to deliver geogrid to the site = 63.

F.4 SUMMARY OF QUANTITIES FOR THE PREFABRICATED VERTICAL DRAINS OPTION

Table F.2 contains a summary of all quantities of materials, fuel, haul distances and number of trips for the SEEAM analysis. Distances were obtained using Google Maps.

Table F.2 LPV 111 Prefabricated Vertical Drains option: total quantities of materials, fuel, haul distances and number of trips.

Material	Quantity	Unit
Polypropylene Wick Drains (Amerdrain - Roll = 305m, 23.6kg)	580,100	kg
Wick Drains Transportation Distance (from manufacturer in Monroe, NC)	1,175	km
Wick Drains Total Number of Truckloads	24	round trip
Geonet Drainage Media (assume 1.082 kg/m^2 based on measured sample (6.12mm thick by 102.80mm wide by 126.26mm long, 14.05g))	714,600	kg
Geonet Transportation Distance (from manufacturer in Houston, TX)	604	km
Geonet Total Number of Truckloads	30	round trip
Geogrid (3 layers) (assume Huesker Fortrac 200 geogrid - 715g/m^2, general plastic)	1,534,200	kg
Geogrid Transportation Distance	1,130	km
Geogrid Total Number of Truckloads	63	round trip
Geotextile Separator Fabric (assume GSE NW8 - Polypropylene, 270g/m2)	191,300	kg
Geotextile Transportation Distance (from manufacturer in Houston, TX)	604	km
Geotextile Total Number of Truckloads	8	round trip
Cement	24,816,000	kg
Distance from Cement Supplier/Batch Plant (Buzzi Unicem USA) to the Site	3.2	km
Number of 23 tonne Truckloads of Cement Delivered to the Site	1,079	round trips
Cement Shipping Distance to Buzzi Unicem Plant by Barge (from Festus, MO)	1,130	km
Bentonite	6,895,000	kg
Distance from Bentonite Supplier in Wyoming to the Site	3,058	km
Number of Truckloads of Bentonite Delivered	282	round trip
Water	137,841,000	L
Cement/Bentonite Cutoff Wall Waste Material (for disposal)	148,589	m^3
Excavated C/B Wall Material for Disposal - Transport Distance	40	km
Excavated C/B Wall Material for Disposal - Number of Truckloads	12,960	round trip
Total Quantity of Clay Borrow	1,322,671	m^3
Average Transportation Distance for Clay Borrow	37	km
Total Number of Truckloads for Clay Borrow	115,333	round trip
Diesel Fuel Consumed to Install PVDs	430,500	L
Diesel Fuel Consumed to Extract Clay Borrow	622,000	L
Diesel Fuel Consumed to Excavate the C/B Wall	263,600	L
Diesel Fuel Consumed for Degrading the Levee	15,000	L
Diesel Fuel Consumed to Place Embankment Fill	3,312,000	L

F.5 ESTIMATING QUANTITIES FOR THE PILE SUPPORTED REINFORCED CONCRETE T-WALL OPTION

F.5.1 Material Quantities

Concrete and Reinforcing Steel Quantities

1) Compute the cross sectional area (*A*) of the T-Wall (see Figure 4.4 for dimensions):

$$4ft(20ft) + 4ft(13.5ft) - 0.5(2ft)(13.5ft) = 120.5ft^2 = 11.19m^2$$

2) Assume the area of steel (A_s) = 2% of the total cross sectional area, A:

$$A_s = 0.02(11.19m^2) = 0.2238m^2$$

3) Compute the area of concrete (A_c):

$$A_c = 11.19m^2 - 0.2238m^2 = 10.9662m^2$$

4) Compute quantity of concrete. Length of protection = 27,330 ft = 8,330 m (URS Group 2008):

$$10.9662m^2(8{,}330m) = 91{,}348m^3$$

5) Compute quantity of steel reinforcement. Length of protection = 27,330 ft = 8,330 m (URS Group 2008), density of steel = 7,850 kg/m^3:

$$0.2238m^2(8{,}330m)\left(7{,}850\frac{kg}{m^3}\right) = 14{,}634{,}394kg$$

Total volume of concrete = 91,350 m^3.

Total mass of reinforcing steel = 14,630,000 kg.

Steel Pile Quantities

Foundation piles: 4, HP14x73 steel piles at 7.5ft (2.286 m) on center along the levee alignment.

- Foundation pile length = 138 ft = 42.06 m
- Pile weight = 73 lbs/ft = 108.6 kg/m

Sheet pile: PZ-22, continuous along the levee alignment.

- Sheet pile length (depth) = 68.75 ft = 20.95 m
- Sheet pile length along levee alignment = 22 inches = 0.559 m
- Pile weight = 40.3 lb/ft = 60 kg/m (Skyline Steel 2015)

1) Compute the total number of steel HP14x73 foundation piles:

$$\frac{8{,}330m}{2.286m}(4) = 14{,}576\, piles$$

2) Compute the total length of steel HP14x73 foundation piles:

$$14{,}576\, piles(42.06m) = 613{,}067m$$

3) Compute the total mass of steel HP14x73 foundation piles:

$$613{,}067m\left(108.6\frac{kg}{m}\right) = 66{,}579{,}076kg \approx 66{,}600{,}000kg$$

4) Compute total number of PZ-22 sheet piles:

$$\frac{8{,}330m}{0.559\frac{m}{pile}} = 14{,}902\, sheet\ piles$$

5) Compute the total length of PZ-22 sheet piles:

$$14{,}902\, piles(20.95m) = 312{,}197m$$

6) Compute the total mass of steel PZ-22 sheet piles:

$$312{,}197m\left(60\frac{kg}{m}\right) = 18{,}731{,}820kg \approx 18{,}730{,}000kg$$

Total steel HP14x73 foundation piles = 66,600,000 kg.

Total steel PZ-22 sheet piles = 18,730,000 kg.

F.6 SUMMARY OF MATERIAL QUANTITIES FOR THE PILE SUPPORTED REINFORCED CONCRETE T-WALL OPTION

Table F.3 contains a summary of all quantities of materials, fuel, haul distances and number of trips for the SEEAM analysis.

Table F.3 Material quantities for the pile supported Reinforced Concrete T-wall option.

Material	Quantity	Unit
Concrete	91,350	m^3
Steel Rebar	14,630,000	kg
Number of Steel Piles (HP14x73)	14,576	piles
Length of Steel Piles (HP14x73)	613,053	m
Mass of Steel Piles (HP14x73)	66,600,000	kg
Number of Steel Sheet Piles (PZ-22)	14,902	piles
Total Length of Steel Sheet Piles (PZ-22)	312,189	m
Mass of Steel Sheet Piles (PZ-22)	18,730,000	kg

F.7 MAGNITUDE OF LPV 111 EMISSIONS – CALCULATIONS FOR THE PICKUP TRUCK EXAMPLE

Known:

- As built, LPV 111 = 147,000 tonnes of CO_2 (Ch. 4)
- Gasoline emissions = 2.83 kg CO_2/L (Ch. 3)
- Average distance to the moon = 384,400 km (NASA 2015)

Assume:

- Pickup truck fuel economy = 15 miles/gallon = 6.38 km/L
- Pickup truck useful life = 322,000 km (200,000 miles)

1) Compute volume of gasoline required to generate 147,000 tonnes of CO_2 emissions:

$$147{,}000{,}000\ kg\ CO_2\left(\frac{1L}{2.83kg\ CO_2}\right) = 51{,}943{,}463L$$

2) Compute the distance this much fuel can propel a 15 mpg (6.38 km/L) pickup truck:

$$51{,}943{,}463L\left(6.38\frac{km}{L}\right) = 331{,}400{,}442km \approx 331{,}400{,}000km$$

3) Compute the number of round trips to the moon a pickup truck can make:

$$\frac{331{,}400{,}000km}{2(384{,}400km)} = 431.1\ round\ trips \approx 432\ round\ trips$$

4) Compute the number of useful truck lifetimes it is to travel this distance:

$$\frac{331{,}400{,}000km}{322{,}000\frac{km}{lifetime}} = 1{,}029.1\ pickup\ truck\ lifetimes$$

A gasoline pickup truck would need to drive 432 round trips to the moon to generate as much CO_2 emissions as the construction at LPV 111. In reality, traveling this distance is equivalent to the operational lifetimes of about 1,030 pickup trucks.

F.8 DEMONSTRATING THE VALIDITY OF THE SEEAM BOUNDARIES BY EQUIPMENT EMBODIED ENERGY

Assume:

- All equipment made of virgin steel.

- Useful life of equipment = 10 projects.

- Deep Soil Mixing Equipment:
    - 8 rigs, ≈ 100 tonnes each
    - 8 grout plants, ≈ 38 tonnes (total)
        - 1 grout mixer, ≈ 4 tonnes
        - 1 agitator, 10m^3, ≈ 4 tonnes
        - 2 grout pumps, ≈ 6 tonnes each
        - 2 cement silos, ≈ 6 tonnes each
        - 1 water tank, 75,000 L, ≈ 6 tonnes

Known Data:

- Deep Soil Mixing SEEAM results (Ch. 4 and Appendix E.5):
    - 998,000 GJ of embodied energy.
    - 134,500 tonnes of CO_2 emissions.

- Embodied Energy coefficient for virgin steel = 35.4 MJ/kg (Table 4.1)

- CO_2 emissions coefficient for virgin steel = 2.71 kg CO_2/kg (Table 4.1)

1) Determine the total mass of all equipment:

$$8 rigs\left(\frac{100\ tonnes}{rig}\right) + 8\ plants\left(\frac{38\ tonnes}{plant}\right) = 1{,}104\ tonnes\ of\ equipment$$

2) Compute the total embodied energy from equipment manufacture:

$$1{,}104{,}000 kg\left(\frac{35.4 MJ}{kg}\right) = 39{,}081{,}600 MJ \approx 39{,}100 GJ$$

3) Compute the total CO_2 emissions from equipment manufacture:

$$1{,}104{,}000 kg\left(\frac{2.71 kg\ CO_2}{kg}\right) = 2{,}991{,}840 kg\ CO_2 \approx 3{,}000\ tonnes\ CO_2$$

Total embodied energy in manufacturing 1,104 tonnes of equipment = 39,100 GJ.

Total CO_2 emissions from manufacturing 1,104 tonnes of equipment = 3,000 tonnes.

4) Divide total embodied energy and CO_2 emissions from equipment manufacture over 10 projects:

$$Embodied\ Energy = \frac{39{,}100GJ}{10\ projects} = 3{,}910\frac{GJ}{project}$$

$$CO_2\ Emissions = \frac{3{,}000\ tonnes\ CO_2}{10\ projects} = 300\ \frac{tonnes\ CO_2}{project}$$

5) Compute the proportion of total embodied energy and CO_2 emissions attributable to equipment manufacturing, based on a useful life of 10 projects:

$$\%\ of\ Deep\ Mixing\ Embodied\ Energy = \frac{3{,}910GJ}{998{,}000GJ}(100\%) = 0.4\%$$

$$\%\ of\ Deep\ Mixing\ CO_2\ Emissions = \frac{300\ tonnes\ CO_2}{134{,}500\ tonnes\ CO_2}(100\%) = 0.2\%$$

If equipment has a useful life of 10 projects, it amounts to 0.4% of total project embodied energy and 0.2% of total project CO_2 emissions. Even if manufacturing doubled the energy and emissions from virgin steel, equipment would still constitute less than 1% of total project embodied energy and CO_2 emissions.

6) Compute the proportion of total embodied energy and CO_2 emissions attributable to equipment manufacturing, based on a useful life for equipment of 1 project (LPV 111):

$$\%\ of\ Deep\ Mixing\ Embodied\ Energy = \frac{39{,}100GJ}{998{,}000GJ}(100\%) = 3.9\%$$

$$\%\ of\ Deep\ Mixing\ CO_2\ Emissions = \frac{3{,}000\ tonnes\ CO_2}{134{,}500\ tonnes\ CO_2}(100\%) = 2.2\%$$

If equipment were manufactured and used for LPV 111 only, the manufacturing process would constitute less than 5% of the total embodied energy and CO_2 emissions associated with construction activities.

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Appendix G: Development of the Embodied Energy and CO_2 Emissions Coefficients of Bentonite

Unlike the embodied energy and CO_2 emissions coefficients for other materials which are from published sources, the coefficients for bentonite have been derived based on an economic input-output life cycle analysis (EIO-LCA) using the online EIO-LCA tool developed by Carnegie Mellon University Green Design Institute (2008). The EIO-LCA for bentonite was conducted using the data and assumptions of Jiang et al. (2011), who included bentonite well drilling mud in their LCA of Marcellus shale gas.

G.1 WELL DRILLING MUD EIO-LCA

G.1.1 Assumptions for EIO-LCA of Well Drilling Mud

The following assumptions were used by Jiang et al. (2011) to include bentonite well drilling mud in EIO-LCA:

- 13,000 kg of bentonite per well
- $1,100 cost of bentonite per well (in 2002 dollars)

G.1.2 Results of EIO-LCA for Well Drilling Mud by Jiang et al. (2011)

The following results were obtained by Jiang et al. (2011) for the bentonite:

- 1,290 tonnes CO_{2eq}/$1,000,000
- 1.4 tonnes CO_{2eq}/Well

G.1.3 Verification of Jiang et al. (2011) Results

In order to confirm the correct usage of the EIO-LCA tool (Carnegie Mellon University Green Design Institute 2008), selections were made to verify the results obtained by Jiang et al. (2011).

Using the EIO-LCA online tool, the following selections were made:

1) US 2002 benchmark producer price model.

2) Make selections:

   a. Select broad sector from the drop down list, “Plastic, rubber and non-metallic mineral products.”

   b. Select detailed sector from the drop down list, “Clay and non-clay refractory manufacturing.”

3) Select $1,000,000 as an amount of economic activity.

4) Select Greenhouse Gases for results from the drop down list.

Clicking “Run Model” yields results of 1,290 tonnes CO_{2eq}/$1,000,000, which agrees with the results from Jiang et al. (2011). See Table G.1 for complete total greenhouse gas emissions results for all sectors from the EIO-LCA tool.

Table G.1 Results from the EIO-LCA online tool for greenhouse gas emissions per $1,000,000 of clay mineral processing. Data from Carnegie Mellon University Green Design Institute (2008), using the assumptions of Jiang et al. (2011).

Emissions Type	Total Emissions (tonnes CO_{2eq})
Total CO_{2eq}	1,290
Fossil CO_2	1,100
Process CO_2	96.2
Methane (CH_4)	71.8
Nitrous Oxide (N_2O)	10.1
Hydroflourocarbon (HFC)/Perflourocarbon (PFC)	12.8

G.2 DETERMINING A BENTONITE CO_2 EMISSIONS COEFFICIENT FROM THE EIO-LCA

In addition to the total of 1,290 tonnes CO_{2eq}/$1,000,000 output from the tool, the following information on greenhouse gas emissions is also generated:

Methane (CH_4) = 71.8 tonnes CO_{2eq}/$1,000,000

Nitrous Oxide (N_20) = 10.1 tonnes CO_{2eq}/$1,000,000

HFC/PFC = 12.8 tonnes CO_{2eq}/$1,000,000

Total non-CO_2 greenhouse gases: = 94.7 tonnes CO_{2eq}/$1,000,000

$$\frac{71.8\ tonnes\ CO_{2eq}}{\$1{,}000{,}000}+\frac{10.1\ tonnes\ CO_{2eq}}{\$1{,}000{,}000}+\frac{12.8\ tonnes\ CO_{2eq}}{\$1{,}000{,}000}=\frac{94.7\ tonnes\ CO_{2eq}}{\$1{,}000{,}000}$$

Now, total CO_2 = 1,195.3 tonnes CO_2/$1,000,000

$$\frac{1{,}290\ tonnes\ CO_{2eq}}{\$1{,}000{,}000}-\frac{94.7\ tonnes\ CO_{2eq}}{\$1{,}000{,}000}=\frac{1{,}195.3\ tonnes\ CO_{2}}{\$1{,}000{,}000}$$

Using the cost, the amount of bentonite required per well and the CO_2 emissions per $1,000,000 from the EIO-LCA, it is possible to determine a CO_2 emissions coefficient per unit mass of bentonite:

$$\frac{1{,}195.3\ tonnes\ CO_2}{\$1{,}000{,}000}\left(\frac{\$1{,}100}{1\ well}\right)\left(\frac{1\ well}{13{,}000kg\ bentonite}\right)\left(\frac{1{,}000kg}{tonne}\right)=0.101\frac{kg\ CO_2}{kg\ bentonite}$$

Bentonite CO_2 emissions coefficient = 0.101 kg CO_2/kg

G.3 DETERMINING A BENTONITE EMBODIED ENERGY COEFFICIENT FROM THE EIO-LCA

Using the same assumptions in the EIO-LCA tool and selecting “Energy” for the results in step 4 (described in section G.1.3), the total energy can be obtained. In this case, the total energy is 19.5 TJ/$1,000,000. See Table G.2.

Table G.2 Results from the EIO-LCA online tool for energy associated with \$1,000,000 of clay mineral processing. Data from Carnegie Mellon Green Design Institute (2008).

Energy Type	Total Energy (TJ)
Total Energy	19.5
Coal	5.06
Natural Gas	8.37
Petroleum	3.03
Bio/Waste	0.752
Non-fossil electricity	2.32

Similar to CO_2, it is possible to determine the amount of energy per unit mass of bentonite from the output of the EIO-LCA.

$$19.5TJ = 19{,}500GJ = 19{,}500{,}000MJ$$

$$\frac{19{,}500{,}000MJ}{\$1{,}000{,}000}\left(\frac{\$1{,}100}{1\ well}\right)\left(\frac{1\ well}{13{,}000kg\ bentonite}\right) = 1.65\frac{MJ}{kg\ bentonite}$$

Bentonite embodied energy coefficient = 1.65 MJ/kg

G.4 REFERENCES

Carnegie Mellon University Green Design Institute (2008). "Economic input-output life cycle assessment (EIO-LCA)." US 2002 National Producer Price Model, (April 28, 2014). <http://www.eiolca.net/>.

Jiang, M., Griffin, M. W., Hendrickson, C., Jaramillo, P., VanBriesen, J., and Venkatesh, A. (2011). "Life cycle greenhouse gas emissions of Marcellus shale gas." *Environmental Research Letters*, 6(3).

Appendix H: Development of Rail and Water Freight Coefficients

H.1 WATER FREIGHT

CO_2 emissions = 0.042 kg/ton-mile (EPA 2014)

Energy = 217 BTU/ton-mile for 2010 (Davis et al. 2012)

1) Convert CO_2 emissions coefficient to kg/tonne-km:

$$0.042\frac{kg\ CO_2}{ton * mile}\left(\frac{1\ mile}{1.60934\ km}\right)\left(\frac{1\ ton}{2{,}000\ lb}\right)\left(\frac{2.20462\ lb}{1\ kg}\right)\left(\frac{1{,}000\ kg}{1\ tonne}\right) = 0.029\frac{kg\ CO_2}{tonne * km}$$

2) Convert energy coefficient to MJ/tonne-km:

$$217\frac{BTU}{ton * mile}\left(\frac{1\ mile}{1.60934\ km}\right)\left(\frac{1\ ton}{2{,}000\ lb}\right)\left(\frac{2.20462\ lb}{1\ kg}\right)\left(\frac{1{,}000\ kg}{1\ tonne}\right)\left(\frac{1.055 * 10^{-3} MJ}{1\ BTU}\right)$$

$$= 0.157\frac{MJ}{tonne * km}$$

Water Freight CO_2 Emissions Coefficient = 0.029 kg/tonne-km

Water Freight Energy Coefficient = 0.157 MJ/tonne-km

H.2 RAIL FREIGHT

CO_2 emissions = 0.026 kg/ton-mile (EPA 2014)

Energy: Derived by converting CO_2 emissions to a quantity of diesel fuel using diesel emissions coefficients from Shillaber et al. (2014), then converting a quantity of diesel into energy using diesel energy coefficients from Shillaber et al. (2014).

1) Convert CO_2 emissions coefficient to kg/tonne-km:

$$0.026\frac{kg\ CO_2}{ton * mile}\left(\frac{1\ mile}{1.60934\ km}\right)\left(\frac{1\ ton}{2{,}000\ lb}\right)\left(\frac{2.20462\ lb}{1\ kg}\right)\left(\frac{1{,}000\ kg}{1\ tonne}\right) = 0.018\frac{kg\ CO_2}{tonne * km}$$

2) Convert CO_2 emissions to a quantity of Diesel fuel:

$$0.018 \frac{kg\ CO_2}{tonne * km}\left(\frac{1L}{3.25\ kg\ CO_2}\right) = 0.00554 \frac{L\ Diesel}{tonne * km}$$

3) Convert quantity of Diesel fuel into energy:

$$0.00554 \frac{L\ Diesel}{tonne * km}\left(\frac{43.0\ MJ}{1L\ Diesel}\right) = 0.238 \frac{MJ}{tonne * km}$$

Rail Freight CO_2 Emissions Coefficient = 0.018 kg/tonne-km

Rail Freight Energy Coefficient = 0.238 MJ/tonne-km

H.3 REFERENCES

Davis, S. C., Diegel, S. W., and Boundy, R. G. (2012). *Transportation Energy Data Book: Edition 31*. Report No. ORNL-6987. U.S. Department of Energy Vehicle Technologies Program; Office of Energy Efficiency and Renewable Energy, U.S. Government.

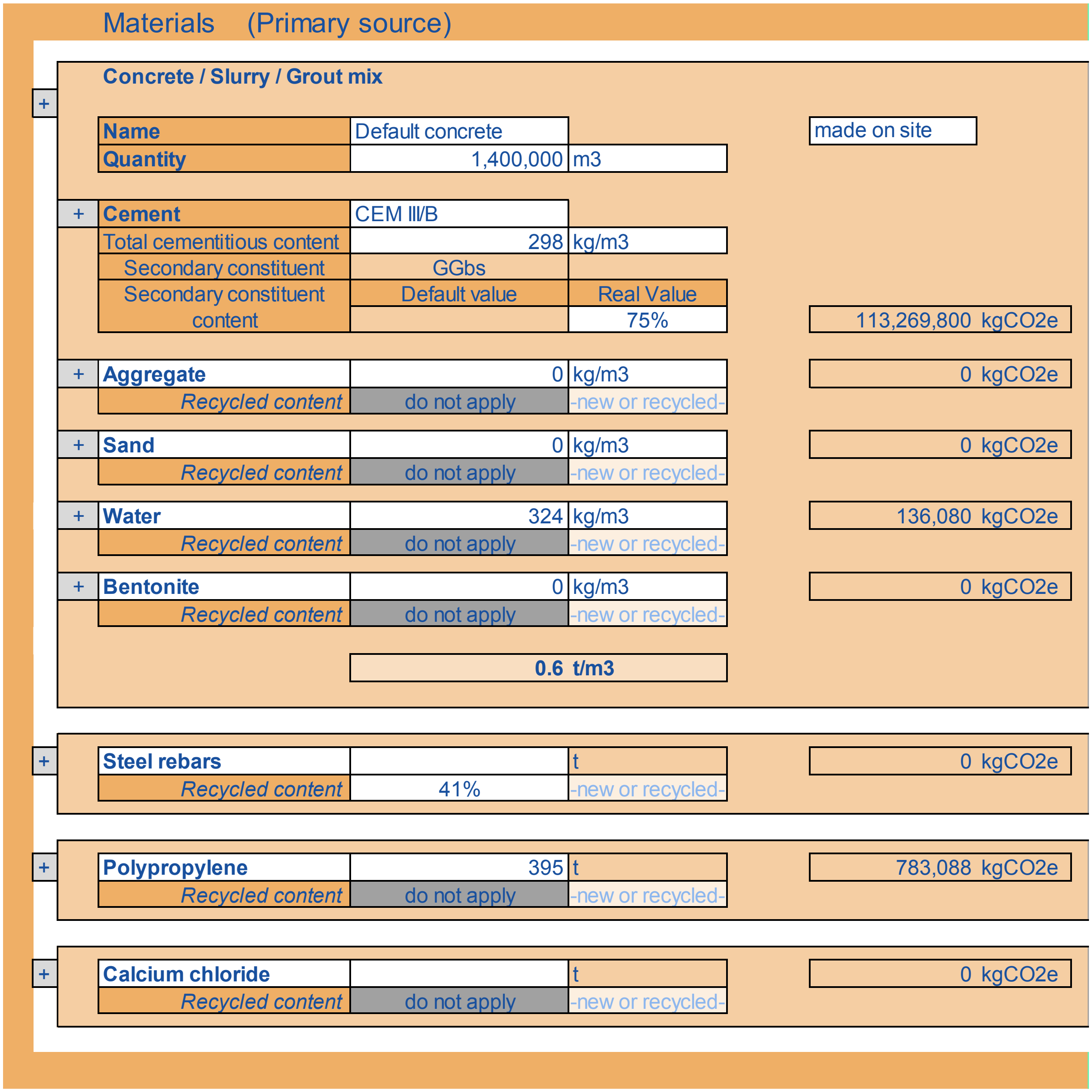
EPA (2014). "Emission factors for greenhouse gas inventories." <http://www.epa.gov/climateleadership/documents/emission-factors.pdf>. (April 21, 2014).

Shillaber, C. M., Mitchell, J. K., and Dove, J. E. (2014). "Assessing environmental impacts in geotechnical construction: insights from the fuel cycle." *Proc., GeoCongress 2014, Geo-Characterization and Modeling for Sustainability*, Geotechnical Special Publication No. 234, ASCE, Reston, VA, 3516-3525.

Appendix I: EFFC-DFI Geotechnical Carbon Calculator Analysis of Deep Mixing at LPV 111

This Appendix contains screen shots of the worksheets in the EFFC-DFI Geotechnical Carbon Calculator, v. 2.3, from an analysis of LPV 111 deep soil mixing. The EFFC-DFI Geotechnical Carbon Calculator is a macro-enabled Microsoft Excel workbook. In this analysis, the recommended database of coefficients was used.

I.1 SCREEN SHOTS OF THE INPUT AND OUTPUT OF THE EFFC-DFI GEOTECHNICAL CARBON CALCULATOR



Materials (Primary source)

Concrete / Slurry / Grout mix

Name	Default concrete		made on site
Quantity	1,400,000	m3	
Cement	CEM III/B		
Total cementitious content	298	kg/m3	
Secondary constituent	GGbs		
Secondary constituent content	Default value	Real Value	
		75%	113,269,800 kgCO2e
Aggregate	0	kg/m3	0 kgCO2e
Recycled content	do not apply	-new or recycled-	
Sand	0	kg/m3	0 kgCO2e
Recycled content	do not apply	-new or recycled-	
Water	324	kg/m3	136,080 kgCO2e
Recycled content	do not apply	-new or recycled-	
Bentonite	0	kg/m3	0 kgCO2e
Recycled content	do not apply	-new or recycled-	
	0.6 t/m3		
Steel rebars		t	0 kgCO2e
Recycled content	41%	-new or recycled-	
Polypropylene	395	t	783,088 kgCO2e
Recycled content	do not apply	-new or recycled-	
Calcium chloride		t	0 kgCO2e
Recycled content	do not apply	-new or recycled-	

Figure I.1 EFFC-DFI Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing materials input.

Freight (Secondary source)

Distance	0	km	Type	Road - Rigid >17t	Load	8	m3	175000	travels	empty-return rate	100%	1.18	0	kgCO2e
Distance	3.2	km	Type	Road - Articulated >33t	Load	23	t	18140	travels	empty-return rate	100%	1.21	140,516	kgCO2e
Distance	37	km	Type	Road - Articulated >33t	Load	15	t	77000	travels	empty-return rate	100%	1.21	######	kgCO2e
Distance	0	km	Type	Road - Articulated >33t	Load	15	t	0	travels	empty-return rate	100%	1.21	0	kgCO2e
Distance	0	km	Type	Road - Rigid >3.5-7.5t	Load	1.0	t	448079	travels	empty-return rate	100%	0.72	0	kgCO2e
Distance	0	km	Type	Road - Articulated >33t	Load	15	t	0	travels	empty-return rate	100%	1.21	0	kgCO2e
Distance	0	km	Type	Road - Articulated >33t	Load	15	t	0	travels	empty-return rate	50%	1.21	0	kgCO2e
Distance	1130	km	Type	Road - Articulated >33t	Load	24	t	17	travels	empty-return rate	50%	1.21	34,876	kgCO2e
Distance	0	km	Type	Road - Articulated >33t	Load	15	t	0	travels	empty-return rate	50%	1.21	0	kgCO2e

Figure I.2 EFFC-DFI Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing freight input.

Energy (Primary source)

+	**Simplified ratio**	OFF	Default	0	kgCO2e
+	**Diesel**	6,072,000	liter	21,876,202	kgCO2e
+	**Network electricity**		kWh	0	kgCO2e

Figure I.3 EFFC-DFI Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing energy input.

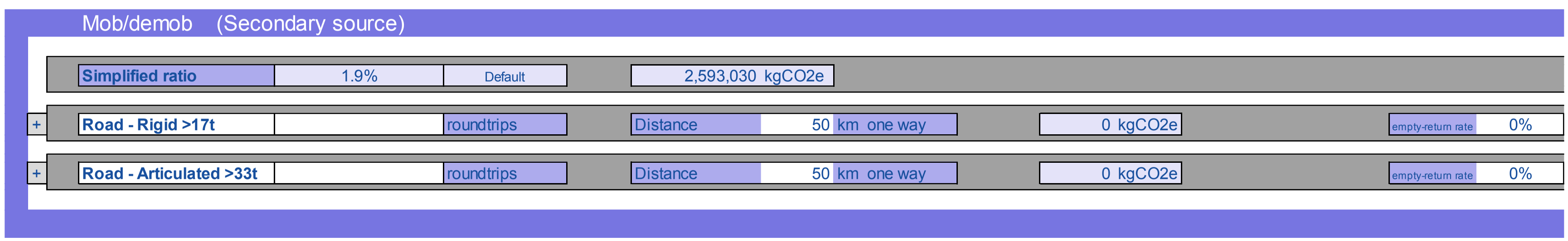


Figure I.4 EFFC-DFI Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing mobilization and demobilization input, default ratio used in this analysis.

People's transportation (Secondary source)

	Coming by	Number of roundtrips	every X day(s)	Average distance (km one way)	
+	Car	0	1	50	0 kgCO2e
+	Bus		1	50	0 kgCO2e
+	Train		5	300	0 kgCO2e

+	Train		pkm	0 kgCO2e

Figure I.5 EFFC-DFI Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing people's transportation input.

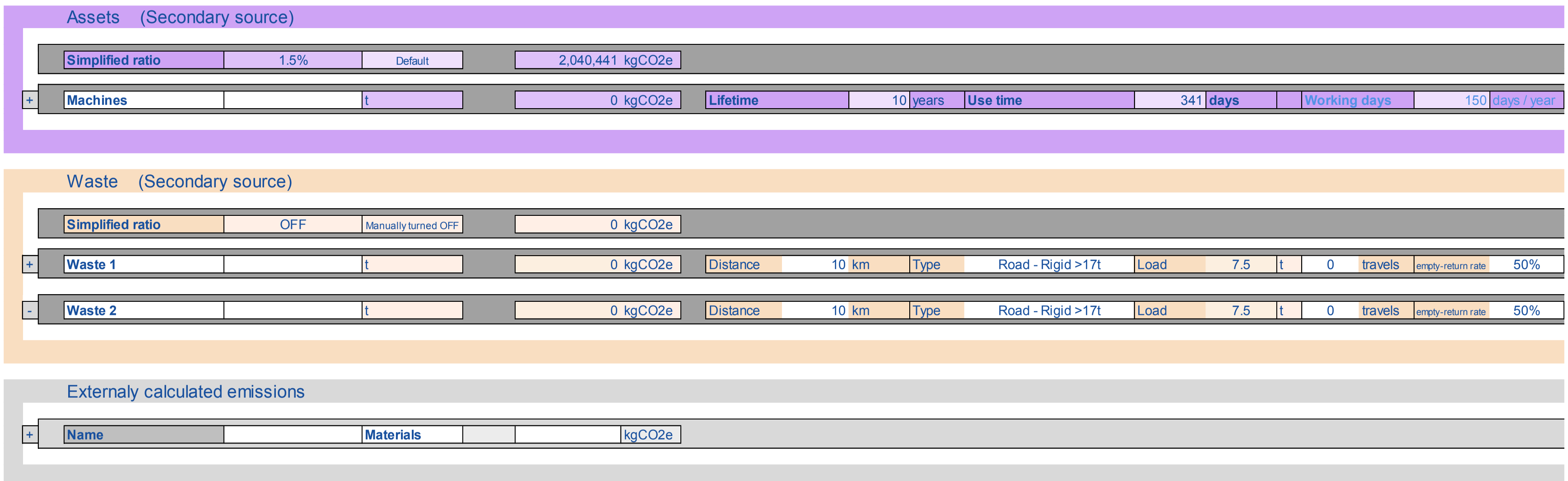


Figure I.6 Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing assets (equipment manufacturing), waste and externally calculated emissions input, default ratios used in this analysis. Waste turned off since the spoil was recycled as embankment fill.

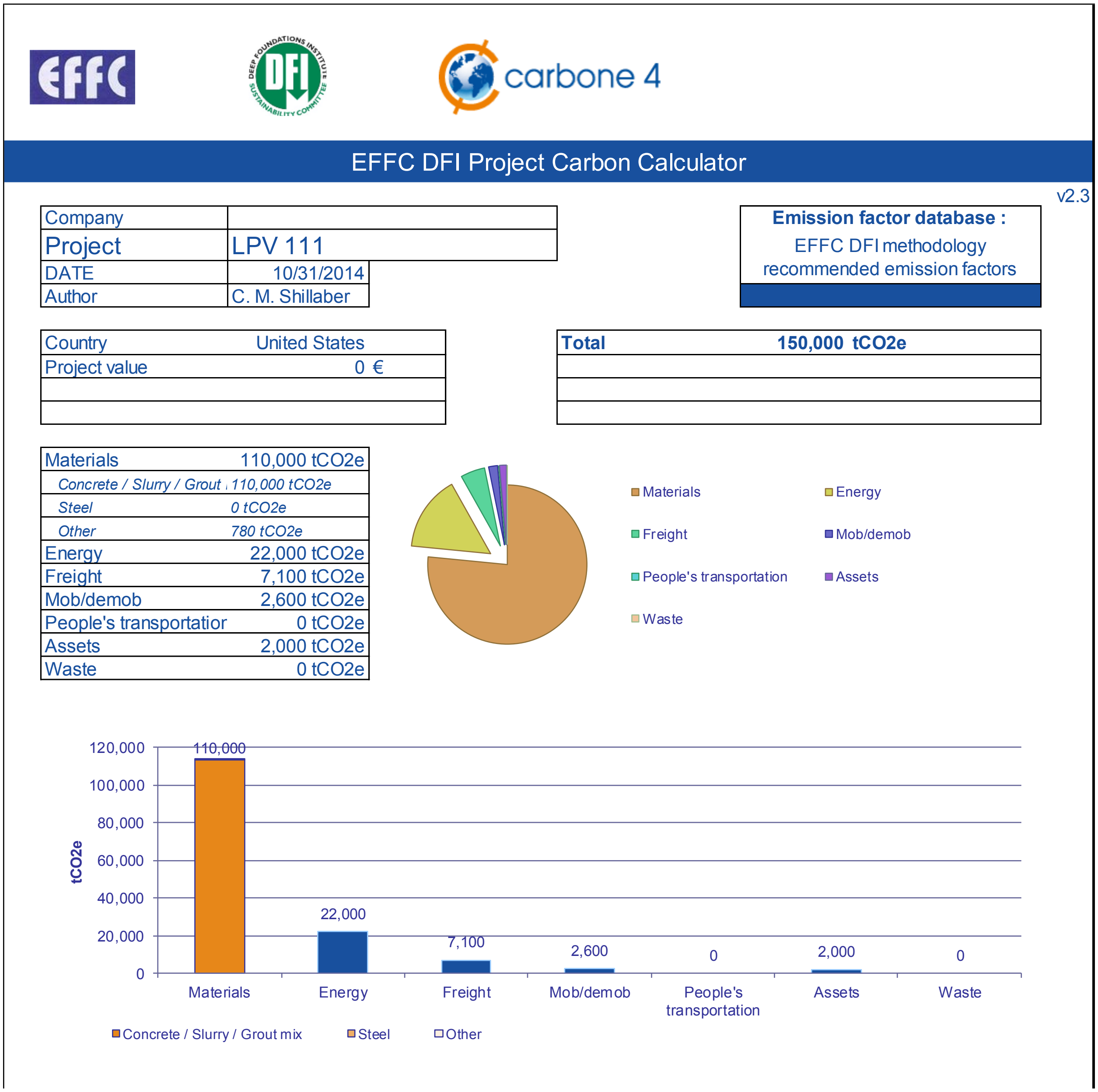


Figure I.7 EFFC-DFI Geotechnical Carbon Calculator, LPV 111 Deep Soil Mixing results.

I.2 COMPARISON OF RESULTS FROM SEEAM AND THE EFFC-DFI GEOTECHNICAL CARBON CALCULATOR FOR DEEP MIXING AT LPV 111

A comparison was made between the results of the EFFC-DFI Geotechnical Carbon Calculator and the SEEAM, as discussed in Chapter 4. Table I.1 shows the contribution of various aspects of the construction at LPV 111 to the total computed CO_2 emissions using both methods. In order for an equivalent comparison, the SEEAM analysis was performed without including barge transport of the cement and slag, as there is not a way to account for barge transport in the EFFC-DFI Geotechnical Carbon Calculator. The difference column in Table I.1 shows the absolute value of the difference between the SEEAM result without barge transport, and the EFFC-DFI Geotechnical Carbon Calculator.

Table I.1 Comparison of results from the EFFC-DFI Geotechnical Carbon Calculator and the SEEAM, with and without accounting for barge transport of cement and slag (the EFFC-DFI Geotechnical Carbon Calculator does not account for barge transport).

	EFFC-DFI Calculator (tonne CO_2e)	**SEEAM - With Barge Transport (tonne CO_2)**	**SEEAM - No Barge Transport (tonne CO_2)**	**Difference (SEEAM no barge to EFFC-DFI)**	**% Difference (Taking SEEAM as baseline)**
Materials	114,189	104,741	104,741	9,448	9.0%
Energy (Site energy)	21,876	19,734	19,734	2,142	10.9%
Freight	7,072	22,047	4,028	3,044	75.6%
Mob/demob	2,593	0	0	2,593	100.0%
People's transportation	0	0	0	0	0.0%
Assets (Equip Manufacture)	2,040	0	0	2,040	100.0%
Waste	0	0	0	0	0.0%
Total	**147,771**	**146,521**	**128,503**	**19,268**	**15.0%**

The most significant difference in the results between the SEEAM and the EFFC-DFI Geotechnical Carbon Calculator for factors that are included in both analyses is the emissions associated with freight (material hauling). In this case, the EFFC-DFI Geotechnical Carbon Calculator result differs from the SEEAM result that does not include barge transportation by

75.6%. The differences between the two for site energy (construction fuel consumption) and materials are both less than 11%, with the SEEAM providing lower emissions than the EFFC-DFI Geotechnical Carbon Calculator. As discussed in section 4.5.2, this makes sense simply because the EFFC-DFI Geotechnical Carbon Calculator result includes CO_2 and other GHG emissions converted into CO_{2eq}, while the SEEAM includes CO_2 emissions alone. The difference in the freight emissions also stems from the fact that the two analyses handle material transportation differently. For highway trucks, the SEEAM uses truck fuel economy to determine the amount of fuel consumed for freight and converts the quantity of fuel consumed into CO_2. Instead of considering truck fuel economy, the EFFC-DFI Geotechnical Carbon Calculator uses emissions coefficients per mass of material transported a unit distance (e.g., tonne-km).

Another significant difference between the SEEAM and the EFFC-DFI Geotechnical Carbon Calculator is accounting for mobilization and demobilization, and assets. These factors are included in the EFFC-DFI Geotechnical Carbon Calculator (using default ratios in this case), but they are not included in the SEEAM, as described in section 4.5.2.

I.3 REFERENCES

Carbone 4. (2014). Geotechnical Carbon Calculator, version 2.3, [Software]. EFFC-DFI, Available from <http://www.geotechnicalcarboncalculator.com/>.

Lemaignan, B., and Wilmotte, J. Y. (2013). *EFFC DFI Carbon Calculator Methodological & User Guide v2.1*. EFFC-DFI. Available from <http://geotechnicalcarboncalculator.com/en/userguide>.

Appendix J: Development of Embodied Energy and CO_2 Emissions Coefficients' Lognormal Distribution Parameters

This Appendix shows the generation of the lognormal distribution parameters (mean and standard deviation) for the embodied energy and CO_2 emissions coefficients included in Table 4.1, with some additional materials that are also included in the SEEAM Spreadsheet Calculator (Appendices A and B). Many (but not all) of the generated lognormal parameters for coefficients are included in Table 6.1; all of the generated coefficient parameters are included in Table J.18 at the end of this Appendix. Table J.18 does not present a standard deviation for all materials listed. This is because there is insufficient data available to determine distribution parameters for all of the materials and fuels that appear in Table 4.1. In these instances, the recommended values of the coefficients presented in Table 4.1 are used as a constant (as listed in Table J.18) in SEEAM analyses. As an alternative to using a constant material-specific coefficient, SEEAM analyses may also be conducted using an applicable general coefficient that has distribution parameters (e.g., using general steel instead of the specific steel bar and rod coefficient).

J.1 UPDATING THE SEEAM DATABASE WITH DISTRIBUTION PARAMETERS

J.1.1 Materials

In all cases, the original recommended value of the coefficient in the database (Table 4.1) is taken as the mean. Depending on the original source of the coefficient, the method of determining the standard deviation varies. For material coefficients derived from available input data (several studies or published values from various production processes in an industry's average life cycle inventory), the standard deviation of values contributing to the recommended (mean) coefficient is computed directly, using Eq. J.1 (Sleep and Duncan 2014):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} \tag{J.1}$$

where x_i is the i^{th} value of the parameter, $\bar{x}$ is the mean value of the parameter x, and N is the total number of values of x (sample size).

For material coefficients sourced from the Inventory of Carbon and Energy (ICE) database (Hammond and Jones 2011), the recommended value of the embodied energy and CO_2 coefficients in the ICE database were taken as the mean in the SEEAM database. The standard deviation for the embodied energy coefficient was sourced directly from the ICE database statistics on the material profile. There are no statistics for CO_2 emissions available in the ICE database. As such, the coefficient of variation (COV) (defined by Eq. J.2, (Sleep and Duncan 2014)) was determined for the embodied energy statistics using the recommended coefficient value as the mean (μ), and the standard deviation published in the ICE database. The COV was then assumed to be the same for CO_2 emissions as for embodied energy and the standard deviation of CO_2 emissions was determined for each material by Eq. J.3, where μ_{CO_2} is the recommended mean value of the CO_2 emissions coefficient.

$$COV = \frac{\sigma}{\mu} \tag{J.2}$$

$$\sigma_{CO_2} = COV(\mu_{CO_2}) \tag{J.3}$$

The only exception to these formulations for the standard deviation was for slag, which uses a coefficient mean from the Slag Cement Association in the U.S., with the standard deviation determined according to the ICE database statistics.

J.1.1.1 General Steel

Table J.1 Determination of the lognormal distribution parameters for General Steel (Virgin) based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

General Steel, Virgin		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	35.4	2.71
St. Dev.	12.07	
COV	0.341	
Coefficient (mean)	**35.4**	**2.71**
St Dev	**12.07**	**0.92**

Table J.2 Determination of the lognormal distribution parameters for General Steel (World Average Recycled Content) based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

General Steel (World Avg. Recycled Content)		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	25.3	1.82
St. Dev.	5.92	
COV	0.234	
Coefficient (mean)	**25.3**	**1.82**
St Dev	**5.92**	**0.43**

J.1.1.2 Portland Cement

The coefficient parameters for Portland cement were determined from published unit embodied energy and CO_2 emissions information for each of four different production processes, detailed in a U.S. life cycle inventory (LCI) by Marceau et al. (2006). Marceau et al. (2006) also report the fraction of all Portland cement in the U.S. produced by each process. This information is presented in the top portion of Table J.3. The bottom portion of the table presents both the arithmetic mean and standard deviation, as well as the weighted mean and standard deviation. The weighted mean was determined by (NIST 1997):

$$\bar{x}^* = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i} \qquad \text{J.4}$$

where x_i is the i^{th} value of the parameter, $\bar{x}^*$ is the weighted mean value of the parameter x, N is the total number of values of x (sample size) and w_i is the weight of each value of x.

Weighted average standard deviation was determined by (NIST 1996):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} w_i (x_i - \bar{x}^*)^2}{\left(\frac{M-1}{M}\right) \sum_{i=1}^{N} w_i}} \qquad \text{J.5}$$

where M is the number of non-zero weights.

Table J.3 Determination of the weighted mean and standard deviation for Portland cement embodied energy and CO_2 emissions coefficients based on life cycle inventory data for four methods of production in the U.S. from Marceau et al. (2006).

Cement Production Method	Fraction of Production	EE (MJ/kg)	CO_2 (kg/kg)
Wet	0.165	6.40	1.100
Long Dry	0.144	5.59	1.010
Preheater	0.158	4.36	0.852
Precalciner	0.533	4.22	0.874
Arithmetic Average		5.14	0.959
Arithmetic St. Dev.		1.04	0.12
Weighted Average		**4.80**	**0.927**
Weighted Average St. Dev.		**0.98**	**0.105**

J.1.1.3 Lime

Table J.4 Determination of the lognormal distribution parameters for Lime based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

Lime		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	5.3	0.78
St. Dev.	2.79	
COV	0.526	
Coefficient (mean)	**5.3**	**0.78**
St Dev	**2.79**	**0.41**

J.1.1.4 Slag

The mean coefficient value for slag is based on a value published by the U.S. Slag Cement Association (2014). The standard deviation was determined using the statistics in the ICE database in the same manner as the other coefficients based on the ICE database (Note: since the recommended coefficient values in the ICE database are larger than the value from the Slag Cement Association, this gives a larger value of standard deviation than applying the ICE COV to the Slag Cement Association coefficients).

Table J.5 Determination of the lognormal distribution parameters for Slag based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3 for standard deviation. Mean values from the Slag Cement Association (2014).

Slag			
		EE (MJ/kg)	**CO_2 (kg/kg)**
Hammond and Jones (2011)	Recommended	1.6	0.083
	St. Dev.	0.21	
	COV	0.131	
Slag Cement Association		0.721	0.021
	Coefficient (mean)	**0.721**	**0.021**
	St Dev	**0.21**	**0.011**

J.1.1.5 Fly Ash

Table J.6 Determination of the lognormal distribution parameters for Fly Ash based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

Fly Ash		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	0.1	0.008
St. Dev.	0.02	
COV	0.200	
Coefficient (mean)	**0.1**	**0.008**
St Dev	**0.02**	**0.002**

J.1.1.6 Aggregate

Table J.7 Determination of the lognormal distribution parameters for Aggregate based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

Aggregate		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	0.083	0.0048
St. Dev.	0.12	
COV	1.446	
Coefficient (mean)	**0.083**	**0.0048**
St Dev	**0.12**	**0.0069**

J.1.1.7 Sand

Table J.8 Determination of the lognormal distribution parameters for Sand based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

Sand		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	0.081	0.0048
St. Dev.	0.23	
COV	2.840	
Coefficient (mean)	**0.081**	**0.0048**
St Dev	**0.23**	**0.0136**

J.1.1.8 General Plastics

Table J.9 Determination of the lognormal distribution parameters for General Plastics based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

General Plastics		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	80.5	2.73
St. Dev.	37.67	
COV	0.468	
Coefficient (mean)	**80.5**	**2.73**
St Dev	**37.67**	**1.28**

J.1.1.9 Polyethylene

Table J.10 Determination of the lognormal distribution parameters for General Polyethylene based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

General Polyethylene		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	83.1	2.04
St. Dev.	32.77	
COV	0.394	
Coefficient (mean)	**83.1**	**2.04**
St Dev	**32.77**	**0.80**

Table J.11 Determination of the lognormal distribution parameters for High Density Polyethylene (HDPE) Resin based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

High Density Polyethylene (HDPE) Resin		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	76.7	1.57
St. Dev.	25.39	
COV	0.331	
Coefficient (mean)	**76.7**	**1.57**
St Dev	**25.39**	**0.52**

Table J.12 Determination of the lognormal distribution parameters for Low Density Polyethylene (LDPE) Resin based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

Low Density Polyethylene (LDPE) Resin		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	78.1	1.69
St. Dev.	16.26	
COV	0.208	
Coefficient (mean)	**78.1**	**1.69**
St Dev	**16.26**	**0.35**

J.1.1.10 General PVC

Table J.13 Determination of the lognormal distribution parameters for General Polyvinyl Chloride (PVC) based on embodied energy statistics in the ICE database (Hammond and Jones 2011), using Eq. J.2 and Eq. J.3.

General Polyvinyl Chloride (PVC)		
	EE (MJ/kg)	**CO_2 (kg/kg)**
Recommended	77.2	2.61
St. Dev.	21	
COV	0.272	
Coefficient (mean)	**77.2**	**2.61**
St Dev	**21.00**	**0.71**

J.1.1.11 Wood Products

The mean and standard deviation for wood products were determined from the values presented in studies by Puettmann and Wilson (2005) and Puettmann et al. (2010). These researchers determined coefficients for certain wood products for various regions across the U.S. [e.g., Pacific Northwest (PNW), Inland Northwest (INW), Southeast (SE), Northeast-North Central (NE-NC)]. The lognormal parameters (mean and standard deviation) for each wood product were determined by finding the mean and standard deviation of the values for the product from each region. See Tables J.14 through J.16.

Note that the total CO_2 emissions resulting from timber are those associated with fossil energy (listed in the CO_2 columns in the tables) and those associated with combustion or decay of the timber (listed as biogenic CO_2 in the tables (EPA 2011; Puettmann et al. 2010)). Total CO_2 emissions from wood are a combination of the two if the uptake of CO_2 into living trees is ignored. Ignoring CO_2 uptake and considering both fossil and biogenic CO_2 emissions will overestimate emissions when sustainable forest practices are used (i.e., when wood is not harvested at a rate faster than it may be naturally replenished). With sustainable practices, uptake reduces emissions.

Table J.14 Determination of the lognormal distribution parameters for Softwood, Planed, Dried Lumber.

	Softwood, Planed, Dried Lumber				
		EE (MJ/kg)	CO_2 (kg/kg)	Biogenic CO_2 (kg/kg)	Reference & Notes
Input Values	PNW	8.971	0.223	0.387	Puettmann and Wilson (2005), density = 413 kg/m^3
	SE	6.847	0.122	0.486	Puettmann and Wilson (2005), density = 510 kg/m^3
	INW	7.314	0.206	0.266	Puettmann et al. (2010), density = 436 kg/m^3
	NE-NC	7.750	0.217	0.449	Puettmann et al. (2010), density = 392 kg/m^3
Lognormal Parameters	**Coefficient (mean)**	**7.72**	**0.19**	**0.40**	
	St Dev	**0.91**	**0.05**	**0.10**	

Table J.15 Determination of the lognormal distribution parameters for Softwood, Green Lumber.

	Softwood, Green Lumber				
		EE (MJ/kg)	CO_2 (kg/kg)	Biogenic CO_2 (kg/kg)	Reference & Notes
Input Values	PNW	1.33	0.07	2.42E-05	Puettmann and Wilson (2005), density = 413 kg/m^3
Lognormal Parameters	**Coefficient (mean)**	**1.33**	**0.07**	**2.42E-05**	
	St Dev				

Table J.16 Determination of the lognormal distribution parameters for Softwood, Plywood.

	Softwood, Plywood				
		EE (MJ/kg)	CO_2 (kg/kg)	Biogenic CO_2 (kg/kg)	Reference & Notes
Input Values	PNW	7.579	0.117	0.304	Puettmann and Wilson (2005), density = 480 kg/m^3
	SE	10.178	0.23	0.413	Puettmann and Wilson (2005), density = 555 kg/m^3
Lognormal Parameters	**Coefficient (mean)**	**8.88**	**0.17**	**0.36**	
	St Dev	**1.84**	**0.08**	**0.08**	

J.1.2 Fuels – Diesel and Gasoline

For fuels, the mean values for the coefficient lognormal distributions were taken directly from a fuel cycle analysis conducted by Shillaber et al. (2014). Standard deviations for diesel and gasoline were determined based on an uncertainty analysis of life cycle emissions from petroleum fuels conducted by Venkatesh et al. (2011). Venkatesh et al. (2011) fit a shifted log-logistic distribution to the life cycle CO_{2eq} emissions associated with diesel and gasoline (see Table J.17 for log-logistic distribution parameters from Venkatesh et al. (2011)).

Table J.17 Shifted log-logistic distribution parameters for diesel and gasoline (data from Venkatesh et al. 2011).

	μ	σ	Shift, δ
Gasoline	2.2	0.2	80
Diesel	2.3	0.2	82

Since the assumption for this uncertainty calculation method is that the coefficients are distributed lognormally, a lognormal distribution was closely matched to the shifted log-logistic distribution of life cycle CO_{2eq} emissions from Venkatesh et al. (2011) by adjusting the lognormal parameters (see Figure J.1). As shown in Figure J.1, the lognormal distribution does underestimate the frequency of emissions levels in the upper (right) tail of the distribution, but otherwise matches the shifted log-logistic distribution well. The standard deviation of the fitted lognormal distribution of life cycle CO_{2eq} for diesel fuel resulted in a COV of 0.0334. The COV for the gasoline lognormal distribution is 0.0311.

In order to determine the standard deviation of CO_2 emissions and embodied energy, it was assumed that the COV of embodied energy and CO_2 emissions are equal to the COV for the lognormal distributions of CO_{2eq} for diesel and gasoline. Therefore, the standard deviation of the embodied energy and CO_2 emissions for diesel and gasoline fuel in the updated SEEAM database were set at 0.0334 and 0.0311 times the total (mean) coefficient values recommended by Shillaber et al. (2014), respectively.

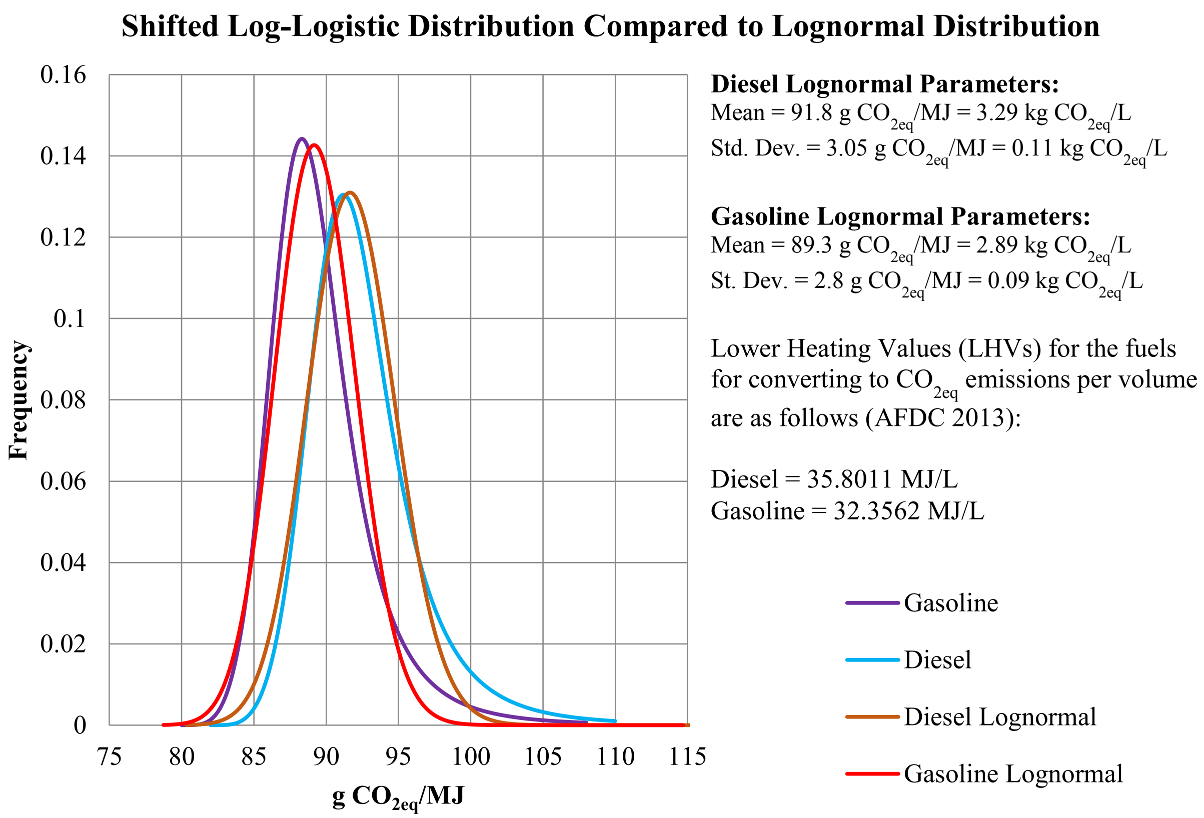


Figure J.1 Comparison of shifted log-logistic distribution (data from Venkatesh et al. 2011) and lognormal distribution for fuel cycle CO_{2eq} emissions.

Embodied Energy:

Diesel:

$$0.0334\left(43.0\frac{MJ}{L}\right) = 1.43\frac{MJ}{L}$$

Gasoline:

$$0.0311\left(39.7\frac{MJ}{L}\right) = 1.23\frac{MJ}{L}$$

CO_2 Emissions:

Diesel:

$$0.0334\left(3.25\frac{kg\ CO_2}{L}\right) = 0.11\frac{kg\ CO_2}{L}$$

Gasoline:

$$0.0311\left(2.83\frac{kg\ CO_2}{L}\right) = 0.09\frac{kg\ CO_2}{L}$$

J.2 SUMMARY

All lognormal parameters for the coefficients are summarized in Table J.18. As stated at the beginning of this Appendix, when a standard deviation is not listed, the coefficient should be used as a constant value for SEEAM analyses.

Table J.18 Lognormal parameters for embodied energy coefficients (EECs) and CO_2 emissions coefficients (CCs). Where a standard deviation is not listed, the mean value is used as a constant.

Material Category	Material	Unit	EEC (MJ/Unit)	EEC St. Dev. (MJ/Unit)	CC (kg CO_2/Unit)	CC St. Dev. (kg CO_2/Unit)	Biogenic CC (kg CO_2/Unit)	Biogenic CC St. Dev. (kg CO_2/Unit)	Reference
Steel	General Steel, Virgin	kg	35.4	12.07	2.71	0.92			ICE v2 Hammond and Jones (2011)
	General Steel, World Avg. Recycled Content	kg	25.3	5.92	1.82	0.43			ICE v2 Hammond and Jones (2011)
	Steel Bar and Rod, Virgin	kg	29.2		2.59				ICE v2 Hammond and Jones (2011)
	Steel Bar and Rod, World Avg. Recycled Content	kg	21.6		1.74				ICE v2 Hammond and Jones (2011)
	Steel Pipe, Virgin	kg	34.7		2.71				ICE v2 Hammond and Jones (2011)
	Steel Pipe, World Avg. Recycled Content	kg	24.9		1.83				ICE v2 Hammond and Jones (2011)
	Engineered Steel Sections, Virgin	kg	38.0		2.82				ICE v2 Hammond and Jones (2011)
	Engineered Steel Sections, World Avg. Recycled Content	kg	27.1		1.89				ICE v2 Hammond and Jones (2011)
Cementitious Materials	Portland Cement (U.S.)	kg	4.8	0.98	0.927	0.105			Marceau et al. (2006)
	Lime	kg	5.3	2.79	0.78	0.41			Based on ICE v2 Hammond and Jones (2011)
	Slag (U.S.)	kg	0.721	0.210	0.021	0.011			Slag Cement Association (2014), ICE v2 Hammond and Jones (2011) for std dev.
	Fly Ash	kg	0.1	0.02	0.008	0.002			Based on ICE v2 Hammond and Jones (2011)
Concrete	35MPa Concrete (Portland Cement Only)	m^3	1,630		313				Marceau et al. (2007)
	25MPA Concrete (Portland Cement Only)	m^3	1,390		262				Marceau et al. (2007)
	20MPa Concrete (Portland Cement Only)	m^3	1,140		211				Marceau et al. (2007)
	20MPa Concrete (20% Fly Ash by Weight)	m^3	944		171				Marceau et al. (2007)
Earth Materials	Bentonite	kg	1.65		0.101				Jiang et al. (2011); Carnegie Mellon University Green Design Institute (2008)
	Aggregate: Sand and Gravel or Crushed Rock	kg	0.083	0.12	0.0048	0.0069			Based on ICE v2 Hammond and Jones (2011)
	Sand	kg	0.081	0.23	0.0048	0.0136			ICE v2 Hammond and Jones (2011)
Plastics	General Plastics (Average)	kg	80.5	37.67	2.73	1.28			Based on ICE v2 Hammond and Jones (2011)
	High Density Polyethylene (HDPE) Resin	kg	76.7	25.39	1.57	0.52			Based on ICE v2 Hammond and Jones (2011)
	Low Density Polyethylene (LDPE) Resin	kg	78.1	16.26	1.69	0.35			Based on ICE v2 Hammond and Jones (2011)
	Polyethylene (General)	kg	83.1	32.77	2.04	0.8			Based on ICE v2 Hammond and Jones (2011)
	PVC (General)	kg	77.2	21.00	2.61	0.71			Based on ICE v2 Hammond and Jones (2011)
	Polypropylene (Injection Molding)	kg	115.1		3.93				ICE v2 Hammond and Jones (2011)
	Polypropylene (Oriented Film)	kg	99.2		2.97				ICE v2 Hammond and Jones (2011)
Wood Products	Softwood (planed, dried lumber)	kg	7.72	0.91	0.19	0.05	0.4	0.1	Puettmann and Wilson (2005); Puettmann et al. 2010
	PNW Softwood (green lumber)	kg	1.33		0.07		0.0000242		Puettmann and Wilson (2005), density = 413 kg/m^3
	Softwood (plywood)	kg	8.88	1.84	0.17	0.08	0.36	0.08	Puettmann and Wilson (2005)
Water	Water	L	0.01		0.001				ICE v2 Hammond and Jones (2011)
Fuel	Diesel	L	43.0	1.43	3.25	0.11			Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
	Gasoline	L	39.7	1.23	2.83	0.09			Shillaber et al. (2014); St Dev based on data from Venkatesh et al. (2011)
	Compressed Natural Gas (CNG)	kg	55.5		2.87				Shillaber et al. (2014)
	Electricity (U.S. Avg. Generation Mix)	kW-hr	8.74		0.63				Shillaber et al. (2014)

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Appendix K: Comparing Monte Carlo Simulation and an Analytical Approach to Handling Uncertainty in SEEAM Analyses

K.1 INTRODUCTION

In this Appendix, two methods for incorporating uncertainty into embodied energy and CO_2 emissions assessments via the SEEAM method (described in Ch. 4) are presented and compared: 1) an analytical method, and 2) Monte Carlo simulation. The comparison was made through analyzing two case history projects, including deep soil mixing for support of an earthen embankment at levee LPV 111 in New Orleans, LA (see Chs. 4 – 5, Appendices E and F), and rammed aggregate columns for support of shallow foundations for Pearson Hall at Virginia Tech (see Chs. 6 – 7 and Appendices L and M).

K.2 ASSUMPTIONS FOR ANALYSIS

Three primary assumptions were made in conducting these analyses which affect both the analytical and Monte Carlo methods. First, for the present analysis it was assumed that all material quantities are fixed. This assumption is good for two primary situations: 1) when the design is not highly dependent upon the subsurface conditions and/or has already accounted for the variability in the subsurface conditions and will not change significantly by any differing conditions encountered during construction; 2) for analyses conducted post construction (of the as-built condition), when all material quantities are known.

The second assumption is that the embodied energy and CO_2 emissions coefficient values are assumed to follow the lognormal distribution when the coefficient is known to be generated from more than one input value. Where only one coefficient value exists with no other data, the coefficient is assumed to be constant at the value, not following a lognormal distribution.

The lognormal distribution is advantageous in that it is a nonlinear transformation of the normal distribution; where X is lognormally distributed, the natural logarithm of X is normally distributed. Given lognormal parameters μ_X and σ^2_X, the parameters μ_{lnX} and σ^2_{lnX} (which define a normal distribution) may be found by Eqs. K.1 and K.2 (Fenton and Griffiths 2008):

$$\sigma^2_{\ln X} = \ln\left(1 + \frac{\sigma_X^2}{\mu_X^2}\right) \tag{K.1}$$

$$\mu_{\ln X} = \ln(\mu_X) - 0.5\sigma^2_{\ln X} \tag{K.2}$$

The probability density function (PDF) of the lognormal distribution is given by Eq. K.3 (Fenton and Griffiths 2008):

$$f(x) = \frac{1}{x\sigma_{\ln X}\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\ln(x) - \mu_{\ln X}}{\sigma_{\ln X}}\right)\right], \quad 0 \leq x < \infty \tag{K.3}$$

Additional rationale for selecting the lognormal distribution is presented in Ch. 6.

The third assumption is that the embodied energy and CO_2 emissions from materials and fuel related activities (site operations and transportation) are independent. Further details about this assumption are given in Ch. 6.

K.3 METHODS OF ANALYSIS

K.3.1 Analytical Approach

The analytical analysis approach involves following the SEEAM methodology (presented in Ch. 4) and conducting the calculations as if the coefficients are random variables. Since all of the calculations in the SEEAM method are linear combinations (addition or multiplication) and the coefficients are assumed to be independent (uncorrelated), the computation of the mean and standard deviation of the results are straightforward. For example, according to the deterministic SEEAM methodology, total material embodied energy is found by Eq. K.4 (see Ch. 4):

$$EE_M = \sum_{i=1}^{n}(Q_i)(EEC_i), \tag{K.4}$$

where EE_M is the total embodied energy from materials in the project, Q_i is the quantity of the i^{th} material used for construction, EEC_i the corresponding embodied energy coefficient for the material, and n the total number of materials involved in the project. Based on information describing operations on random variables from Fenton and Griffiths (2008), determining the expected value (mean) of embodied energy is accomplished by replacing the EEC with its expected value (mean), as shown in Eq. K.5:

$$E[EE_M] = \sum_{i=1}^{n}(Q_i)(E[EEC_i]) \tag{K.5}$$

Similarly, the mean of the total embodied energy for the project is the sum of the means of the materials, materials transportation, site operations and waste transportation embodied energies. The same construct is used for CO_2 emissions by replacing the EEC with the CO_2 emissions coefficient (CC).

Based on information about operations on random variables from Fenton and Griffiths (2008), the method for determining the standard deviation is slightly more complicated. The method for materials is shown in Eq. K.6:

$$\sigma_{EE_M} = \sqrt{Var[EE_M]} = \sqrt{\sum_{i=1}^{n}(Q_i)^2\left(\sigma_{EEC_i}\right)^2} \tag{K.6}$$

In a similar fashion, the standard deviation of the total embodied energy for the project is equal to the square root of the sum of the squared standard deviations of embodied energy from materials, materials transportations, site operations and waste transportation. The same method is also used for CO_2 emissions by replacing the standard deviation of the EEC with the standard deviation of the CC. These analytical computations have been built into the SEEAM Spreadsheet Calculator (the calculator is described in Appendices A and B).

In addition to the mean and standard deviation, it is desirable to obtain the resulting distributions of total embodied energy and CO_2 emissions for determining confidence intervals and statistical inference. Since there is no known exact solution for the sum of lognormal random variables, the approximation suggested by Fenton (1960) based on the mean and standard deviation (often called the Fenton-Wilkinson approximation) has been used to represent the sum of lognormal random variables as a lognormal distribution with mean and standard deviation matching those of the sum distribution. The mean and standard deviation of the sum distribution are the computed mean and standard deviation. Therefore, the distribution of the results is assumed to be approximated by a lognormal distribution generated from the computed mean and standard deviation (which correspond to the sum distribution). A major drawback of this approximation is that it is most accurate for small values of standard deviation (Beaulieu et al. 1995).

Once the approximate lognormal distribution has been generated for the results, 90% confidence intervals for embodied energy and CO_2 emissions for the project may be determined. Other methods of statistical inference, including parametric statistical hypothesis tests, can also be used with the distribution to compare the effect of design changes or design alternatives to see if project embodied energy and CO_2 emissions between alternatives differ with statistical significance.

K.3.2 Monte Carlo Simulation

Monte Carlo simulation is described in Ch. 6. Much of the discussion is repeated in this Appendix for completeness.

Unlike the analytical approach to the analysis, the Monte Carlo simulation does not involve generating an estimated or approximate distribution. Instead, the simulation involves discrete deterministic calculations of possible values of total embodied energy and CO_2 emissions in order to form a simulated data set. Each of the values in the simulated data set is computed following the SEEAM method directly. However, each embodied energy and CO_2 emissions coefficient contributing to the generation of each value in the simulated data set is generated randomly from the assumed lognormal distribution defined by the coefficient mean and standard deviation. Descriptive statistics, such as the mean and standard deviation of total embodied energy and CO_2 emissions, can be determined directly from the simulated data set. By plotting the results in histograms, a realization of the actual distributions of total embodied energy and CO_2 emissions can be observed.

When the Monte Carlo simulation is conducted, confidence intervals for total embodied energy and CO_2 emissions may be determined by querying the resulting simulated data set (i.e., finding which values the desired proportion of the simulated data set fall between) instead of using a distribution function. Since a theoretical distribution is not fit to the data as part of the Monte Carlo simulation and the resulting distribution is not assumed to be normal, statistical inference for detecting differences between project alternatives should be conducted using nonparametric statistical hypothesis tests on the simulated data.

An important consideration with Monte Carlo simulation is how many values are required in the simulated data set to achieve the desired level of accuracy in the results. Often, engineers are concerned with extreme values (e.g., probability of failure), however, in this case it is desirable to generate an accurate mean. Therefore, the appropriate number of simulation values must be determined based on the desired accuracy around the mean. For this analysis, the selected minimum level of accuracy around the mean is +/- 2.5% of the mean value, with 90% confidence. This was selected because this level of accuracy can be achieved with a moderate number of values in the simulated data sets. Assuming the Monte Carlo simulated data set is approximately normally distributed, the confidence interval about the mean is given by Eq. K.7 (Fenton and Griffiths 2008):

$$[CI]_{1-\alpha} = \hat{\mu}_g \pm t_{\frac{\alpha}{2},n-1} \frac{\hat{\sigma}_g}{\sqrt{n}} \tag{K.7}$$

where n is the number of values in the simulated data set, $\hat{\mu}_g$ and $\hat{\sigma}_g$ are the estimated mean and standard deviation of the simulated data set, t is the statistic from the t-distribution and α is the desired significance level. For 90% confidence, α = 0.1. Since the desired error is +/- 2.5% of the mean, Eq. K.7 can be rearranged, and n can be solved for iteratively:

$$Mean\ Error = t_{\frac{\alpha}{2},n-1}\frac{\hat{\sigma}_g}{\sqrt{n}} = 0.025(\hat{\mu}_g) \xrightarrow{yields} n = \left(t_{\frac{\alpha}{2},n-1}\frac{\hat{\sigma}_g}{0.025(\hat{\mu}_g)}\right)^2 \quad \text{(K.8)}$$

An inherent problem of Eqs. K.7 and K.8 to determine an appropriate number of Monte Carlo simulation values is that they depend on the assumption that the results are approximately normally distributed. Given that the input coefficients are all assumed to be lognormally distributed, the assumption of normally distributed results is unlikely to be valid. However, the assumption of normality has still been used in this case to determine a likely minimum number of simulation values to achieve the desired level of accuracy. For the two case histories described in section K.4, it was found that the minimum number of values in the simulated data set required to generate +/-2.5% error in the mean with 90% confidence is n = 600. To ensure this desired level of accuracy is achieved, n = 1,000 values in the simulated data sets will be used. Since the case histories analyzed represent both large and small projects with moderate and high coefficient uncertainty, computing n = 1,000 values in the simulated data set should be sufficient for estimating the mean embodied energy and CO_2 emissions for almost all projects with less than +/- 2.5% error in the estimate of the mean.

K.3.3 Comparing the Analytical Approach and Monte Carlo Simulation

The analytically determined means and standard deviations were used to generate plots of the resulting lognormal distributions for both total embodied energy and CO_2 emissions. Both the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) were plotted. Plots of the analytical PDF and CDF were compared with the empirical PDF and CDF obtained from the Monte Carlo simulation in order to provide an indication of how well the analytically generated lognormal distribution fits the Monte Carlo simulated data. The Monte Carlo simulated data set is believed to follow the "correct" or "true" distribution for total embodied energy and CO_2 emissions.

The validity of the analytical lognormal as a representation of the total embodied energy and CO_2 emissions distributions cannot be interpreted from comparing the shape of the PDF and CDF plots alone. As such, probability-probability (P-P) plots and quantile-quantile (Q-Q) plots were also generated. A P-P plot is a plot of the analytical CDF vs. the Monte Carlo simulation CDF. If the analytical distribution is a good representation of the Monte Carlo results, the plotted points will fall along a line with an intercept of 0 and a slope of 1 in the P-P plot (Fenton and Griffiths 2008).

In Q-Q plots, increments of total probability are used in the inverse CDF to compute the estimated values of the parameter (e.g., total embodied energy or CO_2 emissions) associated with that cumulative probability. In this case, since there are n = 1,000 values in the Monte Carlo simulated data, the cumulative probabilities for computing the embodied energy and CO_2 emissions from the analytical CDF range from 0 to 1 in increments of 0.001. The resulting 1,000 computed values of embodied energy or CO_2 emissions are plotted against the corresponding values from the Monte Carlo simulation (which are sorted in ascending numerical order to correspond with the values computed from the analytical CDF). If the Monte Carlo simulation and the analytically generated lognormal distribution agree well, the Q-Q plot will fall along a line with an intercept of 0 and a slope of 1 (Fenton and Griffiths 2008).

The P-P and Q-Q plots both have strengths and weaknesses. P-P plots tend to amplify differences in the middle of the distribution and obscure differences in the tails, while Q-Q plots do the opposite (Fenton and Griffiths 2008). Regardless, the analytically generated lognormal distribution is a good representation of the distribution generated from the Monte Carlo simulation if both plots, on average, approach a line with an intercept of 0 and slope of 1.

K.4 CASE HISTORIES USED FOR ANALYSIS

K.4.1 Deep Soil Mixing at Levee Section LPV 111, New Orleans, LA

LPV 111 is an 8.5 km long section of levee in New Orleans, LA that was recently repaired and upgraded by raising the levee crest about 3 m to the level of 100 year flood protection (Cali et al. 2012). Additional details about the project, including design and material quantities are included in Chs. 4 – 5 and Appendix F.

K.4.2 Rammed Aggregate Columns at Pearson Hall, Virginia Tech, Blacksburg, VA

In early 2014, construction began on the new Pearson Hall, a replacement of one of the Corps of Cadets dormitories on the Virginia Tech campus. The foundation design for the new building called for spread footings supported by a total of 364, 0.76 m (30 inch) diameter rammed aggregate columns. Additional details about the project, including material quantities, are included in Ch. 6 and Appendix L.

K.5 RESULTS

In this section, the results of both the analytical analysis and the Monte Carlo simulation for embodied energy and CO_2 emissions for the case history projects are described.

K.5.1 Deep Soil Mixing at Levee Section LPV 111, New Orleans, LA

The results for the mean and standard deviation of the total embodied energy and CO_2 emissions for the construction at LPV 111 for each method are shown in Table K.1 (Note: the analytical calculations were conducted by the SEEAM Spreadsheet Calculator and the line-by-line calculation results are included in Appendix E, Figure E.1). As observed in Table K.1, the means and standard deviations determined by each method agree with each other very well, with a maximum difference of 3.66%. For the means alone, the maximum difference is 0.23%, which is much less than the desired maximum of 2.5% error. (Note: This is only representing one realization of n = 1,000 values; other realizations could have greater difference from the analytical mean).

Table K.1 LPV 111: Total embodied energy and CO_2 emissions by analysis method.

Method of Analysis	Embodied Energy		CO_2 Emissions	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Analytical	1,174,195	122,535	146,521	11,496
Monte Carlo Simulation	1,176,156	122,782	146,864	11,916
% Difference	**0.17%**	**0.20%**	**0.23%**	**3.66%**

The lognormal PDFs and CDFs from the analytically derived means and standard deviations were plotted along with the distribution of values from the Monte Carlo simulation, as shown in Figures K.1 through K.4.

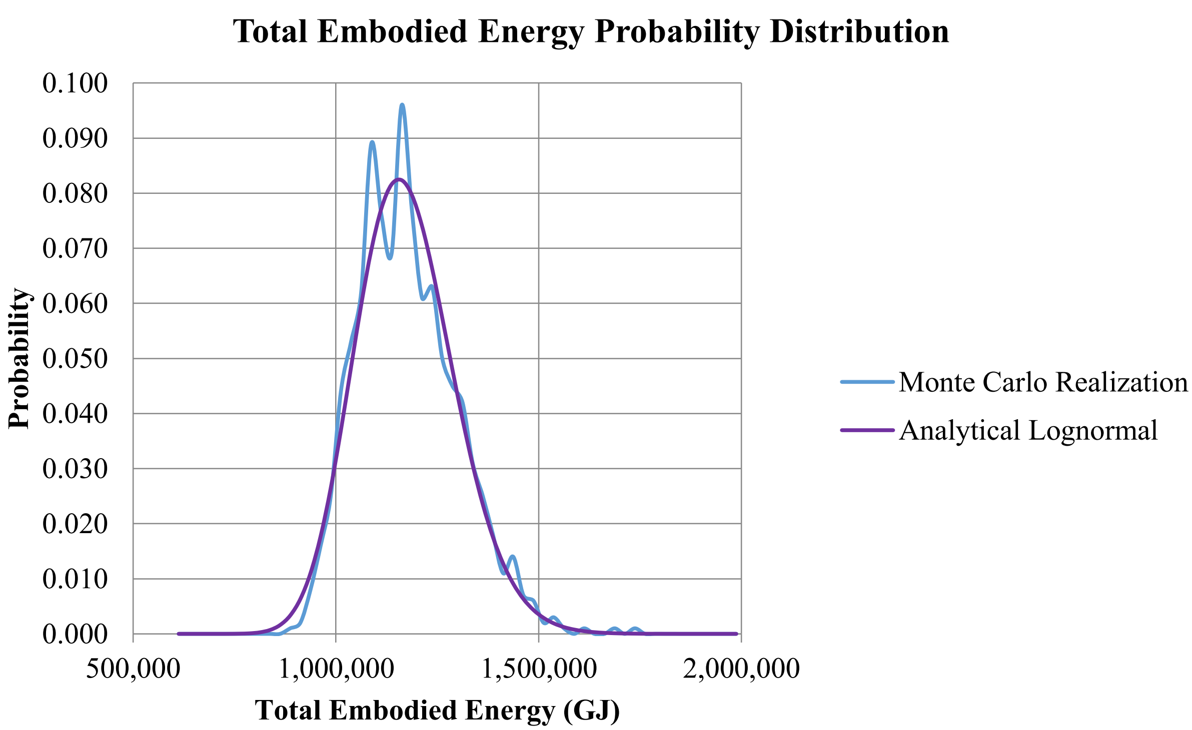

Figure K.1 LPV 111: Comparative plot of total embodied energy probability density functions.

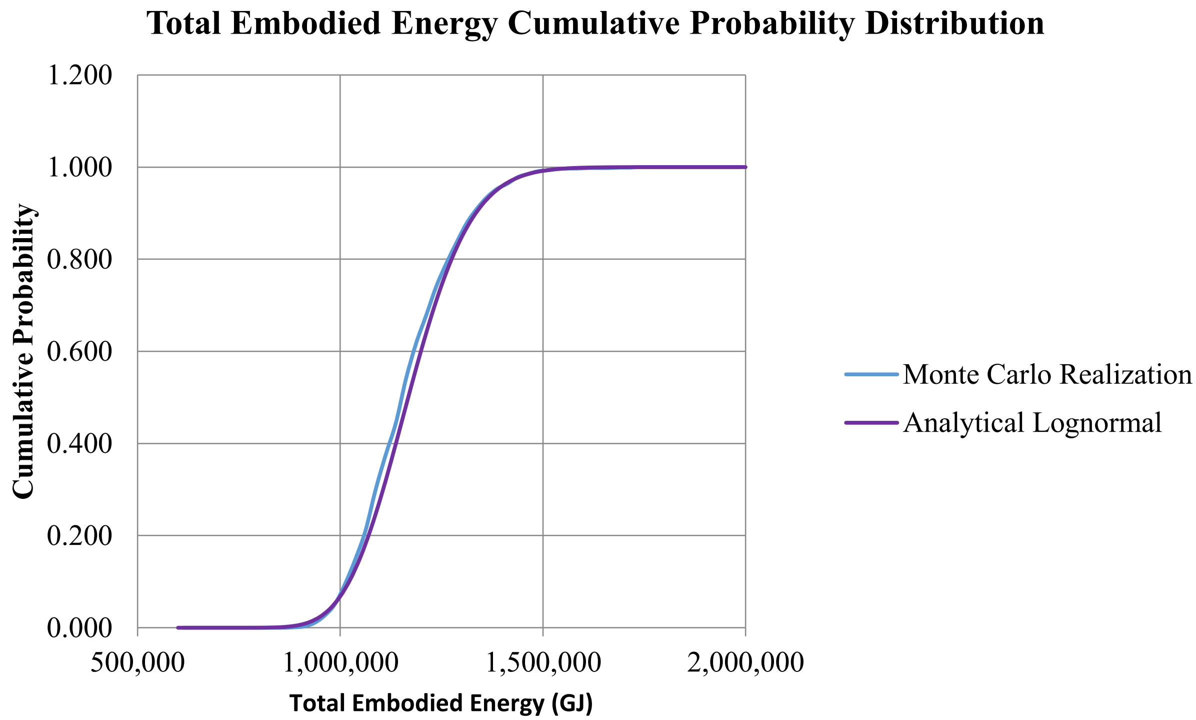

Figure K.2 LPV 111: Comparative plot of total embodied energy cumulative distribution functions.

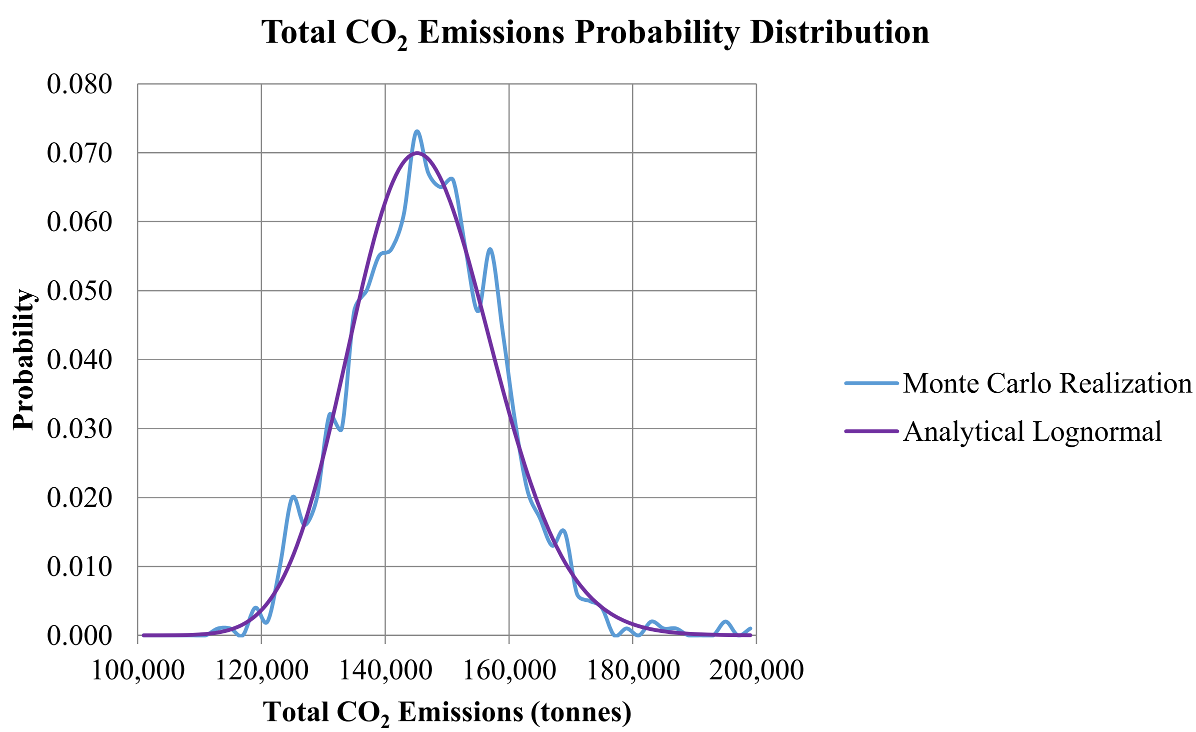

Figure K.3 LPV 111: Comparative plot of total CO_2 emissions probability density functions.

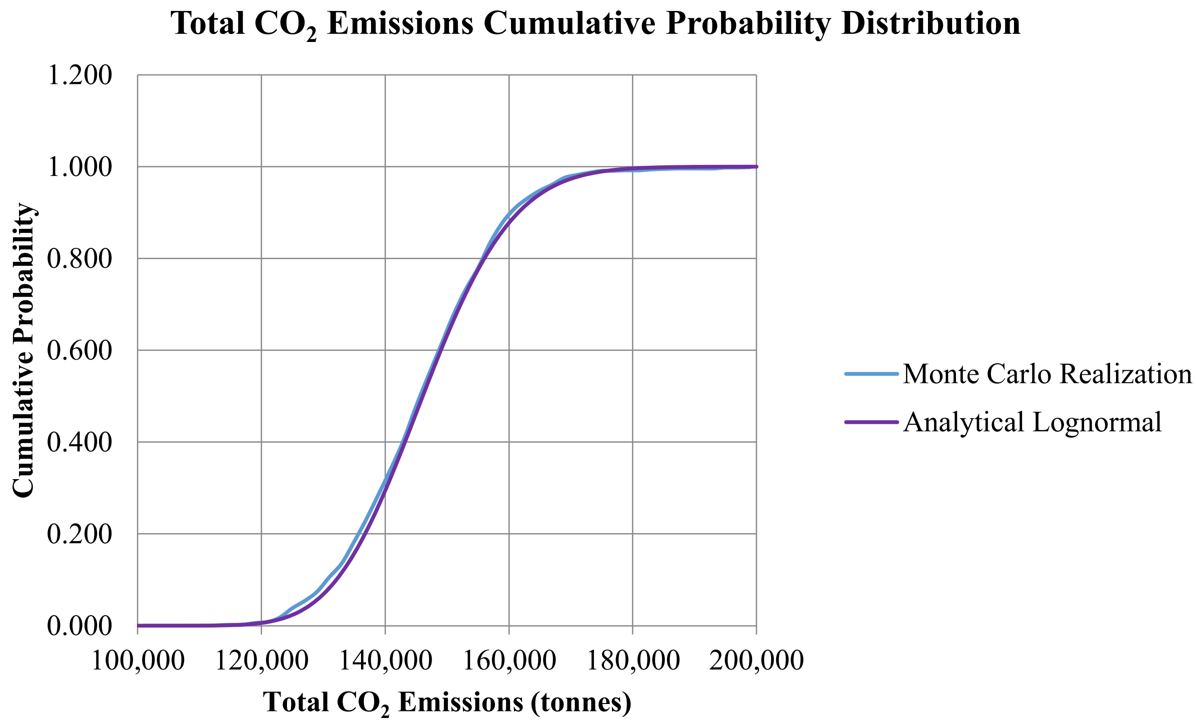

Figure K.4 LPV 111: Comparative plot of total CO_2 emissions cumulative distribution functions.

For embodied energy and CO_2 emissions at LPV 111, the distributions from both the analytical and Monte Carlo approaches match very well for both the PDF and CDF plots, as shown in Figures K.1 – K.4.

P-P plots for the total embodied energy and CO_2 emissions for the LPV 111 project are shown in Figures K.5 and K.6. The P-P plots for embodied energy and CO_2 emissions both indicate that the lognormal distribution derived from the analytical approach generates cumulative probabilities that agree with the Monte Carlo simulation, generally following a 1:1 relationship.

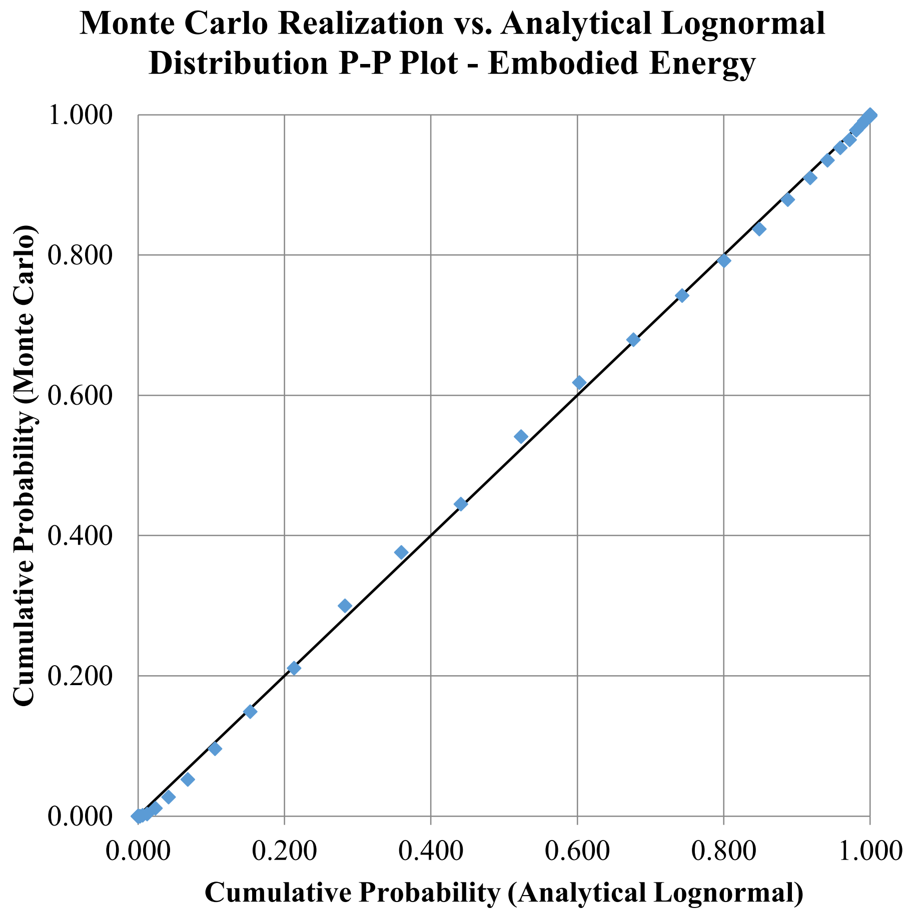

Figure K.5 LPV 111: Embodied energy P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

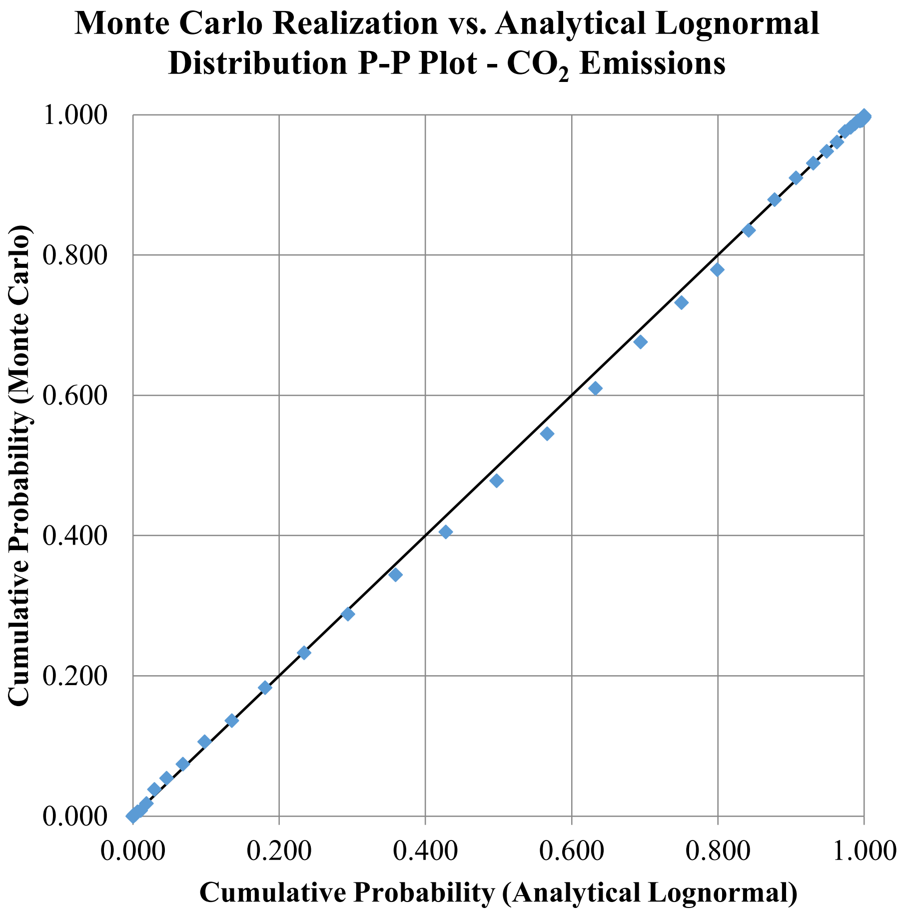

Figure K.6 LPV 111: CO_2 emissions P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

Q-Q plots for the total embodied energy and CO_2 emissions for the LPV 111 project are shown in Figures K.7 and K.8. The embodied energy Q-Q plot shows good agreement between the analytically generated lognormal distribution and the Monte Carlo simulation for all but the most extreme values, where the lognormal distribution slightly underestimates the amount of embodied energy observed in the Monte Carlo simulation. The CO_2 emissions Q-Q plot shows the analytically derived lognormal distribution underestimates CO_2 emissions in the upper tail of the distribution more significantly than the embodied energy plot. Otherwise, Figures K.7 and K.8

show that the analytical approach and Monte Carlo simulation agree well for the analysis of LPV 111.

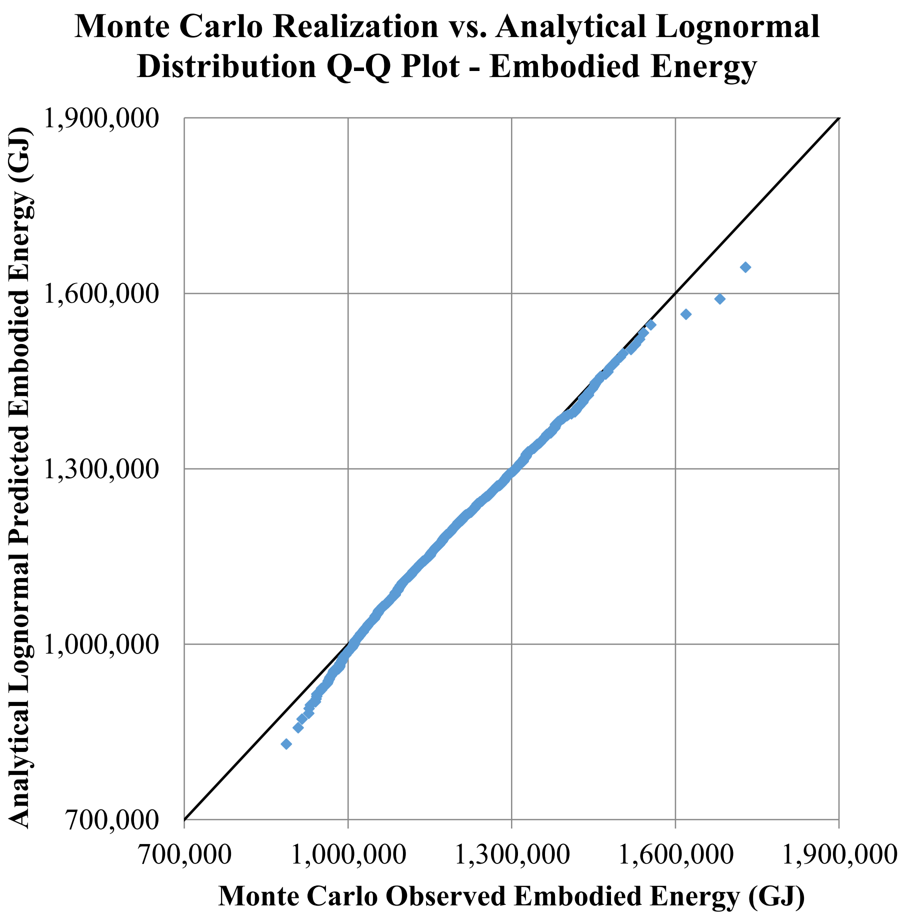

Figure K.7 LPV 111: Embodied energy Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of embodied energy from the lognormal distribution. The estimated embodied energy is plotted against the Monte Carlo "observed" embodied energy.

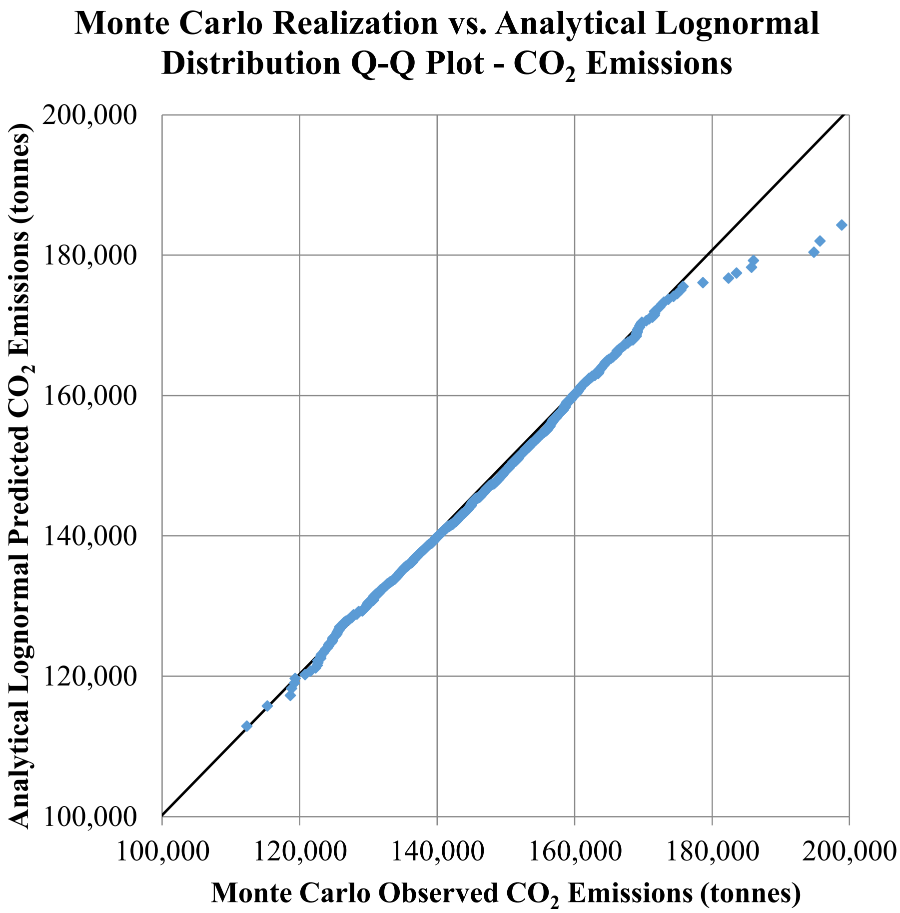

Figure K.8 LPV 111: CO_2 emissions Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of CO_2 emissions. The estimated CO_2 emissions are plotted against the Monte Carlo "observed" CO_2 emissions.

In general, the analytically derived lognormal distributions are a good approximation of the "true" distributions from the Monte Carlo simulation for embodied energy and CO_2 emissions at LPV 111. However, there is a tendency to underestimate values of embodied energy and CO_2 emissions in the extreme tails of the distribution. Despite this, overall, the lognormal approximation seems like a reasonable approach to use based on the LPV 111 results.

K.5.2 Rammed Aggregate Columns at Pearson Hall, Virginia Tech, Blacksburg, VA

The results for the mean and standard deviation of the total embodied energy and CO_2 emissions for the construction of the rammed aggregate columns at Pearson Hall for both the analytical and Monte Carlo methods of accounting for uncertainty in SEEAM analyses are shown in Table K.2. The SEEAM Spreadsheet Calculator line-by-line calculations are shown in Appendix M, Figure M.1. As observed in Table K.2, the means and standard deviations determined by each method agree with each other fairly well, with a maximum difference of 9.90%. For the means alone, the maximum difference is 0.48%, which is much less than the desired maximum of 2.5% mean error. (Note: This is only representing one realization of n = 1,000 values; other realizations could have greater difference from the analytical mean).

Table K.2 Pearson Hall: Total embodied energy and CO_2 emissions by analysis method.

Method of Analysis	Embodied Energy		CO_2 Emissions	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Analytical	1,925	647	232	40
Monte Carlo Simulation	1,934	711	232	36
% Difference	**0.48%**	**9.90%**	**0.32%**	**8.86%**

The lognormal PDFs and CDFs from the analytically derived means and standard deviations were plotted along with the actual distribution of values from the Monte Carlo simulation, as shown in Figures K.9 through K.12.

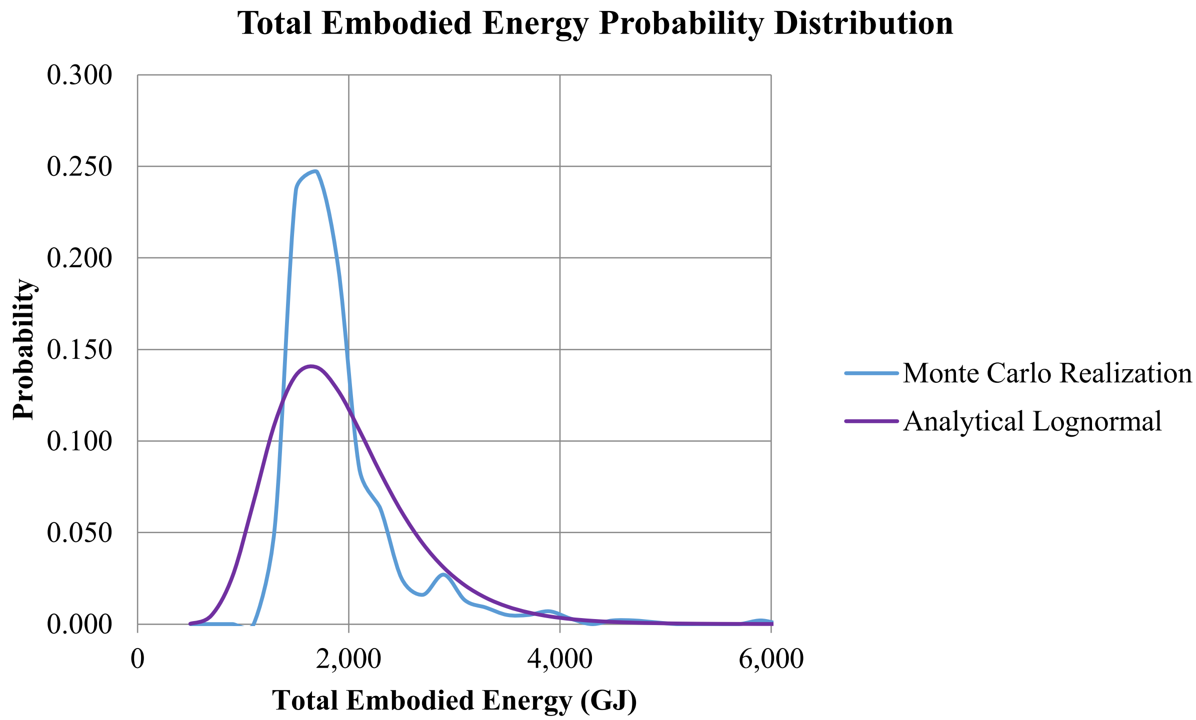

Figure K.9 Pearson Hall: Comparative plot of total embodied energy probability density functions.

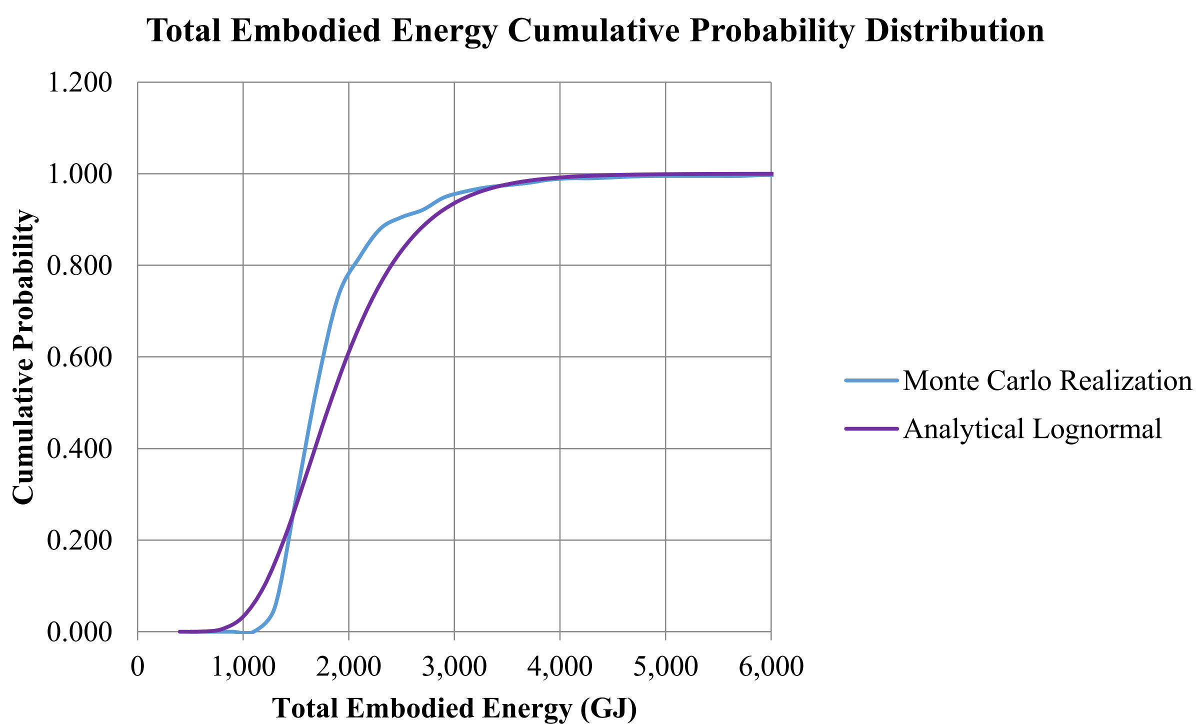

Figure K.10 Pearson Hall: Comparative plot of total embodied energy cumulative distribution functions.

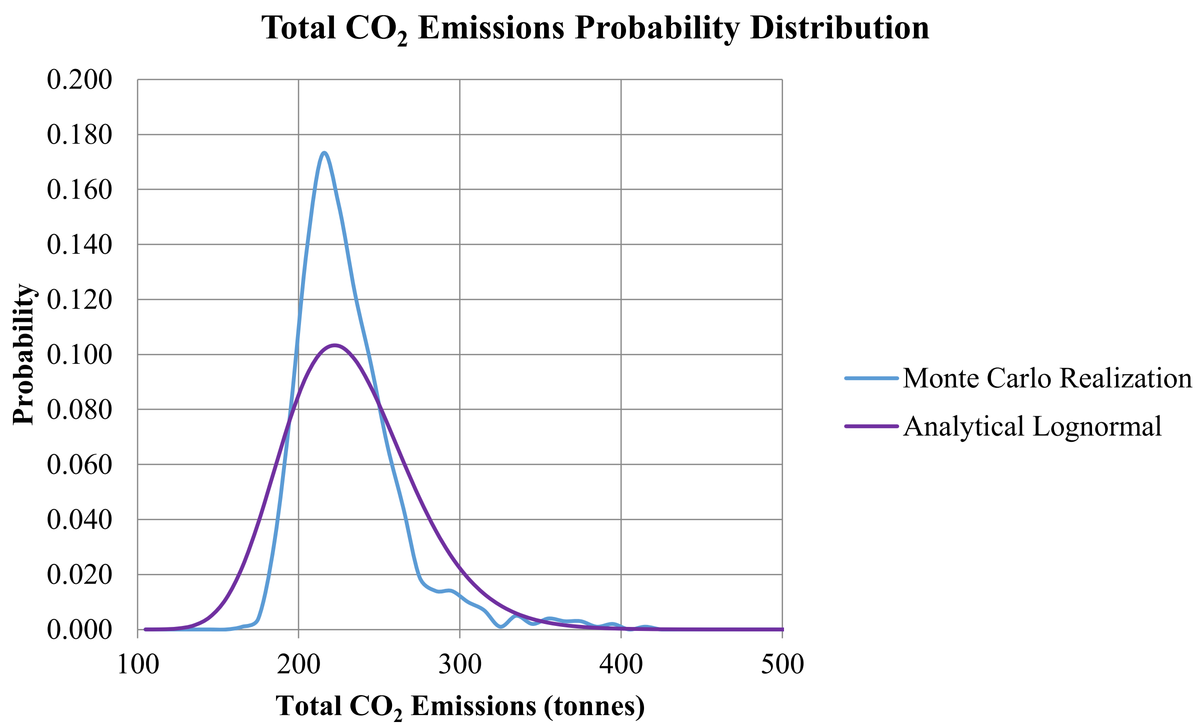

Figure K.11 Pearson Hall: Comparative plot of total CO_2 emissions probability density functions.

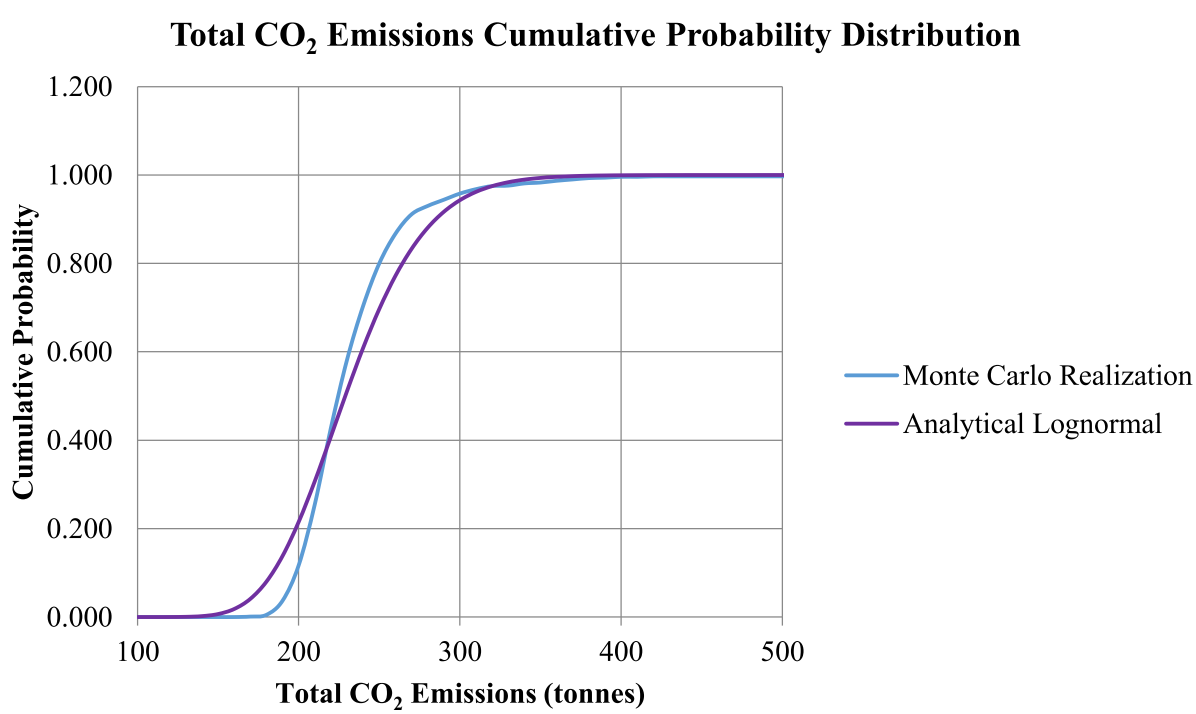

Figure K.12 Pearson Hall: Comparative plot of total CO_2 emissions cumulative distribution functions.

For embodied energy at Pearson Hall, the distribution from the analytical and Monte Carlo approaches do not agree very well for both the PDF and CDF plots, as shown in Figures K.9 and K.10. In this case, the analytical PDF shows a much less pronounced peak than the PDF generated from Monte Carlo simulated data. Taken together, the differences in the PDF and CDF plots indicate that the lognormal distribution overestimates the frequency of low embodied energy values and underestimates the frequency of values of embodied energy in the middle of the distribution.

For CO_2 emissions at Pearson Hall, the distribution from the analytical and Monte Carlo approaches do not agree very well for both the PDF and CDF plots, as shown in Figures K.11 and K.12. The discrepancies are similar to the embodied energy plots, with the lognormal distribution overestimating the frequency of low CO_2 emissions, while underestimating the frequency of CO_2 emissions values in the middle of the distribution.

P-P plots for the total embodied energy and CO_2 emissions for the Pearson Hall project are shown in Figures K.13 and K.14. Both P-P plots are not very linear, indicating that the lognormal distributions derived from the analytical approach significantly overestimate low cumulative probabilities (< 0.4), while underestimating the cumulative probability from 0.4 to 0.95.

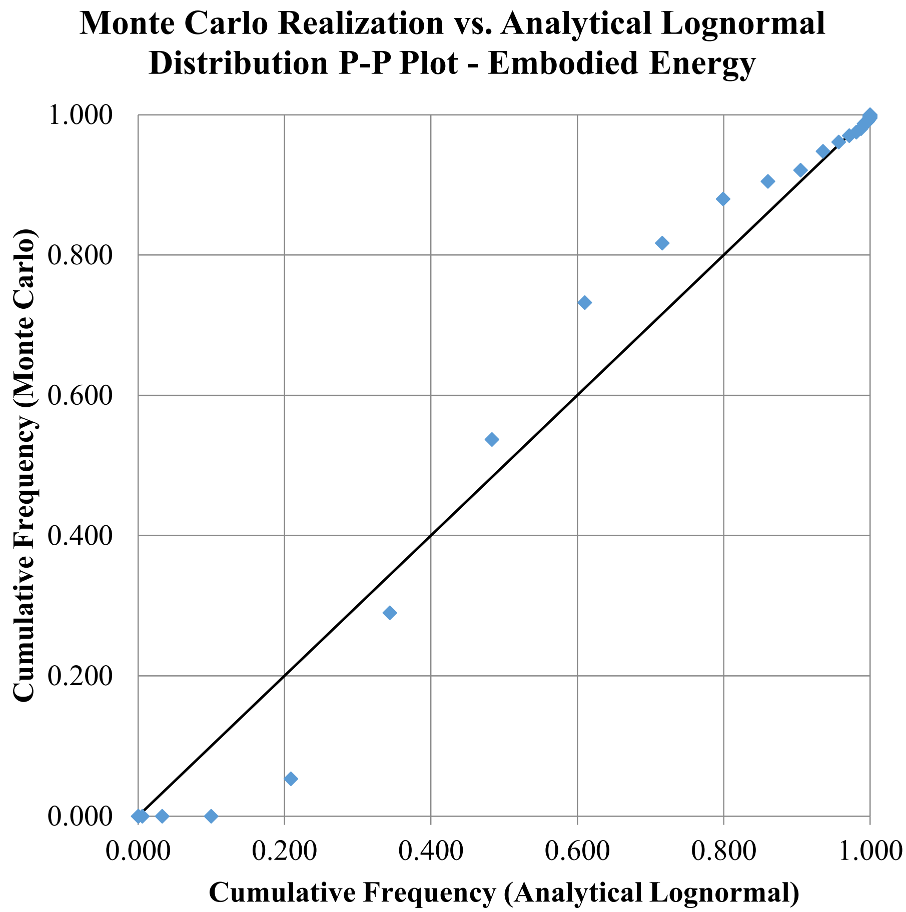

Figure K.13 Pearson Hall: Embodied energy P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

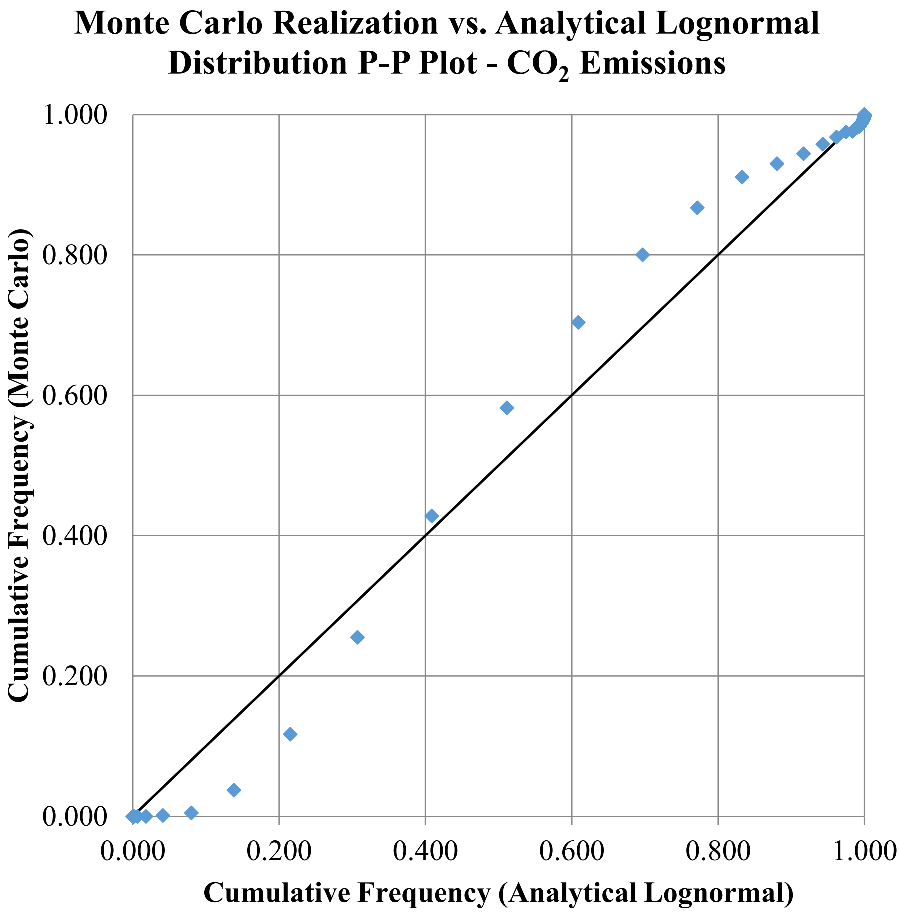

Figure K.14 Pearson Hall: CO_2 emissions P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

Q-Q plots for the total embodied energy and CO_2 emissions for the Pearson Hall project are shown in Figures K.15 and K.16. Both Q-Q plots indicate that the lognormal distributions underestimate extreme values of total embodied energy and CO_2 emissions, especially high extreme values. The lognormal distributions also overestimate total embodied energy and CO_2 emissions through the middle of the range.

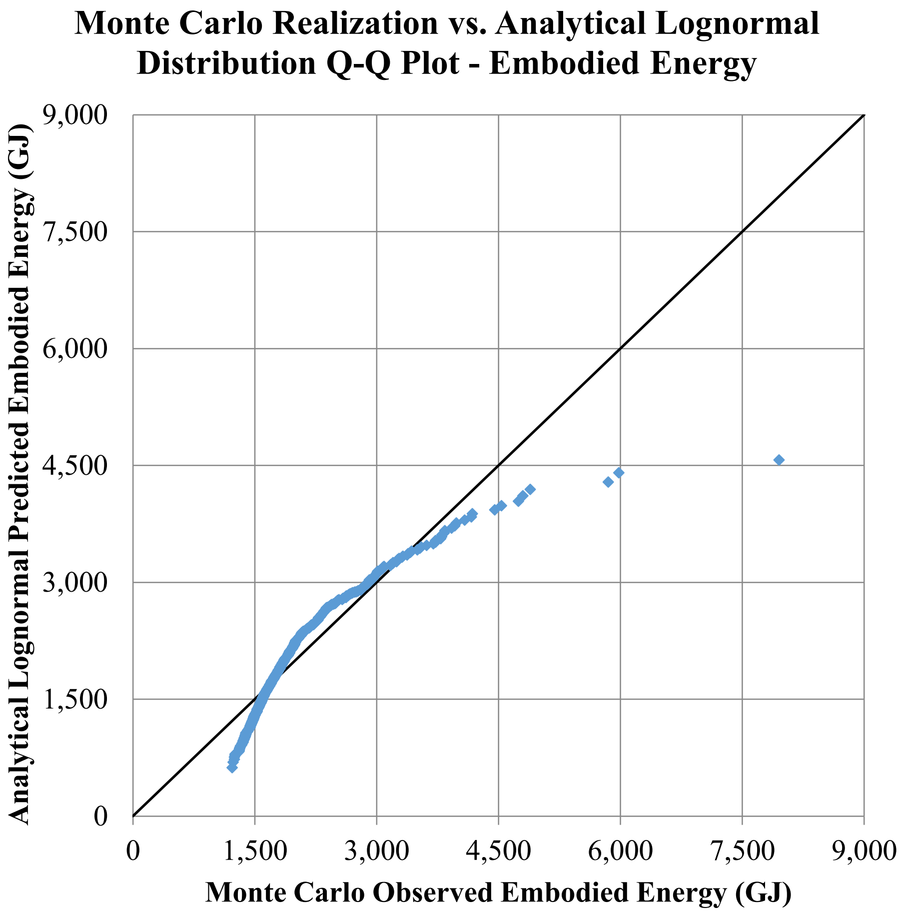

Figure K.15 Pearson Hall: Embodied energy Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of embodied energy from the lognormal distribution. The estimated embodied energy is plotted against the Monte Carlo "observed" embodied energy.

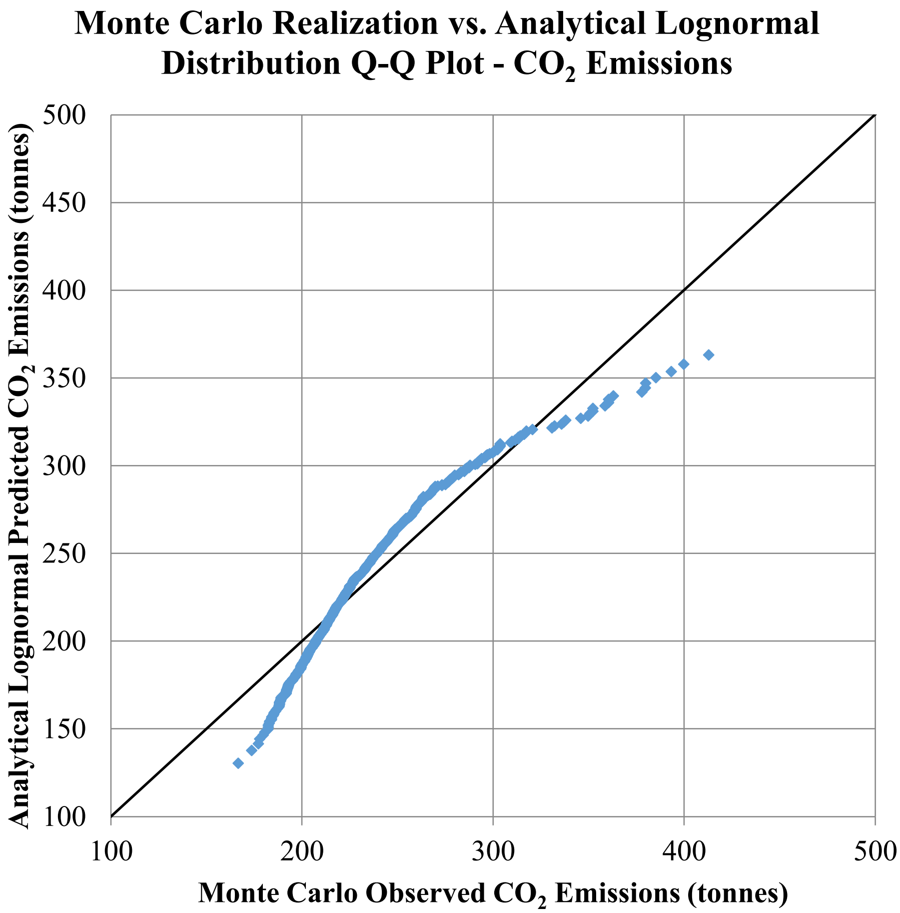

Figure K.16 Pearson Hall: CO_2 emissions Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of CO_2 emissions. The estimated CO_2 emissions are plotted against the Monte Carlo "observed" CO_2 emissions.

Given these results, the analytically derived lognormal distribution is not a good approximation of the "true" distribution from the Monte Carlo simulation for total embodied energy or CO_2 emissions at Pearson Hall.

K.6 DISCUSSION

Raising the crest of LPV 111 was a geotechnical project of enormous scale, consuming large quantities of materials and diesel fuel over the course of 14 months. In contrast, the installation of rammed aggregate columns as part of the foundation support for the new Pearson Hall at Virginia Tech was a relatively small project, consuming 0.04% of the quantity of cementitious material used in LPV 111, and 0.2% of the quantity of diesel fuel. Construction of the rammed aggregate columns was completed in a month. As very large and small projects, the energy and CO_2 emissions from the deep mixing at LPV 111 and the rammed aggregate columns installation at Virginia Tech are likely "bookends" of a reasonable range of embodied energy and CO_2 emissions for typical geotechnical ground improvement construction projects.

For both projects, the analytical method used to compute the mean and standard deviation of total embodied energy and CO_2 emissions agreed well with the mean and standard deviation from the n = 1,000 Monte Carlo simulation. This agreement implies that regardless of the method used, a reasonable mean and standard deviation of total embodied energy and CO_2 emissions for a project can be determined.

The LPV 111 probability distributions derived from Monte Carlo simulation for total embodied energy and CO_2 emissions agree reasonably well with the lognormal distribution generated from the analytically computed mean and standard deviation. However, the same is not true for the analysis of rammed aggregate columns installation at Pearson Hall, where the lognormal distribution significantly underestimates the probability at the mode, and overestimates the probability of low values of embodied energy and CO_2 emissions. Two reasons for the discrepancy between these results (agreement vs. disagreement between the lognormal distribution and the Monte Carlo simulated data) were hypothesized and investigated: 1) the scale of the project (particularly number of materials) influences the distribution of the results, and 2) the results are significantly affected by one (or more) of the input embodied energy and CO_2 emissions coefficients.

K.6.1 Influence of Number of Materials

The influence of project scale (number and quantities of materials) was evaluated by adding a reinforced earth mat over the top of the rammed aggregate columns at Pearson Hall. This change was assumed to add 20 tonnes of plastic geogrid to the materials (transportation of the geogrid was ignored). The SEEAM Spreadsheet Calculator line-by-line calculations for this alternative are shown in Appendix M, Figure M.4. The mean and standard deviation resulting from the analysis are summarized in Table A.3. (Note: This is only representing one realization of n = 1,000 values; other realizations could have greater difference from the analytical mean).

Table K.3 Pearson Hall with geogrid: Total embodied energy and CO_2 emissions by analysis method.

Method of Analysis	Embodied Energy		CO_2 Emissions	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Analytical	3,535	993	287	48
Monte Carlo Simulation	3,531	906	288	50
% Difference	**0.11%**	**8.70%**	**0.30%**	**5.75%**

In this case, the means and standard deviations from the two analyses agree well (maximum 8.70% difference). The lognormal PDF and CDF plots also show better agreement with the Monte Carlo simulation results with the addition of the geogrid than they do for the design case of columns only, as shown in Figures K.17 through K.20.

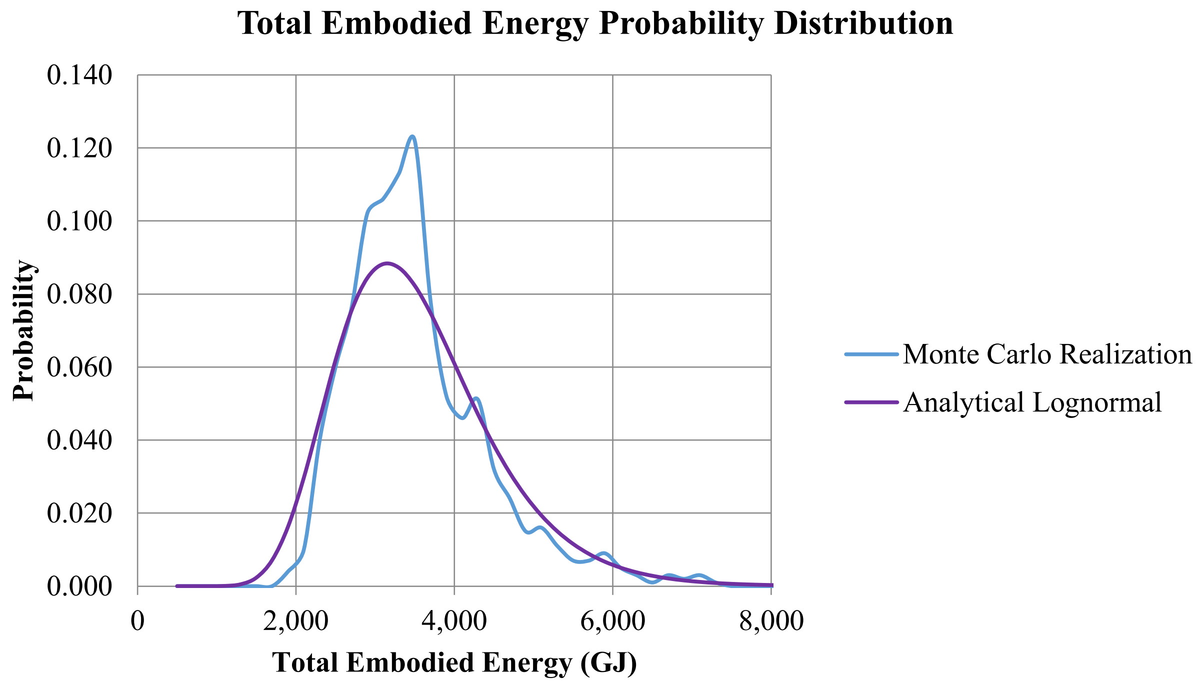

Figure K.17 Pearson Hall with geogrid: Comparative plot of total embodied energy probability density functions.

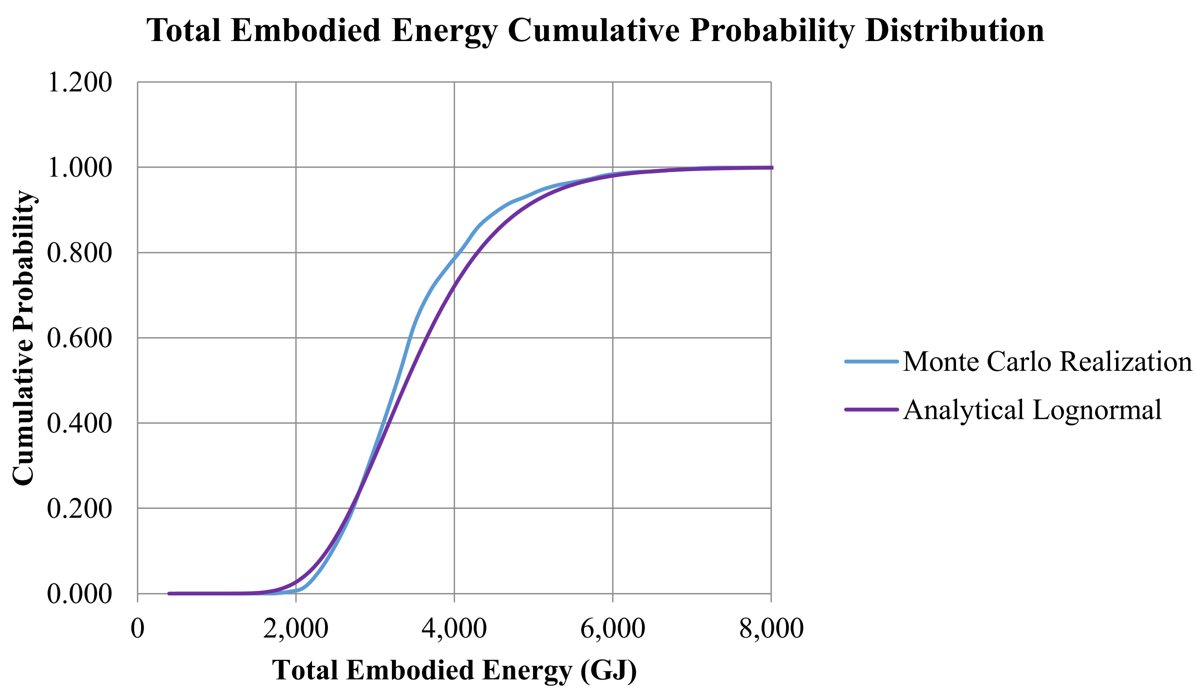

Figure K.18 Pearson Hall with geogrid: Comparative plot of total embodied energy cumulative distribution functions.

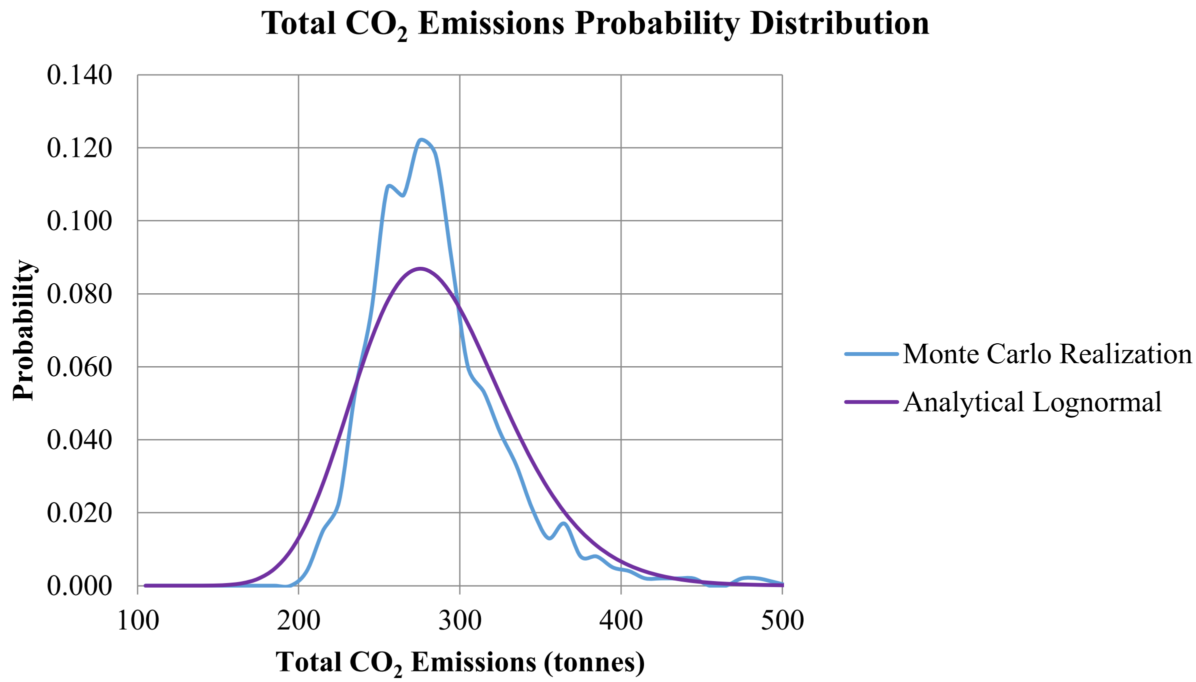

Figure K.19 Pearson Hall with geogrid: Comparative plot of total CO_2 emissions probability density functions.

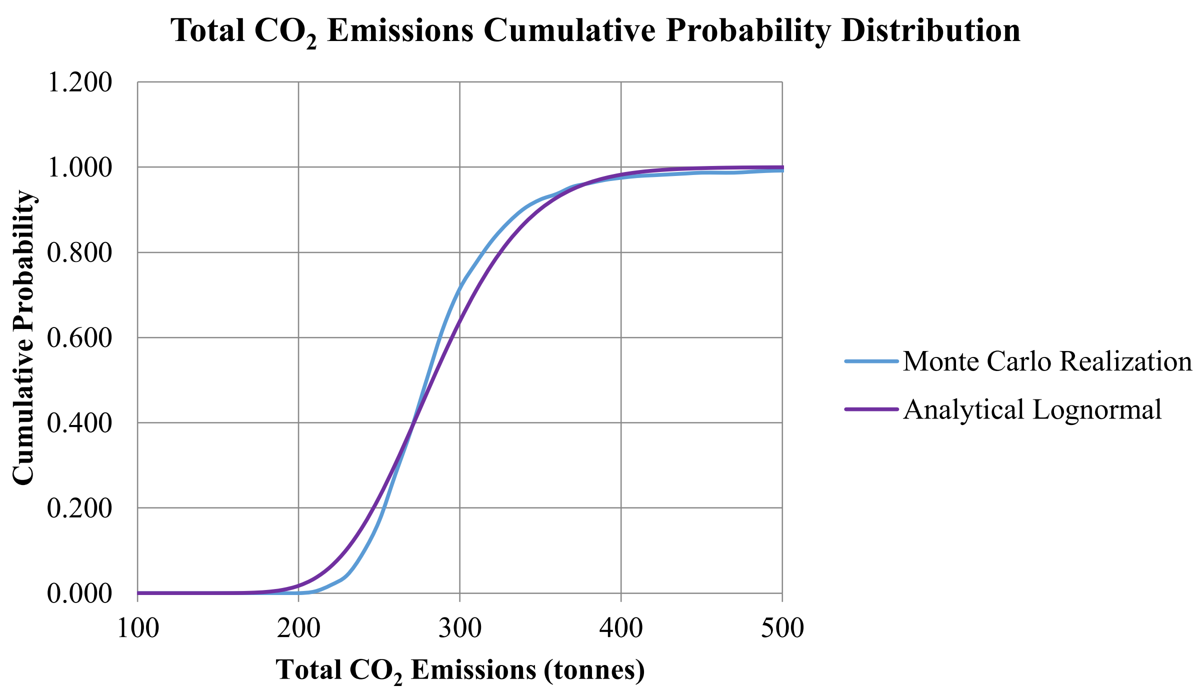

Figure K.20 Pearson Hall with geogrid: Comparative plot of total CO_2 emissions cumulative distribution functions.

Similar to the PDF and CDF plots, the P-P plots and Q-Q plots for rammed aggregate columns at Pearson Hall with the addition of geogrid also show better agreement between the lognormal distribution and the distribution derived through the n = 1,000 Monte Carlo simulation, as shown in Figures K.21 through K.24.

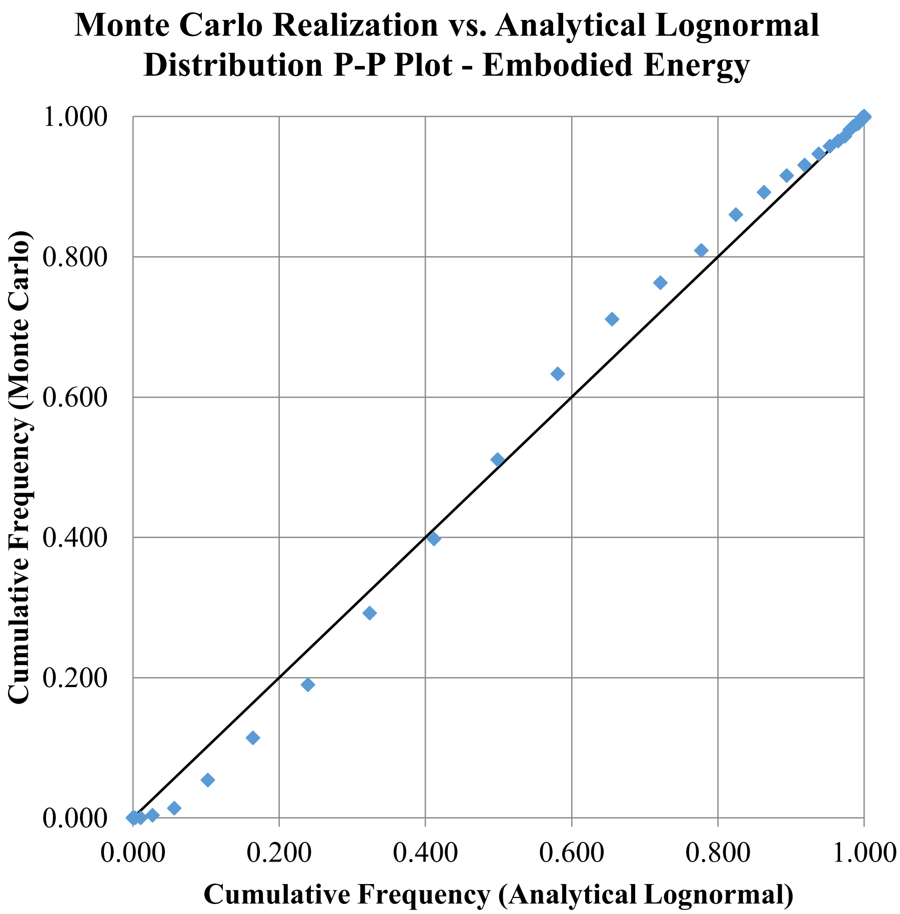

Figure K.21 Pearson Hall with geogrid: Embodied energy P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

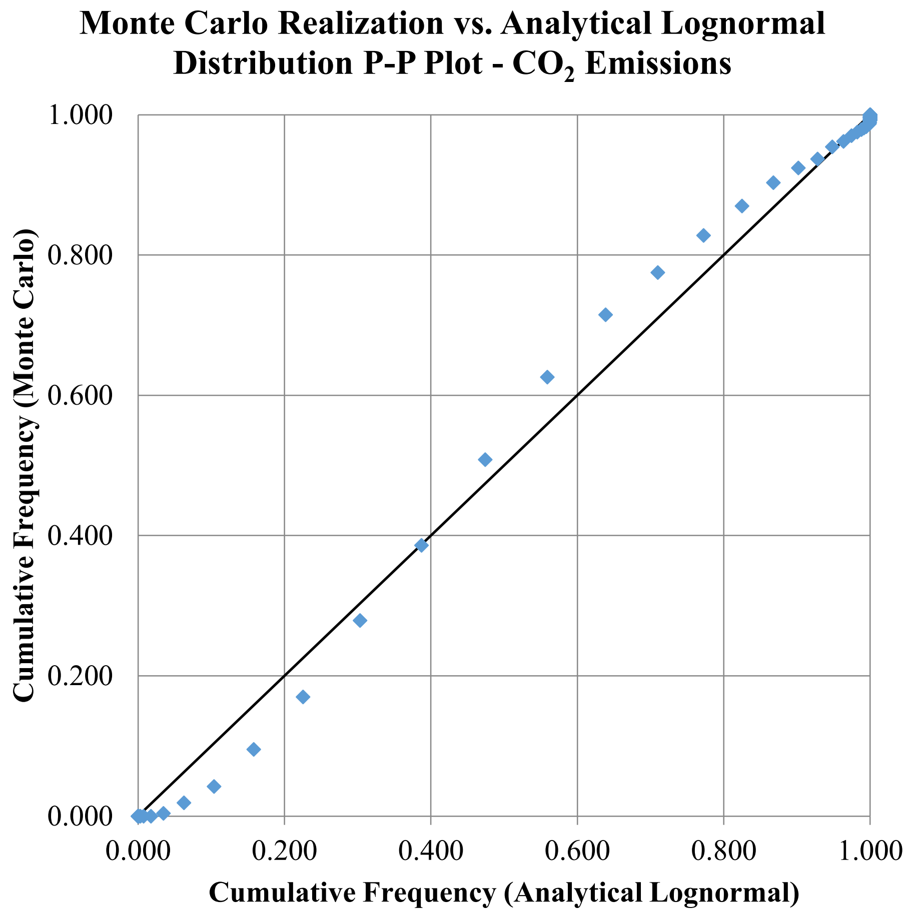

Figure K.22 Pearson Hall with geogrid: CO_2 emissions P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

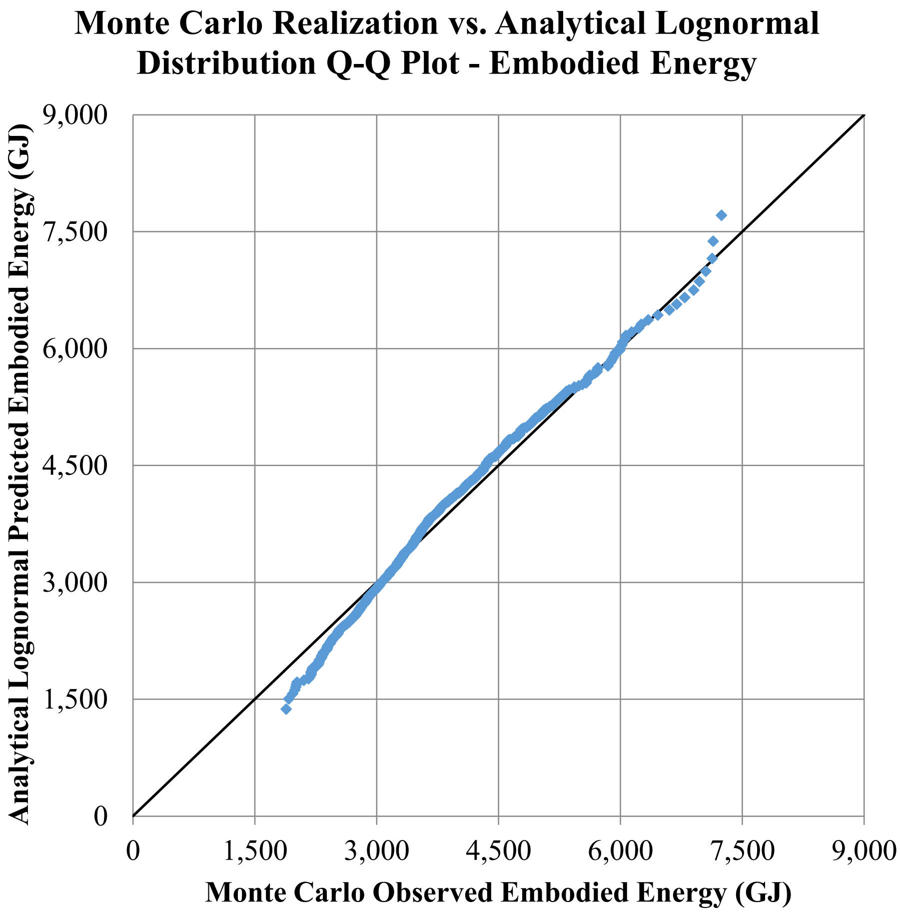

Figure K.23 Pearson Hall with geogrid: Embodied energy Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of embodied energy from the lognormal distribution. The estimated embodied energy is plotted against the Monte Carlo "observed" embodied energy.

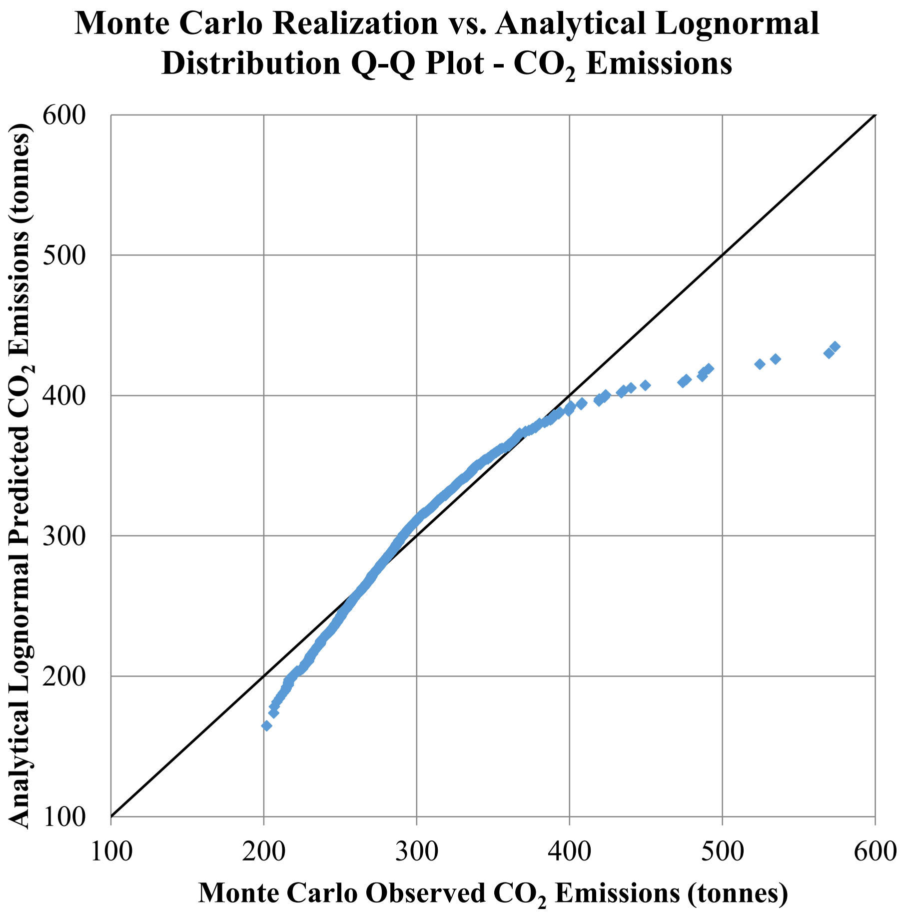

Figure K.24 Pearson Hall with geogrid: CO_2 emissions Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of CO_2 emissions. The estimated CO_2 emissions are plotted against the Monte Carlo "observed" CO_2 emissions.

Based on these results, it appears that additional materials do improve the agreement between the total embodied energy and CO_2 emissions distributions from Monte Carlo simulation and the lognormal distribution. However, this is not believed to be the biggest factor influencing the level of agreement between the distributions, as the trend of underestimating values in the distribution tails is still present, particularly for CO_2 emissions.

K.6.2 Influence of Coefficients

When comparing LPV 111 and Pearson Hall, it is also significant that the predominant construction materials in each project are different. At LPV 111, the predominant material is slag;

the embodied energy coefficient for slag has a coefficient of variation (COV) of 0.29 and the CO_2 emissions coefficient has a COV of 0.52 (See Appendix J for a definition of COV). At Pearson Hall, the predominant material is aggregate; the embodied energy and CO_2 emissions coefficients for aggregate both have a COV of 1.44, which indicates the standard deviation is larger than the mean. Notably, the average COV of all materials with both a mean and standard deviation listed in Table 1 is 0.48 for embodied energy coefficients and 0.51 for CO_2 emissions coefficients. Removing aggregate and sand from the average (both of which have a COV > 1) reduces the average COV for materials to 0.26 for embodied energy coefficients and 0.30 for CO_2 emissions coefficients.

It is very likely that the large COV for aggregate compared to other materials is influencing the results for the total embodied energy and CO_2 emissions distributions. To explore this, the COV for both aggregate coefficients was reduced to 0.5 (approximately equivalent to the highest COV for slag) by decreasing the standard deviation. The adjusted aggregate coefficient standard deviations were then used in an analysis of the rammed aggregate columns construction at Pearson Hall. The analytical SEEAM Spreadsheet Calculator line-by-line calculations for this alternative are shown in Appendix M, Figure M.7. The mean and standard deviations of total embodied energy and CO_2 emissions from the analysis are shown in Table K.4. (Note: This is only representing one realization of n = 1,000 values; other realizations could have greater difference from the analytical mean).

Table K.4 Pearson Hall with aggregate COV = 0.5: Total embodied energy and CO_2 emissions by analysis method.

Method of Analysis	Embodied Energy		CO_2 Emissions	
	Mean	St. Dev.	Mean	St. Dev.
Analytical	1,925	272	232	22
Monte Carlo Simulation	1,919	277	232	22
% Difference	**0.34%**	**1.95%**	**0.14%**	**1.61%**

In this case, the means from the two analyses agree very well (maximum 0.34% difference). The standard deviations also agree well, with a maximum of 1.95% difference for total embodied energy. The PDF and CDF plots also show better agreement between the methods with the reduced COV for the aggregate coefficients, as shown in Figures K.25 through K.28.

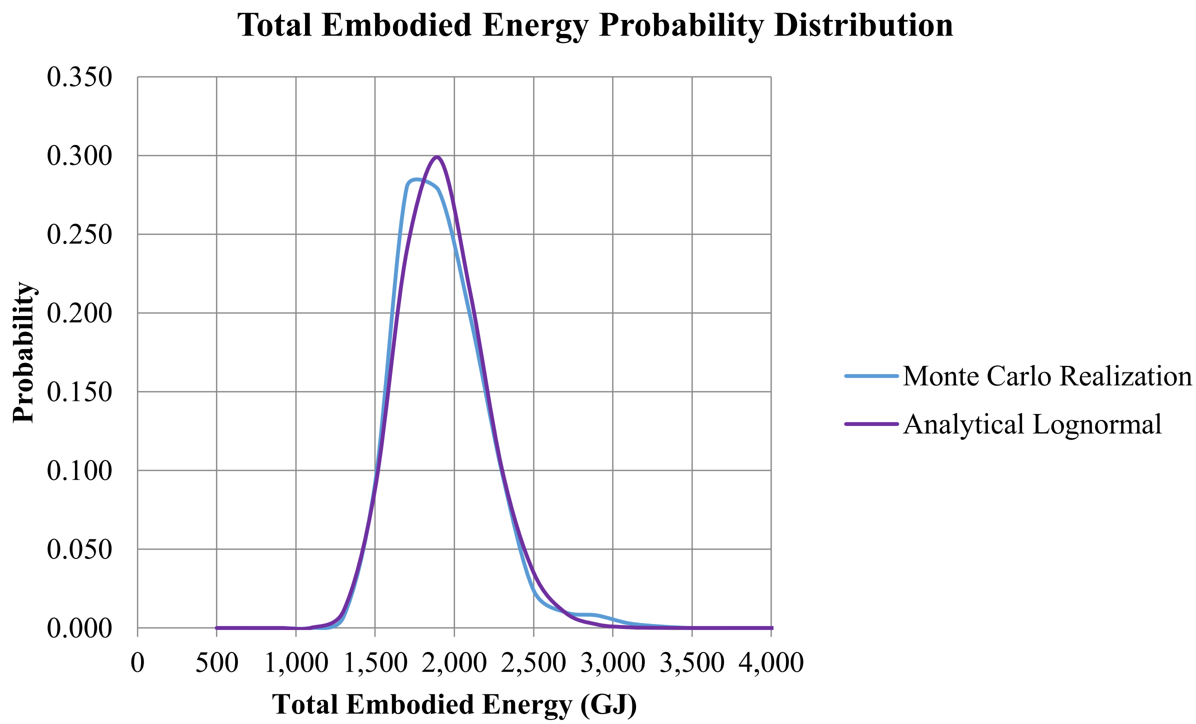

Figure K.25 Pearson Hall with aggregate COV = 0.5: Comparative plot of total embodied energy probability density functions.

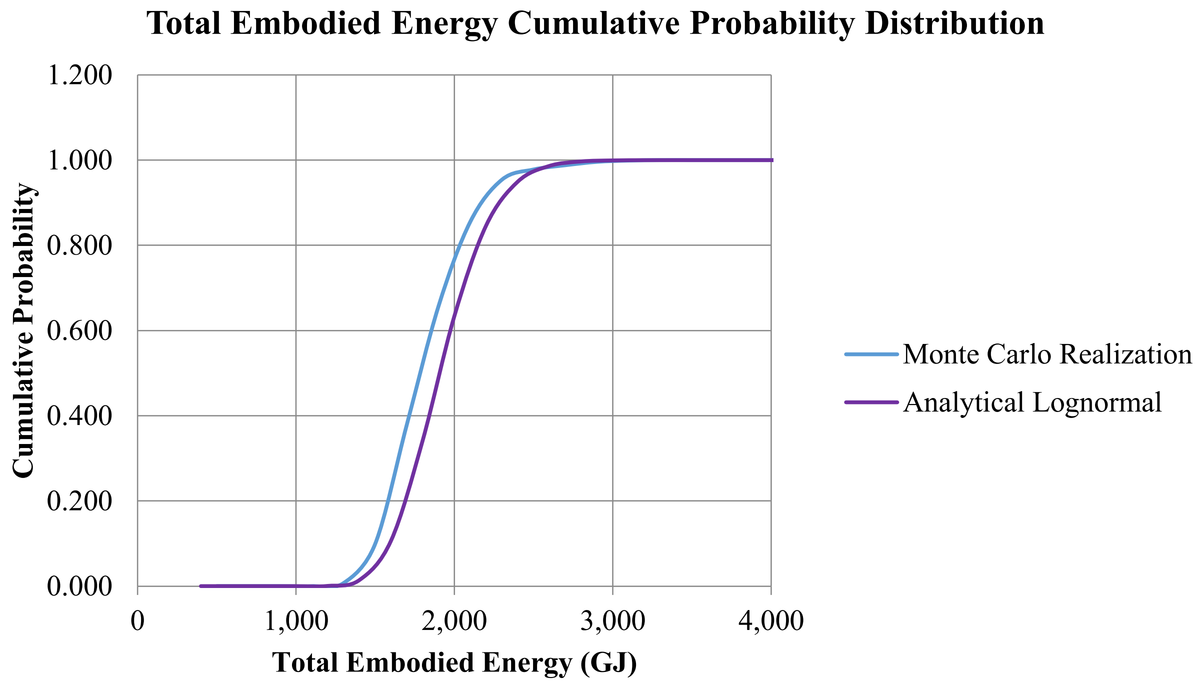

Figure K.26 Pearson Hall with aggregate COV = 0.5: Comparative plot of total embodied energy cumulative distribution functions.

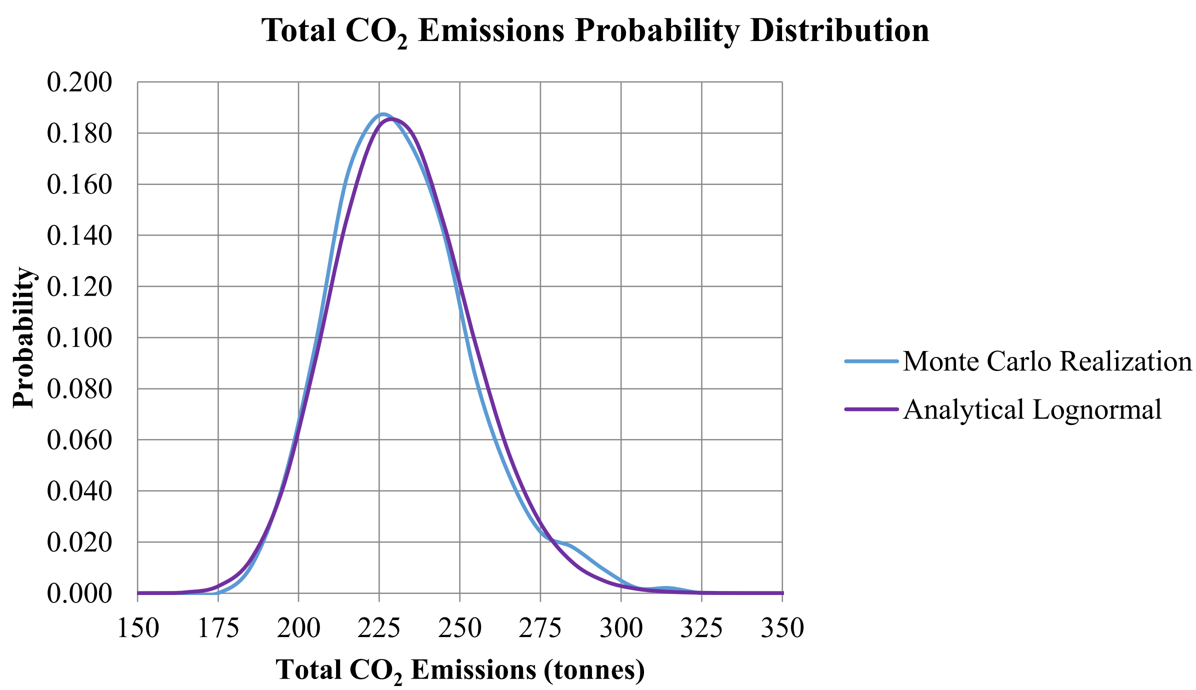

Figure K.27 Pearson Hall with aggregate COV = 0.5: Comparative plot of total CO_2 emissions probability density functions.

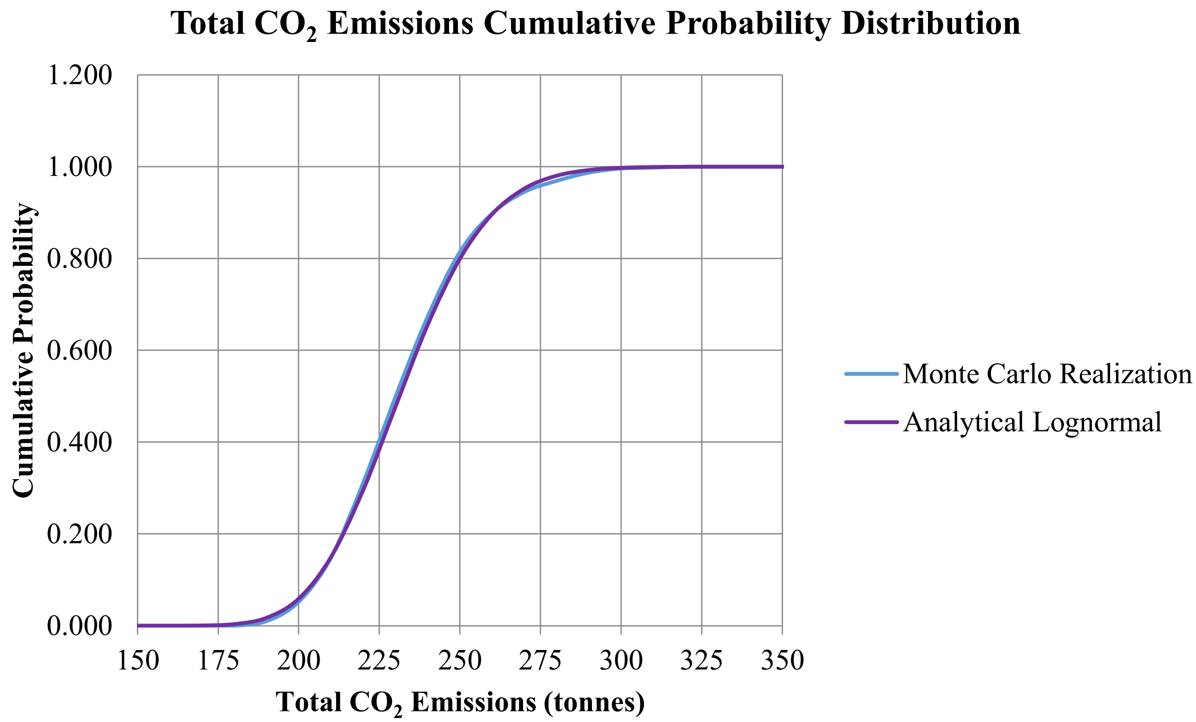

Figure K.28 Pearson Hall with aggregate COV = 0.5: Comparative plot of total CO_2 emissions cumulative distribution functions.

Similar to the PDF and CDF plots, the P-P plots and Q-Q plots for rammed aggregate columns at Pearson Hall with the aggregate coefficients' COV = 0.5 also show better agreement between the lognormal distribution and the empirical distribution derived through the n = 1,000 Monte Carlo simulation, as shown by the plotted points being more aligned with the 1:1 line in Figures K.29 through K.32. While the agreement is much better, there is still a tendency to underestimate the amount of embodied energy and CO_2 emissions in the distribution tails based on the Q-Q plots in Figures K.31 and K.32.

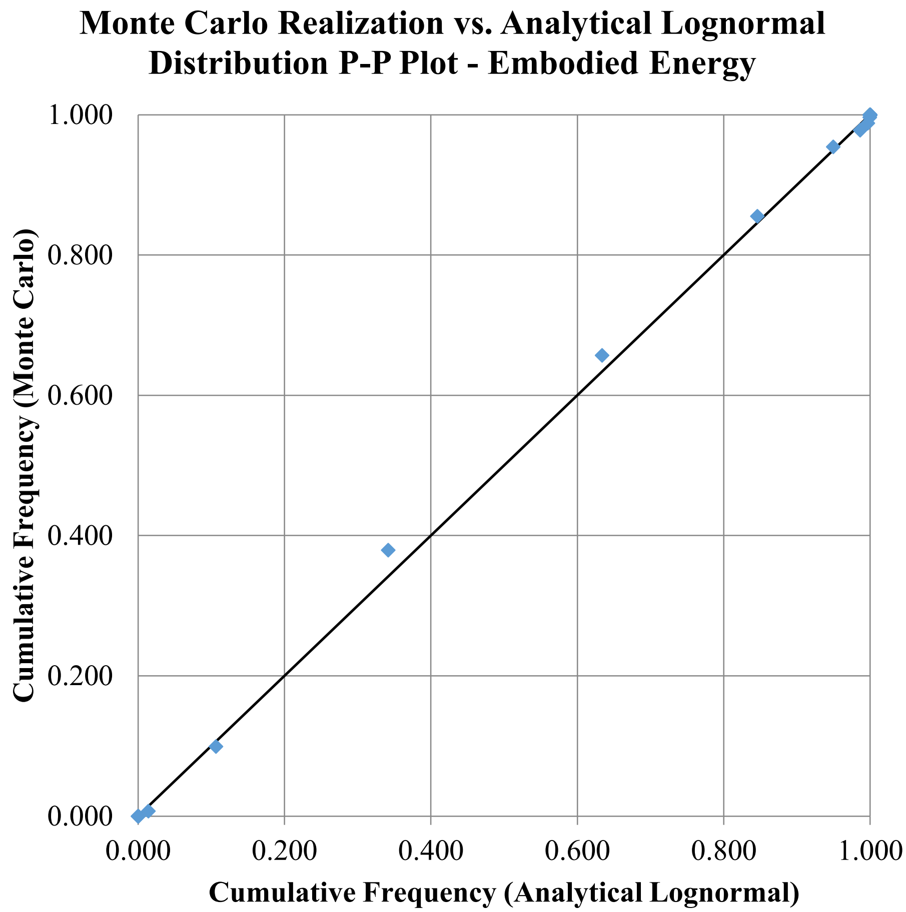

Figure K.29 Pearson Hall with aggregate COV = 0.5: Embodied energy P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

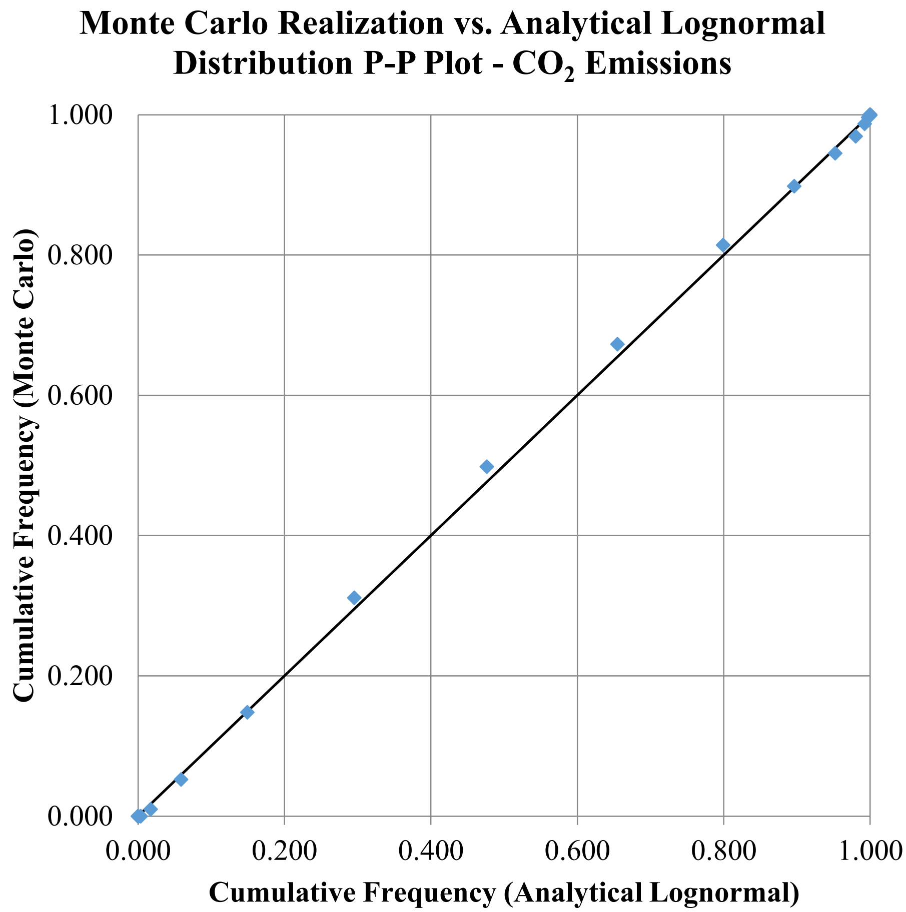

Figure K.30 Pearson Hall with aggregate COV = 0.5: CO_2 emissions P-P plot, showing the cumulative probability from the Monte Carlo simulated data against the cumulative probability from the theoretical lognormal distribution generated from the analytically derived mean and standard deviation.

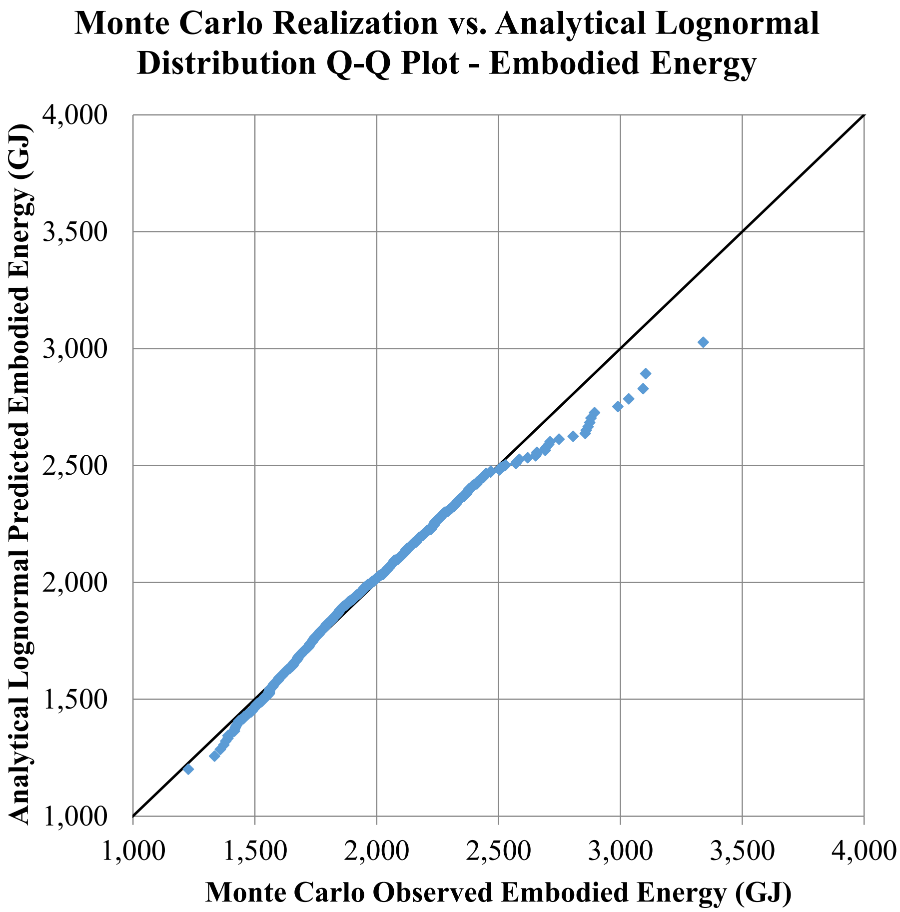

Figure K.31 Pearson Hall with aggregate COV = 0.5: Embodied energy Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of embodied energy from the lognormal distribution. The estimated embodied energy is plotted against the Monte Carlo “observed” embodied energy.

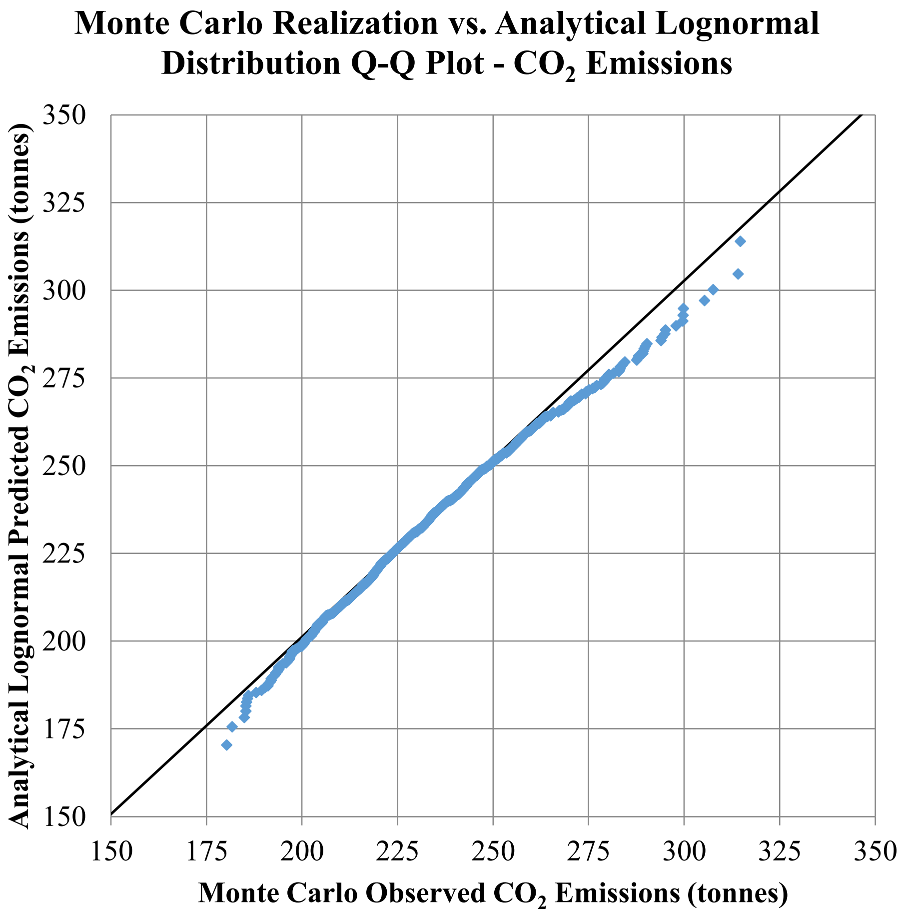

Figure K.32 Pearson Hall with aggregate COV = 0.5: CO_2 emissions Q-Q plot, generated by assigning a cumulative probability to each of the Monte Carlo simulated values, then inverting the theoretical lognormal distribution for each cumulative probability to determine an estimated value of CO_2 emissions. The estimated CO_2 emissions are plotted against the Monte Carlo "observed" CO_2 emissions.

Reducing the COV for the aggregate coefficients from 1.44 to 0.5 by reducing the standard deviation had a significant influence on the results of the total embodied energy and CO_2 emissions analysis. While the mean and standard deviations determined through the analytical and Monte Carlo methods still agree well, the lower COV significantly improves the agreement between the theoretical lognormal distribution, and the distribution from the Monte Carlo simulated data. Aside from underestimating the upper and lower extreme values as shown in the Q-Q plots (similar to

LPV 111, Figures K.7 and K.8), the lognormal distribution appears to be a reasonable fit for the Monte Carlo simulation results.

Based on these results, the embodied energy and CO_2 emissions coefficients' COV appears to be the single most important factor affecting the agreement between the theoretical lognormal distribution derived from a computed mean and standard deviation, and the Monte Carlo simulation. These findings also support the statement made by Beaulieu et al. (1995) that the Fenton-Wilkinson approximation for representing the sum of lognormal random variables as a lognormal distribution is best for small standard deviations.

Given the average COV for materials and the results from this analysis with an aggregate COV of 0.5, it seems that when the coefficients' COV are below 0.5, the lognormal distribution is likely a good approximation of the results, when the embodied energy and CO_2 emissions coefficients follow the lognormal distribution. Even with the presence of materials with a high COV for the coefficients, if a sufficient number of materials are used in sufficient quantities, it can also offset the influence of the large COV and provide better agreement between the distribution from Monte Carlo simulated data and the theoretical lognormal distribution. Ultimately, the standard deviation (and therefore the COV) of the coefficients cannot realistically be changed given the available data. Therefore, the theoretical lognormal approximation is not a good representation of the results for all circumstances.

K.6.3 Recommendations

The findings from the study in this Appendix suggest that the best way to estimate the mean, standard deviation, confidence intervals and likely distribution of total embodied energy and CO_2 emissions for geotechnical projects is through Monte Carlo simulation with at least n = 1,000 values in the simulated data set, generated by computations following the SEEAM methodology. The simulation provides a mean error of +/- 2.5% or less, with 90% confidence for projects ranging from small (Pearson Hall) to massive (LPV 111).

The most critical assumption for the assessment is that the coefficients are distributed lognormally, based on a known mean and standard deviation from input data. The validity of this assumption is crucial to the accuracy of the results, but at the present time the actual distribution of input data is unknown and could not be determined from available information in the reference sources. Therefore, to improve embodied energy and CO_2 emissions assessments that utilize streamlined LCA methods and coefficients, it is imperative to update and improve the coefficients continually. Significant future research could be directed at gathering more input data for the coefficients, such that the distribution of data for the coefficients can be determined (rather than assumed lognormal) and the COV can hopefully be reduced to less than 0.5 for all material coefficients. Improvement in the coefficients can reduce uncertainty in embodied energy and CO_2 emissions assessments, resulting in greater accuracy in the distributions of total project embodied energy and CO_2 emissions.

K.7 CONCLUSIONS

- Considering the coefficients as random variables and performing appropriate computations for the SEEAM method yields values of mean and standard deviation for total embodied energy and CO_2 emissions that are comparable to those generated through a Monte Carlo simulation for $n = 1{,}000$ values.
- Based on the two case history projects analyzed, having $n = 1{,}000$ values in the Monte Carlo simulated data is sufficient to generate mean values of total embodied energy and CO_2 emissions with < +/- 2.5% error in the mean with 90% confidence, when the SEEAM method and coefficients are used.

- The sum distribution of total embodied energy and CO_2 emissions from Monte Carlo simulation does not necessarily agree with the approximated lognormal distribution based on the computed mean and standard deviation.
    - Agreement is best for large projects with many materials, and for projects that utilize materials with coefficients that have small COV (less than about 0.5). When materials with high COV for the embodied energy and CO_2 emissions coefficients are included in the construction, the number of materials can obscure the influence of the high COV on the resulting distribution.
- At present, the better of the two methods for determining the total embodied energy and CO_2 emissions means, standard deviations, distributions, confidence intervals, etc. for geotechnical projects is to perform a Monte Carlo simulation rather than rely on the Fenton-Wilkinson approximation (or other method) to represent the sum of lognormal random variables as a lognormal distribution.
    - Nonparametric statistical hypothesis tests can be used to compare the Monte Carlo simulation results for different project alternatives (See Appendices O and P).
- Additional data to inform the embodied energy and CO_2 emissions coefficients is needed to determine the actual distribution for each coefficient, and to reduce the coefficients' COVs. Any additional data reduces epistemic uncertainty and can be used to improve the accuracy of total project embodied energy and CO_2 emissions assessments.

K.8 REFERENCES

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Appendix L: Pearson Hall Rammed Aggregate Columns Construction Data and Unit Quantities

This Appendix contains subsurface investigation and construction data for the rammed aggregate columns construction at Pearson Hall.

L.1 COLUMN LOCATIONS AND ELEVATIONS

Table L.1 (9 pages) contains top and bottom elevations for all Cement Treated Aggregate (CTA) rammed aggregate columns, as installed at Pearson Hall. Table L.2 (1 page) contains top and bottom elevations for all Untreated Aggregate (UA) rammed aggregate columns, as installed at Pearson Hall. The aggregates used in the untreated columns include 21A and #57, as specified in the Virginia Department of Transportation Road and Bridge Specifications (2007). Table L.3 contains ground surface and top of rock elevations for all of the geotechnical borings performed on-site. Note that the ground surface elevations in table L.3 were determined from a contour map of the site and are not actual surveyed elevations. The top of rock elevations at each boring were determined based on the depth where rock was encountered as documented in the boring logs. The X and Y location coordinates listed in Tables L.1, L.2 and L.3 for each rammed aggregate column and boring correspond to an assumed local coordinate system on the site. Figure L.1 (similar to Figure 6.1) shows a plan view of the locations of each type of rammed aggregate column, and all of the geotechnical borings.

Table L.1 Pearson Hall Cement Treated Rammed Aggregate Columns: top and bottom elevations and location coordinates.

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
1	2089.3	2046.3	462.4	235.0
2	2089.3	2043.3	466.8	237.6
3	2089.3	2043.3	471.2	235.0
5	2089.5	2043.5	469.6	225.0
6	2089.5	2045.5	462.6	218.9
9	2089.5	2056.5	462.6	203.3
12	2089.3	2057.3	490.0	171.0
13	2089.3	2056.3	490.0	160.5
14	2089.6	2041.6	511.6	136.5
15	2089.3	2047.3	483.6	128.7
16	2089.3	2044.3	493.0	128.7
17	2089.3	2046.3	488.5	124.1
18	2089.3	2046.3	483.6	119.5
19	2089.3	2047.3	493.0	119.5
20	2089.5	2057.5	456.3	114.8
21	2089.5	2054.5	462.6	114.8
22	2089.5	2048.5	456.3	106.5
23	2089.5	2044.5	462.6	106.5
24	2089.5	2048.5	456.3	98.2
25	2089.5	2046.5	462.6	98.2
26	2089.3	2038.3	483.6	94.1
27	2089.3	2043.3	493.0	94.1
28	2089.3	2043.3	488.5	88.9
29	2089.3	2043.3	483.6	84.3
30	2089.3	2043.3	493.0	84.3
64	2088.2	2057.2	367.7	14.5
65	2088.2	2044.2	377.1	14.5
66	2088.0	2046.0	372.2	9.7
67	2088.2	2052.2	367.7	4.8
68	2088.0	2058.0	377.1	4.8
69	2088.0	2044.0	402.5	14.5
70	2088.0	2049.0	414.2	14.5
71	2088.0	2053.0	405.5	9.7
72	2088.0	2050.0	411.5	9.7
73	2088.0	2046.0	402.5	4.8
74	2088.0	2040.0	414.2	4.8
79	2089.5	2054.5	425.8	221.4

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
80	2089.5	2057.5	433.2	221.4
81	2089.5	2046.5	440.6	221.4
82	2089.5	2052.5	447.9	221.4
83	2089.5	2054.5	455.2	221.4
84	2089.5	2056.5	425.8	215.3
85	2089.5	2057.5	433.2	215.3
86	2089.5	2058.5	440.6	215.3
87	2089.5	2060.5	447.9	215.3
88	2089.3	2060.3	455.2	215.3
89	2089.5	2059.5	446.7	209.2
90	2089.5	2062.5	438.2	209.2
91	2089.5	2066.5	429.7	209.2
92	2089.5	2063.5	455.2	209.2
93	2089.5	2062.5	448.5	203.1
94	2089.5	2064.5	441.9	203.1
95	2089.5	2046.5	435.3	203.1
96	2089.7	2047.7	455.2	203.1
97	2089.0	2050.0	441.2	64.3
98	2089.0	2047.0	447.4	64.3
99	2088.6	2048.6	424.0	56.0
100	2088.6	2048.6	430.8	59.0
101	2088.6	2033.6	436.7	59.0
102	2088.6	2041.6	444.2	59.0
103	2088.6	2047.6	424.0	50.5
104	2088.6	2048.6	430.8	52.0
105	2088.6	2040.6	436.7	52.0
106	2088.6	2048.6	444.2	52.0
107	2088.6	2047.6	451.0	52.0
108	2088.6	2048.6	457.8	52.0
109	2088.6	2039.6	464.7	52.0
110	2088.6	2038.6	430.8	45.0
111	2088.6	2041.6	436.7	45.0
112	2089.0	2042.0	444.2	45.0
113	2089.5	2038.5	451.0	45.0
114	2089.0	2038.0	457.8	45.0
115	2089.0	2040.0	464.7	45.0
116	2089.0	2038.0	430.8	38.0
117	2089.0	2040.0	436.7	38.0
118	2089.0	2045.0	444.2	38.0

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
119	2089.0	2044.0	451.0	38.0
120	2089.0	2041.0	457.8	38.0
121	2088.5	2046.5	464.7	38.0
122	2089.0	2044.0	430.8	31.0
123	2089.5	2043.5	436.7	31.0
124	2089.5	2041.5	444.2	31.0
125	2089.7	2050.7	296.9	59.8
126	2089.7	2046.7	303.4	59.8
127	2089.7	2046.7	310.0	59.8
128	2089.7	2051.7	316.5	59.8
129	2089.7	2054.7	323.1	59.8
130	2089.7	2049.7	329.6	59.8
131	2089.7	2047.7	296.9	53.1
132	2089.7	2050.7	303.4	53.1
133	2089.7	2050.7	310.0	53.1
134	2089.7	2045.7	316.5	53.1
135	2089.7	2054.7	323.1	53.1
136	2089.7	2049.7	329.6	53.1
137	2089.7	2053.7	296.9	46.5
138	2089.7	2044.7	303.4	46.5
139	2089.7	2044.7	310.0	46.5
140	2089.7	2049.7	316.5	46.5
141	2089.7	2054.7	293.0	39.9
142	2089.7	2054.7	299.7	39.9
143	2089.7	2046.7	306.4	39.9
144	2089.7	2042.7	313.0	39.9
145	2089.7	2049.7	293.0	33.2
146	2089.7	2046.7	299.7	33.2
147	2089.7	2055.7	306.4	33.2
148	2089.7	2042.7	313.0	33.2
149	2089.7	2051.7	293.0	26.6
150	2089.7	2055.7	299.7	26.6
151	2089.7	2052.7	295.2	20.5
152	2089.7	2052.7	301.3	20.5
153	2089.7	2059.7	295.2	14.1
154	2089.7	2050.7	301.3	14.1
155	2089.7	2050.7	300.8	8.3
156	2088.0	2055.0	321.8	8.3
157	2088.8	2061.8	327.3	11.1

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
158	2088.7	2061.7	336.4	11.1
159	2088.4	2072.4	347.5	11.1
160	2088.4	2052.4	358.9	11.1
161	2088.0	2044.0	382.2	7.7
162	2088.0	2044.0	389.9	7.7
163	2088.0	2046.0	397.6	7.7
164	2088.0	2047.0	419.8	11.1
165	2089.9	2041.9	441.2	11.1
166	2088.6	2046.6	450.9	11.1
167	2088.6	2052.6	459.7	9.7
168	2088.6	2048.6	459.7	3.3
169	2088.6	2057.6	465.4	3.3
170	2088.6	2049.6	471.4	3.3
171	2088.6	2047.6	474.8	5.2
172	2088.6	2045.6	481.0	5.2
173	2088.6	2058.6	484.5	3.3
174	2088.6	2053.6	490.3	3.3
175	2088.6	2046.6	496.5	3.3
176	2088.6	2043.6	497.0	9.2
177	2088.6	2053.6	497.0	15.0
178	2088.6	2049.6	494.0	19.0
179	2088.6	2048.6	493.6	25.0
180	2088.6	2046.6	497.0	29.0
181	2088.6	2054.6	497.0	34.5
182	2088.6	2045.6	497.0	40.2
183	2088.6	2039.6	491.7	40.2
184	2088.6	2049.6	486.7	40.2
185	2088.6	2039.6	486.6	48.7
186	2088.6	2048.6	486.6	57.9
187	2088.6	2053.6	486.6	67.7
188	2088.6	2043.6	486.6	77.4
189	2089.3	2041.3	490.0	99.4
190	2089.3	2043.3	490.0	106.5
191	2089.3	2037.3	490.0	114.0
192	2089.3	2051.3	486.6	135.9
193	2089.3	2057.3	486.6	144.2
194	2089.3	2056.3	490.0	152.7
195	2089.3	2054.3	490.0	177.1
196	2089.3	2051.3	486.6	183.2

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
197	2089.3	2050.3	486.6	193.1
198	2089.3	2054.3	486.6	203.1
199	2089.3	2050.3	486.6	213.4
200	2089.3	2053.3	486.6	223.4
201	2089.6	2047.6	512.7	144.2
202	2089.6	2047.6	512.7	153.8
203	2086.7	2049.7	512.7	163.8
204	2086.7	2049.7	512.7	173.8
205	2086.7	2053.7	512.7	183.7
206	2086.7	2049.7	512.7	193.7
207	2086.7	2049.7	512.7	203.1
208	2086.7	2046.7	512.7	209.2
209	2086.7	2045.7	512.7	217.2
210	2086.6	2048.6	512.7	225.7
211	2086.7	2046.7	512.7	231.3
212	2087.3	2050.3	507.2	234.1
213	2087.3	2054.3	501.1	231.3
214	2089.3	2052.3	495.6	234.1
215	2089.3	2050.3	489.5	231.3
216	2089.3	2052.3	489.5	236.9
217	2089.3	2060.3	493.4	242.9
218	2089.3	2058.3	489.5	249.0
219	2089.3	2059.3	493.4	254.6
220	2089.3	2058.3	487.1	258.2
221	2089.3	2060.3	481.2	254.6
222	2089.3	2061.3	475.4	258.2
223	2089.3	2061.3	469.9	254.6
224	2089.3	2061.3	469.0	263.2
225	2089.3	2065.3	463.7	258.2
226	2089.3	2061.3	457.4	254.6
227	2089.3	2070.3	457.9	263.2
228	2089.3	2068.3	451.9	258.2
229	2089.3	2061.3	445.8	254.6
230	2089.5	2068.5	440.2	258.2
231	2089.5	2065.5	440.2	247.0
232	2089.5	2051.5	444.1	241.3
233	2089.5	2057.5	444.1	229.4
234	2089.5	2058.5	440.2	235.2
235	2089.5	2057.5	435.3	230.8

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
236	2089.5	2056.5	430.3	226.3
237	2089.5	2058.5	447.4	198.1
238	2089.5	2055.5	443.3	192.6
239	2089.3	2058.3	447.4	187.0
240	2089.5	2057.5	443.3	182.6
241	2089.5	2047.5	443.3	175.7
242	2089.5	2045.5	440.2	170.2
243	2089.5	2040.5	443.3	165.2
244	2089.5	2044.5	440.2	159.5
245	2089.5	2045.5	443.3	154.5
246	2089.5	2054.5	440.2	148.8
247	2089.5	2046.5	443.3	143.8
248	2089.5	2040.5	446.1	138.7
249	2089.0	2040.0	443.3	133.1
250	2089.5	2058.5	462.6	122.4
251	2089.5	2063.5	457.1	125.9
252	2089.5	2056.5	451.6	122.4
253	2089.0	2045.0	446.1	128.0
254	2089.0	2044.0	443.3	122.4
255	2089.5	2044.5	436.7	125.2
256	2089.5	2038.5	433.3	121.4
257	2089.5	2048.5	436.7	117.7
258	2089.5	2046.5	433.3	114.0
259	2089.5	2049.5	436.7	110.3
260	2089.5	2053.5	433.3	106.5
261	2089.5	2049.5	436.7	102.8
262	2089.5	2044.5	433.3	99.1
263	2089.5	2048.5	436.7	95.4
264	2089.5	2046.5	433.3	91.6
265	2089.5	2053.5	436.7	87.9
266	2089.0	2051.0	459.9	87.2
267	2089.5	2054.5	455.7	90.6
268	2089.5	2049.5	451.6	87.2
269	2089.5	2051.5	447.4	89.9
270	2089.5	2051.5	444.7	83.7
271	2089.5	2051.5	447.4	80.2
272	2089.5	2049.5	444.7	74.7
273	2089.0	2049.0	447.4	70.5
274	2088.3	2044.3	420.3	51.5

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
275	2088.3	2044.3	415.3	54.2
276	2088.3	2041.3	405.4	39.8
277	2088.3	2046.3	410.3	43.7
278	2088.3	2056.3	405.4	47.6
279	2088.3	2048.3	410.3	51.5
280	2088.3	2048.3	405.4	54.2
281	2088.0	2043.0	408.7	60.9
282	2088.3	2054.3	404.8	64.2
283	2088.3	2052.3	401.2	60.9
284	2088.3	2057.3	397.3	64.2
285	2088.4	2055.4	393.8	60.9
286	2088.3	2046.3	389.9	64.2
287	2088.3	2056.3	386.3	60.9
288	2088.3	2053.3	382.4	64.2
289	2088.3	2057.3	378.9	60.9
290	2088.3	2054.3	374.9	64.2
291	2088.3	2056.3	371.4	60.9
292	2088.3	2036.3	374.2	38.7
293	2088.3	2043.3	370.5	41.5
294	2088.3	2043.3	374.2	44.8
295	2088.5	2054.5	373.8	50.9
296	2088.5	2061.5	368.6	54.8
297	2088.5	2057.5	364.1	50.9
298	2088.5	2053.5	358.9	54.8
299	2088.5	2049.5	354.4	50.9
300	2088.5	2054.5	349.2	54.8
301	2088.5	2055.5	344.7	50.9
302	2088.5	2057.5	339.5	54.8
303	2088.5	2054.5	335.1	50.9
304	2088.5	2051.5	321.8	41.5
305	2088.5	2056.5	319.0	34.9
306	2088.5	2062.5	325.7	34.9
307	2088.3	2070.3	336.7	34.9
308	2088.3	2072.3	349.5	34.9
309	2088.5	2051.5	360.5	41.5
310	2088.0	2074.0	359.5	34.9
311	2088.0	2047.0	369.6	34.9
312	2088.0	2036.0	379.9	34.9
313	2088.0	2039.0	389.9	34.9

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
314	2088.0	2045.0	400.4	34.9
315	2088.0	2064.0	325.7	28.4
316	2088.0	2072.0	335.4	28.4
317	2088.0	2065.0	348.4	28.4
318	2088.0	2071.0	357.4	28.4
319	2088.0	2055.0	366.9	28.4
320	2088.0	2051.0	376.0	28.4
321	2088.0	2031.0	385.1	28.4
322	2088.0	2039.0	394.6	28.4
323	2088.0	2046.0	406.7	28.4
324	2089.5	2049.5	432.2	28.4
325	2089.5	2047.5	441.2	28.4
326	2088.6	2050.6	450.2	28.4
327	2089.5	2045.5	459.7	28.4
328	2088.6	2040.6	459.7	18.0
329	2088.6	2049.6	466.1	22.8
330	2088.6	2045.6	475.9	27.7
331	2088.6	2046.6	485.6	29.0
332	2088.6	2047.6	477.0	34.3
333	2088.6	2048.6	477.0	40.7
334	2089.0	2046.0	469.6	40.0
335	2089.0	2044.0	469.6	49.8
336	2089.0	2041.0	469.6	59.5
337	2089.5	2039.5	469.6	69.2
338	2089.5	2040.5	469.6	78.9
339	2089.0	2046.0	469.6	89.0
340	2089.5	2043.5	469.6	98.3
341	2089.5	2049.5	469.6	108.5
342	2089.5	2044.5	469.6	118.0
343	2089.5	2055.5	469.6	128.8
344	2089.5	2064.5	469.6	137.2
345	2089.5	2064.5	469.6	147.0
346	2089.5	2060.5	469.6	156.7
347	2089.5	2064.5	469.6	166.5
348	2089.5	2054.5	469.6	176.3
349	2089.5	2053.5	469.6	186.1
350	2089.5	2051.5	469.6	195.9
351	2089.5	2053.5	476.8	203.7
352	2089.3	2049.3	479.5	210.3

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
353	2088.6	2040.6	462.6	57.4
354	2089.5	2042.5	462.6	71.3
355	2089.5	2041.5	462.6	81.6
356	2089.5	2048.5	462.6	91.3
357	2089.5	2066.5	462.6	133.4
358	2089.5	2066.5	462.6	142.2
359	2089.5	2058.5	462.6	150.9
360	2089.5	2053.5	462.6	159.7
361	2089.5	2063.5	462.6	168.4
362	2089.5	2063.5	462.6	177.2
363	2089.5	2047.5	462.6	185.9
364	2089.5	2044.5	455.7	186.7

Table L.2 Pearson Hall Untreated Rammed Aggregate Columns: top and bottom elevations and location coordinates.

Column No.	Actual Top Elevation (ft)	Actual Bottom Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
4	2089.6	2072.6	453.0	230.2
7	2089.5	2068.5	468.5	80.8
8	2089.5	2068.5	470.7	78.6
10	2089.5	2073.5	469.6	203.7
11	2089.5	2073.5	462.6	192.6
31	2088.5	2077.5	462.6	64.3
32	2088.5	2073.5	330.7	36.0
33	2088.5	2073.5	332.9	33.8
34	2088.2	2074.2	340.6	36.0
35	2088.2	2074.2	343.4	33.8
36	2088.4	2073.4	407.0	36.0
37	2088.4	2073.4	409.2	33.8
38	2088.4	2073.4	412.6	36.0
39	2088.4	2072.4	414.8	33.8
40	2088.8	2068.8	423.9	36.0
41	2088.8	2067.8	426.7	33.8
42	2089.8	2069.8	306.9	28.8
43	2089.8	2070.8	387.1	26.6
44	2089.8	2069.8	306.9	24.3
45	2089.8	2076.8	319.6	29.1
46	2089.8	2076.8	321.8	26.9
47	2088.8	2071.8	331.4	28.4
48	2088.4	2072.4	341.9	28.4
49	2088.4	2074.4	399.3	29.1
50	2088.4	2073.4	401.5	26.9
51	2088.4	2070.4	414.0	29.9
52	2088.4	2070.4	412.2	26.6
53	2088.4	2070.4	415.9	26.6
54	2088.8	2068.8	423.9	29.1
55	2088.8	2068.8	426.7	26.9
56	2089.8	2070.8	307.4	9.7
57	2089.8	2069.8	309.6	6.9
58	2089.8	2070.8	315.2	9.7
59	2089.8	2070.8	317.4	6.9
60	2088.8	2074.8	331.4	11.1
61	2088.4	2064.4	340.6	12.5
62	2088.4	2070.4	343.4	9.7
63	2088.4	2075.4	352.8	11.1
75	2090.9	2072.9	423.9	12.5
76	2090.9	2074.9	426.7	9.7
77	2090.9	2074.9	429.4	10.4
78	2090.9	2077.9	433.6	8.3

Table L.3 Ground surface elevation, top of rock elevation, and location coordinates from the geotechnical borings around Pearson Hall.

Boring No.	Surface Elevation (ft)	Top of Rock Elevation (ft)	X coordinate (ft)	Y coordinate (ft)
1	2095	2053.5	175.6	67.8
2	2098	2057.5	98.1	77.2
3	2100	2073.0	75.6	166.7
4	2100	2056.4	95.9	245.9
5	2088	2048.0	10.8	203.7
6	2090	2037.0	21.4	84.9
7	2091	2059.0	29.9	3.2
8	2092	2037.0	127.4	3.2
9	2092	2027.0	192.9	4.8
10	2100	2047.5	501.1	263.0
11	2100	2026.4	425.8	125.6
12	2096	2043.5	388.2	70.8
13	2095	2035.0	303.0	64.4
14	2092	2052.0	312.4	1.4
15	2092	2027.0	394.9	0.6
16	2091	2036.0	505.5	2.2
17	2092	2041.0	505.3	67.5
18	2099	2049.0	505.0	116.2

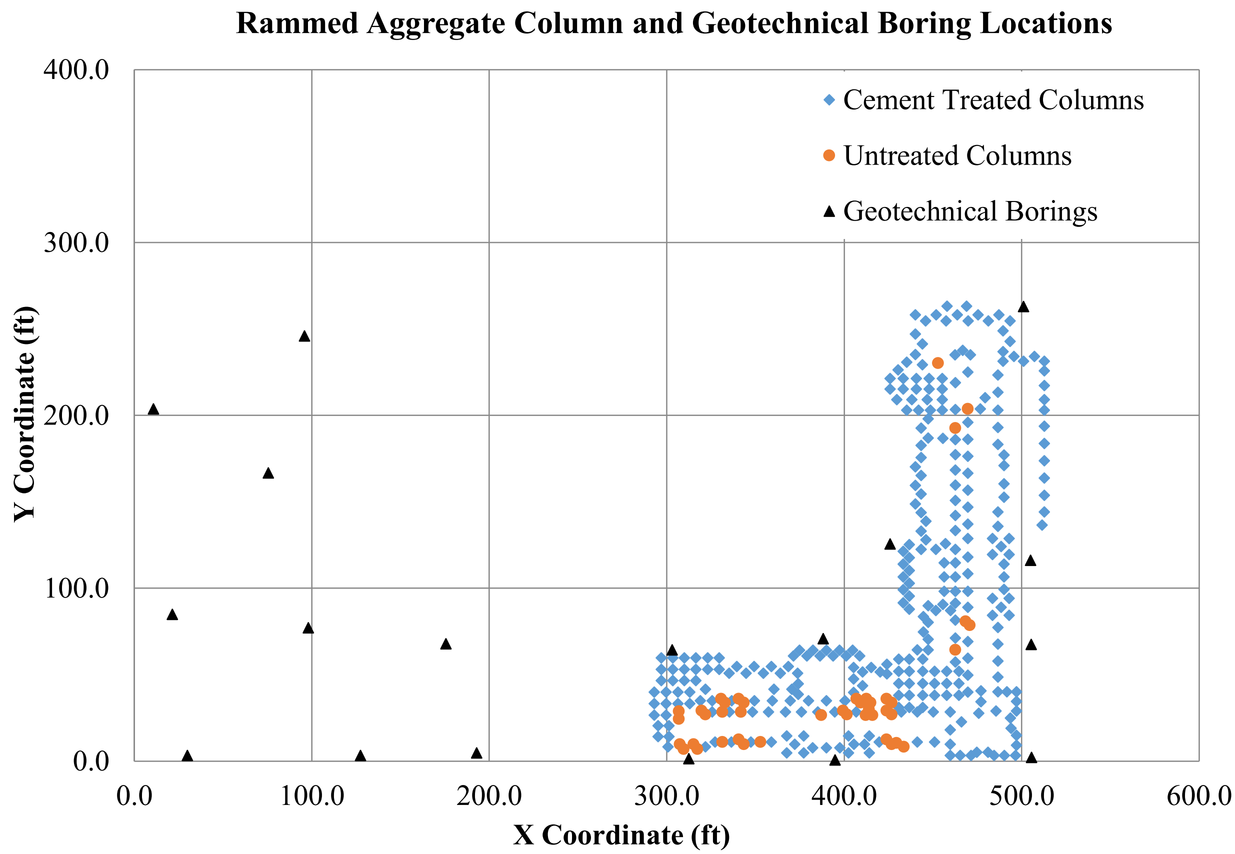

Figure L.1 Rammed Aggregate Column and geotechnical boring locations plot for Pearson Hall (similar to Figure 6.1).

L.2 TOTAL CONSTRUCTION QUANTITIES

Table L.4 Total lengths of Rammed Aggregate Columns at Pearson Hall as reported by the contractor, and as discerned from detailed installation records.

<table>
<tr><th>Item</th><th>Quantity</th><th>Unit</th><th>Notes</th></tr>
<tr><td>Total Drilled Linear Ft</td><td>12,450</td><td>ft</td><td rowspan="2">Contractor Reported Lengths</td></tr>
<tr><td>Actual Linear Ft of Piers</td><td>10,983</td><td>ft</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Total Length of Cement Treated Aggregate</td><td>10,561</td><td>ft</td><td rowspan="3">Lengths from Contractor Detailed Records. Note that discrepancies arise because the working pad elevation is higher than the design top of column elevation. Untreated aggregate was used to bring all columns up to the working pad elevation.</td></tr>
<tr><td>Total Length of Untreated 21A</td><td>2,436</td><td>ft</td></tr>
<tr><td>Total Length of Untreated #57</td><td>32</td><td>ft</td></tr>
<tr><td>TOTAL LENGTH OF COLUMNS</td><td>13,029</td><td>ft</td><td></td></tr>
</table>

Table L.5 Material quantities used in Rammed Aggregate Column construction at Pearson Hall, as obtained from the general contractor and subcontractor.

Material	Quantity	Unit	Notes
Cement Treated Aggregate (CTA)	4,613	tons	CTA quantity from Barton-Malow (actual).
Cement fraction in CTA	0.04		4% cement in CTA by weight (assumed)
Cement in CTA	185	tons	
Aggregate in CTA	4,429	tons	
21A Aggregate	1,150	tons	From GeoStructures, Inc. (actual)
#57 Aggregate	165	tons	From GeoStructures, Inc. (actual)
Total Aggregate	**5,210,665**	**kg**	
Total Cement	**167,405**	**kg**	
Diesel Fuel	$12,622.03	USD	Convert to gallons based on price. Highway diesel used according to the site superintendent.
Unit price of Diesel Fuel	$4.25	USD	Estimated based on U.S. Energy Information Administration (2015) data for the Central Atlantic region between March 17 and April 14, 2014.
Total Diesel Fuel	2,970	gallons	Estimated based on the average unit price of highway diesel fuel in March/April 2014
Total Diesel Fuel	**11,250**	**L**	(Approximate)

Table L.6 Material transportation quantities for Rammed Aggregate Columns construction at Pearson Hall.

Transportation	Quantity	Unit	Notes
Cement Treated Aggregate (CTA)	257	truckloads	From Barton-Malow (actual) (this is about 18.05 tons/truck).
21A Aggregate	64	truckloads	Estimated based on data from Barton-Malow for CTA transport (18.05 tons/truck).
#57 Aggregate	10	truckloads	Estimated based on data from Barton-Malow for CTA transport (18.05 tons/truck).
Trucking Distance	5	miles	All aggregate materials supplied from Acco Stone, distance obtained from Google Maps.
Trucking Distance	8	km	Converted to metric units.

Table L.7 Waste quantities for Rammed Aggregate Columns construction at Pearson Hall.

Waste Item	Quantity	Unit	Notes
Drill Spoil	0.18	CY/ft	Determined by the excavation calculator from Dirt Guy Excavating (2015). The reference was received from GeoStructures' project manager.
Drill Spoil	196	Truckloads	Estimated based on the quantity of spoil computed for all drilling, assuming 12 CY/truck.
Trucking Distance	10	Miles	Assumed distance.
Trucking Distance	16	km	Converted to metric units.

L.3 CONSTRUCTION QUANTITIES PER UNIT LENGTH OF COLUMNS

Construction quantities per unit length were determined by dividing the total quantity of a material (e.g., cement) by the total length of applicable columns (e.g., CTA columns). Table L.8 contains the total length of each type of column in both English and metric units. Note that the total quantities of materials for entry into the SEEAM Spreadsheet Calculator are in bold font in Table L.5, however, quantities per length are based on the amount of each material in each type of column rather than the overall total quantities.

Table L.8 Total length of different types of Rammed Aggregate Columns at Pearson Hall in both English and Metric units.

Item	English Units		Metric Units	
	Quantity	**Unit**	**Quantity**	**Unit**
Total Length of Cement Treated Aggregate	10,561	ft	3,219	m
Total Length of Untreated 21A Aggregate	2,436	ft	742	m
Total Length of Untreated #57 Aggregate	32	ft	10	m
Total Length of Columns	**13,029**	**ft**	**3,971**	**m**

Total material quantities per unit length of column are shown in Table L.9. These were used for the analysis presented in Ch. 6 in order to determine total material quantities based on estimated column lengths from the top of rock elevation.

Table L.9 Total material quantities per unit length of Rammed Aggregate Columns at Pearson Hall.

Material or Item	Blended Units		Metric Units	
	Quantity	**Unit**	**Quantity**	**Unit**
Cement (in Cement Treated Aggregate)	16	kg/ft	52	kg/m
Aggregate (in Cement Treated Aggregate)	380	kg/ft	1,248	kg/m
Aggregate (in Untreated Columns)	428	kg/ft	1,405	kg/m
Diesel (All Columns)	0.86	L/ft	2.83	L/m
Drill Spoil (All Columns)	0.18	CY/ft	0.45	m^3/m
Drill Spoil per Truck	12	CY	9.17	m^3
Aggregate Delivered per Truck	18.05	tons	16.37	tonnes

L.4 REFERENCES

Dirt Guy Excavating (2015). "Excavation calculator: calculate material to be excavated." <http://dirtguyexcavating.com/excavation_calculator.htm>. (August 18, 2015).

U.S. Energy Information Administration (2015). "Petroleum and other liquids: gasoline and diesel fuel update." <http://www.eia.gov/petroleum/gasdiesel/>. (August 18, 2015).

Virginia Department of Transportation (VDOT) (2007). *2007 Road and Bridge Specifications.* Virginia Department of Transportation. Richmond, VA.

Appendix M: Pearson Hall SEEAM Spreadsheet Calculator Analytical Results and Monte Carlo Simulation Results

This Appendix contains tables and figures that present the results of SEEAM analyses conducted for the rammed aggregate columns at Pearson Hall. The results presented in this Appendix follow the analytical and Monte Carlo simulation methods for determining the mean and standard deviation of total embodied energy and CO_2 emissions (see Appendix K) and rely on fixed material quantities. Summaries of the results from the Monte Carlo simulation for 1,000 values of total embodied energy and CO_2 emissions include the mean, standard deviation, maximum, minimum and mean error. Complete Monte Carlo simulation data sets, along with the quantile and accompanying estimates of total embodied energy and CO_2 emissions from lognormal distributions are also presented. The lognormal distributions used for making the estimates were defined by the analytically computed means and standard deviations of total embodied energy and CO_2 emissions. The estimates were made by inverting the lognormal cumulative distribution function using the quantile as the probability.

The results of the analyses included in this Appendix are summarized in the comparison of the analytical and Monte Carlo analysis methods for handling uncertainty in SEEAM analyses, which is presented in Appendix K.

M.1 PEARSON HALL RAMMED AGGREGATE COLUMNS, AS-BUILT

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Portland Cement (U.S.)	804	164	155	18
2	Other	Aggregate: Sand and Gravel or Crushed Rock	432	625	25	36
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	1,236	646	180	40
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	0	0	0	0
		MATERIALS TOTAL	1,236	646	180	40

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Cement delivery to site	3	0	0	0
2	Heavy Duty Truck	Aggregate delivery to site	91	3	7	0
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	94	3	7	0
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	0	0	0	0
		MATERIALS TRANSPORTATION TOTAL	94	3	7	0

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Diesel Consumed by all Equipment	484	16	37	1
2						
3						
4						
		SITE OPERATIONS TOTAL	484	16	37	1

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Drill Spoil Disposal Trucking	111	4	8	0
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	111	4	8	0

Figure M.1 Line by line SEEAM calculations for Rammed Aggregate Columns at Pearson Hall, as-built. Computations follow the analytical method described in Appendix K.

Table M.1 SEEAM results from the analytical method for the as-built Rammed Aggregate Columns at Pearson Hall, showing the contribution of materials, materials transportation, site operations and waste transportation to total embodied energy and CO_2 emissions.

	Embodied Energy (GJ)			CO_2 Emissions (tonnes)		
	Mean	**St Dev**	**% of Total**	**Mean**	**St Dev**	**% of Total**
Materials	1,236	646	64%	180	40	78%
Materials Transportation	94	3	5%	7	0	3%
Site Operations	484	16	25%	37	1	16%
Waste Transportation	111	4	6%	8	0	4%
TOTAL	**1,925**	**647**	**100%**	**232**	**40**	**100%**

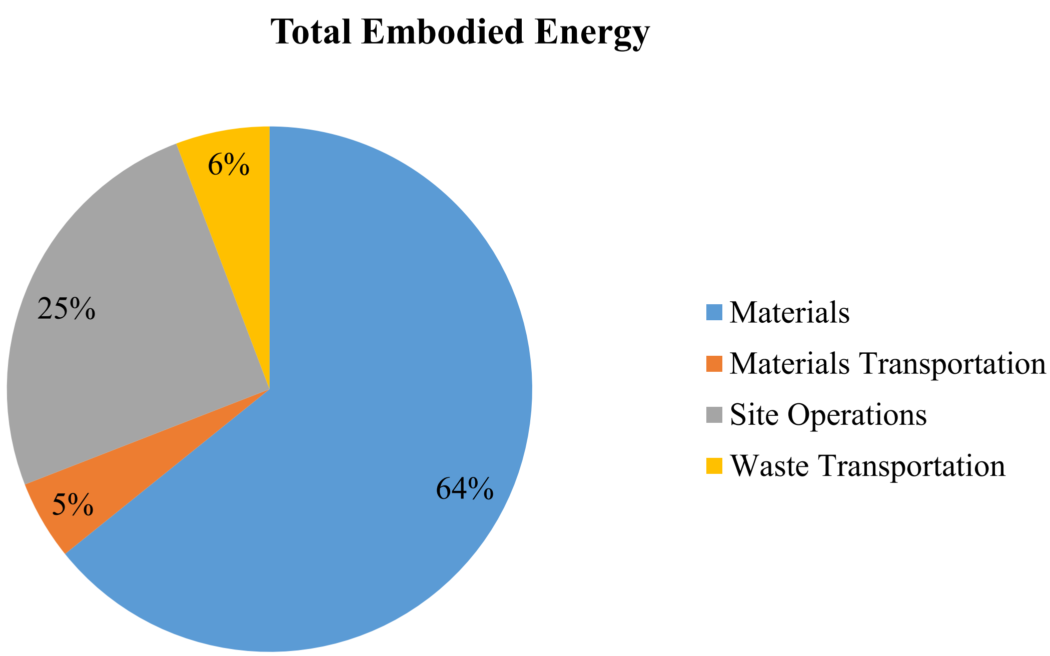

Figure M.2 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation from the analytical method of analysis for Rammed Aggregate Columns at Pearson Hall, as-built.

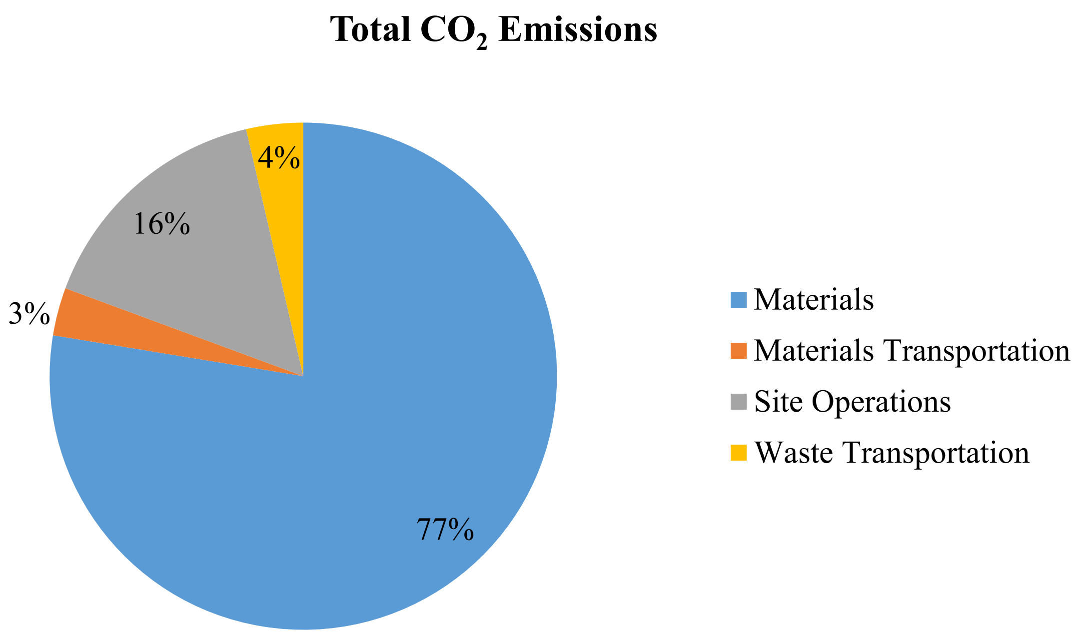

Figure M.3 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation from the analytical method of analysis for Rammed Aggregate Columns at Pearson Hall, as-built.

Table M.2 Summary statistics for Monte Carlo simulated data sets of n = 1,000 values for total embodied energy and CO_2 emissions for Pearson Hall, as built.

Statistics	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Notes
Mean	1,934	232	
St. Dev.	711	36	
Maximum	11,408	553	
Minimum	1,221	167	
Mean Error (+/-)	37	2	90% Confidence; 1,000 values
Mean Error % (+/-)	1.91%	0.82%	
No. of Values for +/- 2.5% Error	587	110	90% Confidence

Table M.3 Monte Carlo Simulation data, quantile, and lognormal estimates of total embodied energy and CO_2 emissions for Pearson Hall, as built. Sorted in ascending numerical order.

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
1	1,221	167	0.0005	622	130
2	1,234	174	0.0015	691	138
3	1,249	177	0.0025	729	142
4	1,250	178	0.0035	756	144
5	1,255	180	0.0045	777	146
6	1,256	181	0.0055	795	148
7	1,272	182	0.0065	810	150
8	1,301	182	0.0075	824	151
9	1,306	182	0.0085	836	152
10	1,307	183	0.0095	848	153
11	1,311	183	0.0105	858	154
12	1,313	184	0.0115	868	155
13	1,317	184	0.0125	877	156
14	1,319	184	0.0135	885	157
15	1,322	185	0.0145	894	158
16	1,324	185	0.0155	901	158
17	1,337	185	0.0165	909	159
18	1,340	186	0.0175	916	160
19	1,341	186	0.0185	923	160
20	1,343	187	0.0195	929	161
21	1,344	187	0.0205	935	161
22	1,350	187	0.0215	942	162
23	1,354	188	0.0225	947	162
24	1,354	188	0.0235	953	163
25	1,355	188	0.0245	959	163
26	1,357	188	0.0255	964	164
27	1,360	188	0.0265	969	164
28	1,362	188	0.0275	974	165
29	1,364	188	0.0285	979	165
30	1,366	189	0.0295	984	166
31	1,367	189	0.0305	989	166
32	1,369	189	0.0315	994	167
33	1,371	189	0.0325	998	167
34	1,372	189	0.0335	1,003	167
35	1,373	189	0.0345	1,007	168
36	1,373	189	0.0355	1,011	168

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
37	1,377	189	0.0365	1,015	168
38	1,381	190	0.0375	1,019	169
39	1,381	191	0.0385	1,024	169
40	1,384	191	0.0395	1,028	169
41	1,384	191	0.0405	1,031	170
42	1,384	192	0.0415	1,035	170
43	1,385	192	0.0425	1,039	170
44	1,386	192	0.0435	1,043	171
45	1,387	192	0.0445	1,046	171
46	1,389	192	0.0455	1,050	171
47	1,389	192	0.0465	1,054	172
48	1,389	192	0.0475	1,057	172
49	1,390	192	0.0485	1,061	172
50	1,392	192	0.0495	1,064	173
51	1,392	192	0.0505	1,067	173
52	1,394	192	0.0515	1,071	173
53	1,395	193	0.0525	1,074	173
54	1,403	193	0.0535	1,077	174
55	1,406	193	0.0545	1,081	174
56	1,409	193	0.0555	1,084	174
57	1,409	193	0.0565	1,087	175
58	1,410	193	0.0575	1,090	175
59	1,410	193	0.0585	1,093	175
60	1,412	193	0.0595	1,096	175
61	1,413	193	0.0605	1,099	176
62	1,415	193	0.0615	1,102	176
63	1,416	193	0.0625	1,105	176
64	1,418	194	0.0635	1,108	176
65	1,424	194	0.0645	1,111	177
66	1,427	194	0.0655	1,114	177
67	1,428	194	0.0665	1,117	177
68	1,429	194	0.0675	1,119	177
69	1,430	195	0.0685	1,122	177
70	1,433	195	0.0695	1,125	178
71	1,433	195	0.0705	1,128	178
72	1,434	195	0.0715	1,130	178
73	1,439	195	0.0725	1,133	178
74	1,439	195	0.0735	1,136	179

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
75	1,440	196	0.0745	1,138	179
76	1,441	196	0.0755	1,141	179
77	1,441	196	0.0765	1,144	179
78	1,443	196	0.0775	1,146	179
79	1,443	196	0.0785	1,149	180
80	1,443	196	0.0795	1,151	180
81	1,443	197	0.0805	1,154	180
82	1,444	197	0.0815	1,156	180
83	1,444	197	0.0825	1,159	180
84	1,445	197	0.0835	1,161	181
85	1,448	197	0.0845	1,164	181
86	1,450	197	0.0855	1,166	181
87	1,450	197	0.0865	1,169	181
88	1,451	197	0.0875	1,171	181
89	1,453	197	0.0885	1,174	182
90	1,453	198	0.0895	1,176	182
91	1,454	198	0.0905	1,178	182
92	1,454	198	0.0915	1,181	182
93	1,456	198	0.0925	1,183	182
94	1,457	198	0.0935	1,185	183
95	1,458	198	0.0945	1,188	183
96	1,459	198	0.0955	1,190	183
97	1,459	198	0.0965	1,192	183
98	1,460	199	0.0975	1,195	183
99	1,460	199	0.0985	1,197	184
100	1,462	199	0.0995	1,199	184
101	1,464	199	0.1005	1,201	184
102	1,465	199	0.1015	1,203	184
103	1,465	199	0.1025	1,206	184
104	1,466	199	0.1035	1,208	184
105	1,466	199	0.1045	1,210	185
106	1,467	199	0.1055	1,212	185
107	1,467	199	0.1065	1,214	185
108	1,468	199	0.1075	1,217	185
109	1,469	199	0.1085	1,219	185
110	1,470	199	0.1095	1,221	185
111	1,472	200	0.1105	1,223	186
112	1,473	200	0.1115	1,225	186

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
113	1,473	200	0.1125	1,227	186
114	1,476	200	0.1135	1,229	186
115	1,477	200	0.1145	1,231	186
116	1,478	200	0.1155	1,233	186
117	1,479	200	0.1165	1,236	187
118	1,479	200	0.1175	1,238	187
119	1,479	200	0.1185	1,240	187
120	1,479	200	0.1195	1,242	187
121	1,480	200	0.1205	1,244	187
122	1,480	200	0.1215	1,246	187
123	1,480	201	0.1225	1,248	188
124	1,482	201	0.1235	1,250	188
125	1,483	201	0.1245	1,252	188
126	1,483	201	0.1255	1,254	188
127	1,483	201	0.1265	1,256	188
128	1,485	201	0.1275	1,258	188
129	1,486	201	0.1285	1,260	189
130	1,487	201	0.1295	1,262	189
131	1,488	201	0.1305	1,264	189
132	1,488	201	0.1315	1,266	189
133	1,488	202	0.1325	1,267	189
134	1,489	202	0.1335	1,269	189
135	1,489	202	0.1345	1,271	189
136	1,490	202	0.1355	1,273	190
137	1,490	202	0.1365	1,275	190
138	1,490	202	0.1375	1,277	190
139	1,491	202	0.1385	1,279	190
140	1,492	202	0.1395	1,281	190
141	1,493	202	0.1405	1,283	190
142	1,493	202	0.1415	1,285	190
143	1,494	202	0.1425	1,286	191
144	1,496	202	0.1435	1,288	191
145	1,498	202	0.1445	1,290	191
146	1,499	202	0.1455	1,292	191
147	1,500	203	0.1465	1,294	191
148	1,500	203	0.1475	1,296	191
149	1,501	203	0.1485	1,298	191
150	1,501	203	0.1495	1,299	192

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
151	1,501	203	0.1505	1,301	192
152	1,503	203	0.1515	1,303	192
153	1,503	203	0.1525	1,305	192
154	1,503	203	0.1535	1,307	192
155	1,504	203	0.1545	1,308	192
156	1,504	203	0.1555	1,310	192
157	1,507	203	0.1565	1,312	193
158	1,508	203	0.1575	1,314	193
159	1,509	203	0.1585	1,316	193
160	1,509	203	0.1595	1,317	193
161	1,510	203	0.1605	1,319	193
162	1,511	203	0.1615	1,321	193
163	1,515	203	0.1625	1,323	193
164	1,515	204	0.1635	1,324	194
165	1,515	204	0.1645	1,326	194
166	1,516	204	0.1655	1,328	194
167	1,516	204	0.1665	1,330	194
168	1,518	204	0.1675	1,331	194
169	1,520	204	0.1685	1,333	194
170	1,523	204	0.1695	1,335	194
171	1,523	204	0.1705	1,337	194
172	1,524	204	0.1715	1,338	195
173	1,524	204	0.1725	1,340	195
174	1,524	204	0.1735	1,342	195
175	1,525	204	0.1745	1,343	195
176	1,526	204	0.1755	1,345	195
177	1,526	204	0.1765	1,347	195
178	1,526	204	0.1775	1,349	195
179	1,527	204	0.1785	1,350	196
180	1,527	205	0.1795	1,352	196
181	1,527	205	0.1805	1,354	196
182	1,527	205	0.1815	1,355	196
183	1,527	205	0.1825	1,357	196
184	1,527	205	0.1835	1,359	196
185	1,528	205	0.1845	1,360	196
186	1,528	205	0.1855	1,362	196
187	1,529	205	0.1865	1,364	197
188	1,529	205	0.1875	1,365	197

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
189	1,530	206	0.1885	1,367	197
190	1,530	206	0.1895	1,369	197
191	1,530	206	0.1905	1,370	197
192	1,531	206	0.1915	1,372	197
193	1,531	206	0.1925	1,374	197
194	1,532	206	0.1935	1,375	197
195	1,532	206	0.1945	1,377	198
196	1,536	206	0.1955	1,379	198
197	1,539	206	0.1965	1,380	198
198	1,539	206	0.1975	1,382	198
199	1,541	206	0.1985	1,383	198
200	1,541	206	0.1995	1,385	198
201	1,541	206	0.2005	1,387	198
202	1,541	207	0.2015	1,388	198
203	1,543	207	0.2025	1,390	198
204	1,543	207	0.2035	1,391	199
205	1,545	207	0.2045	1,393	199
206	1,546	207	0.2055	1,395	199
207	1,546	207	0.2065	1,396	199
208	1,546	207	0.2075	1,398	199
209	1,547	207	0.2085	1,399	199
210	1,547	207	0.2095	1,401	199
211	1,548	207	0.2105	1,403	199
212	1,549	207	0.2115	1,404	200
213	1,550	207	0.2125	1,406	200
214	1,550	207	0.2135	1,407	200
215	1,551	207	0.2145	1,409	200
216	1,551	207	0.2155	1,411	200
217	1,551	207	0.2165	1,412	200
218	1,553	207	0.2175	1,414	200
219	1,554	207	0.2185	1,415	200
220	1,555	207	0.2195	1,417	201
221	1,555	207	0.2205	1,418	201
222	1,555	208	0.2215	1,420	201
223	1,557	208	0.2225	1,422	201
224	1,558	208	0.2235	1,423	201
225	1,558	208	0.2245	1,425	201
226	1,558	208	0.2255	1,426	201

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
227	1,558	208	0.2265	1,428	201
228	1,560	208	0.2275	1,429	201
229	1,562	208	0.2285	1,431	202
230	1,562	208	0.2295	1,432	202
231	1,562	208	0.2305	1,434	202
232	1,562	208	0.2315	1,435	202
233	1,565	208	0.2325	1,437	202
234	1,565	208	0.2335	1,439	202
235	1,565	209	0.2345	1,440	202
236	1,566	209	0.2355	1,442	202
237	1,567	209	0.2365	1,443	202
238	1,567	209	0.2375	1,445	203
239	1,568	209	0.2385	1,446	203
240	1,570	209	0.2395	1,448	203
241	1,570	209	0.2405	1,449	203
242	1,572	209	0.2415	1,451	203
243	1,573	209	0.2425	1,452	203
244	1,573	209	0.2435	1,454	203
245	1,574	209	0.2445	1,455	203
246	1,574	209	0.2455	1,457	203
247	1,575	209	0.2465	1,458	204
248	1,575	210	0.2475	1,460	204
249	1,576	210	0.2485	1,461	204
250	1,576	210	0.2495	1,463	204
251	1,577	210	0.2505	1,464	204
252	1,578	210	0.2515	1,466	204
253	1,578	210	0.2525	1,467	204
254	1,579	210	0.2535	1,469	204
255	1,580	210	0.2545	1,470	204
256	1,581	210	0.2555	1,472	205
257	1,581	210	0.2565	1,473	205
258	1,582	210	0.2575	1,475	205
259	1,582	210	0.2585	1,476	205
260	1,582	210	0.2595	1,478	205
261	1,584	211	0.2605	1,479	205
262	1,584	211	0.2615	1,481	205
263	1,584	211	0.2625	1,482	205
264	1,584	211	0.2635	1,484	205

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
265	1,585	211	0.2645	1,485	206
266	1,586	211	0.2655	1,487	206
267	1,586	211	0.2665	1,488	206
268	1,587	211	0.2675	1,490	206
269	1,587	211	0.2685	1,491	206
270	1,588	211	0.2695	1,493	206
271	1,588	211	0.2705	1,494	206
272	1,588	211	0.2715	1,496	206
273	1,588	211	0.2725	1,497	206
274	1,589	211	0.2735	1,499	206
275	1,590	211	0.2745	1,500	207
276	1,592	211	0.2755	1,502	207
277	1,593	211	0.2765	1,503	207
278	1,594	211	0.2775	1,505	207
279	1,594	211	0.2785	1,506	207
280	1,595	212	0.2795	1,507	207
281	1,596	212	0.2805	1,509	207
282	1,596	212	0.2815	1,510	207
283	1,596	212	0.2825	1,512	207
284	1,596	212	0.2835	1,513	208
285	1,596	212	0.2845	1,515	208
286	1,596	212	0.2855	1,516	208
287	1,597	212	0.2865	1,518	208
288	1,597	212	0.2875	1,519	208
289	1,598	212	0.2885	1,521	208
290	1,598	212	0.2895	1,522	208
291	1,601	212	0.2905	1,524	208
292	1,601	212	0.2915	1,525	208
293	1,603	212	0.2925	1,526	208
294	1,604	212	0.2935	1,528	209
295	1,604	212	0.2945	1,529	209
296	1,605	212	0.2955	1,531	209
297	1,608	212	0.2965	1,532	209
298	1,608	213	0.2975	1,534	209
299	1,608	213	0.2985	1,535	209
300	1,609	213	0.2995	1,537	209
301	1,609	213	0.3005	1,538	209
302	1,609	213	0.3015	1,539	209

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
303	1,609	213	0.3025	1,541	210
304	1,609	213	0.3035	1,542	210
305	1,611	213	0.3045	1,544	210
306	1,611	213	0.3055	1,545	210
307	1,612	213	0.3065	1,547	210
308	1,612	213	0.3075	1,548	210
309	1,612	213	0.3085	1,550	210
310	1,613	213	0.3095	1,551	210
311	1,615	213	0.3105	1,552	210
312	1,615	213	0.3115	1,554	210
313	1,616	213	0.3125	1,555	211
314	1,616	213	0.3135	1,557	211
315	1,616	213	0.3145	1,558	211
316	1,618	213	0.3155	1,560	211
317	1,618	213	0.3165	1,561	211
318	1,619	213	0.3175	1,562	211
319	1,619	213	0.3185	1,564	211
320	1,619	213	0.3195	1,565	211
321	1,620	214	0.3205	1,567	211
322	1,620	214	0.3215	1,568	211
323	1,620	214	0.3225	1,570	212
324	1,620	214	0.3235	1,571	212
325	1,621	214	0.3245	1,572	212
326	1,622	214	0.3255	1,574	212
327	1,623	214	0.3265	1,575	212
328	1,624	214	0.3275	1,577	212
329	1,626	214	0.3285	1,578	212
330	1,627	214	0.3295	1,580	212
331	1,628	214	0.3305	1,581	212
332	1,628	214	0.3315	1,582	212
333	1,629	214	0.3325	1,584	213
334	1,631	214	0.3335	1,585	213
335	1,631	214	0.3345	1,587	213
336	1,632	214	0.3355	1,588	213
337	1,632	214	0.3365	1,590	213
338	1,632	215	0.3375	1,591	213
339	1,635	215	0.3385	1,592	213
340	1,636	215	0.3395	1,594	213

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
341	1,637	215	0.3405	1,595	213
342	1,637	215	0.3415	1,597	213
343	1,638	215	0.3425	1,598	214
344	1,639	215	0.3435	1,600	214
345	1,640	215	0.3445	1,601	214
346	1,640	215	0.3455	1,602	214
347	1,641	215	0.3465	1,604	214
348	1,641	215	0.3475	1,605	214
349	1,643	215	0.3485	1,607	214
350	1,646	215	0.3495	1,608	214
351	1,646	215	0.3505	1,610	214
352	1,647	215	0.3515	1,611	214
353	1,647	216	0.3525	1,612	215
354	1,648	216	0.3535	1,614	215
355	1,648	216	0.3545	1,615	215
356	1,648	216	0.3555	1,617	215
357	1,649	216	0.3565	1,618	215
358	1,649	216	0.3575	1,619	215
359	1,649	216	0.3585	1,621	215
360	1,649	216	0.3595	1,622	215
361	1,649	216	0.3605	1,624	215
362	1,651	216	0.3615	1,625	215
363	1,651	216	0.3625	1,627	216
364	1,652	216	0.3635	1,628	216
365	1,653	216	0.3645	1,629	216
366	1,656	216	0.3655	1,631	216
367	1,657	216	0.3665	1,632	216
368	1,658	216	0.3675	1,634	216
369	1,660	216	0.3685	1,635	216
370	1,661	216	0.3695	1,636	216
371	1,661	216	0.3705	1,638	216
372	1,662	217	0.3715	1,639	216
373	1,663	217	0.3725	1,641	217
374	1,663	217	0.3735	1,642	217
375	1,663	217	0.3745	1,644	217
376	1,664	217	0.3755	1,645	217
377	1,664	217	0.3765	1,646	217
378	1,664	217	0.3775	1,648	217

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
379	1,665	217	0.3785	1,649	217
380	1,668	217	0.3795	1,651	217
381	1,668	217	0.3805	1,652	217
382	1,668	217	0.3815	1,653	217
383	1,669	217	0.3825	1,655	217
384	1,669	217	0.3835	1,656	218
385	1,670	217	0.3845	1,658	218
386	1,670	217	0.3855	1,659	218
387	1,670	217	0.3865	1,661	218
388	1,674	217	0.3875	1,662	218
389	1,677	217	0.3885	1,663	218
390	1,677	217	0.3895	1,665	218
391	1,678	217	0.3905	1,666	218
392	1,679	217	0.3915	1,668	218
393	1,679	218	0.3925	1,669	218
394	1,680	218	0.3935	1,671	219
395	1,680	218	0.3945	1,672	219
396	1,680	218	0.3955	1,673	219
397	1,681	218	0.3965	1,675	219
398	1,682	218	0.3975	1,676	219
399	1,682	218	0.3985	1,678	219
400	1,683	218	0.3995	1,679	219
401	1,684	218	0.4005	1,680	219
402	1,684	218	0.4015	1,682	219
403	1,685	218	0.4025	1,683	219
404	1,685	218	0.4035	1,685	220
405	1,685	218	0.4045	1,686	220
406	1,686	218	0.4055	1,688	220
407	1,688	218	0.4065	1,689	220
408	1,690	218	0.4075	1,690	220
409	1,691	218	0.4085	1,692	220
410	1,691	218	0.4095	1,693	220
411	1,691	218	0.4105	1,695	220
412	1,694	218	0.4115	1,696	220
413	1,695	218	0.4125	1,698	220
414	1,696	218	0.4135	1,699	220
415	1,696	219	0.4145	1,700	221
416	1,698	219	0.4155	1,702	221

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
417	1,699	219	0.4165	1,703	221
418	1,699	219	0.4175	1,705	221
419	1,699	219	0.4185	1,706	221
420	1,699	219	0.4195	1,708	221
421	1,700	219	0.4205	1,709	221
422	1,700	219	0.4215	1,710	221
423	1,701	219	0.4225	1,712	221
424	1,701	219	0.4235	1,713	221
425	1,701	220	0.4245	1,715	222
426	1,702	220	0.4255	1,716	222
427	1,702	220	0.4265	1,718	222
428	1,703	220	0.4275	1,719	222
429	1,705	220	0.4285	1,720	222
430	1,706	220	0.4295	1,722	222
431	1,706	220	0.4305	1,723	222
432	1,707	220	0.4315	1,725	222
433	1,707	220	0.4325	1,726	222
434	1,708	220	0.4335	1,728	222
435	1,709	220	0.4345	1,729	223
436	1,710	220	0.4355	1,730	223
437	1,710	221	0.4365	1,732	223
438	1,711	221	0.4375	1,733	223
439	1,711	221	0.4385	1,735	223
440	1,711	221	0.4395	1,736	223
441	1,714	221	0.4405	1,738	223
442	1,715	221	0.4415	1,739	223
443	1,716	221	0.4425	1,741	223
444	1,718	221	0.4435	1,742	223
445	1,718	221	0.4445	1,743	223
446	1,718	221	0.4455	1,745	224
447	1,718	221	0.4465	1,746	224
448	1,719	221	0.4475	1,748	224
449	1,722	221	0.4485	1,749	224
450	1,723	221	0.4495	1,751	224
451	1,723	221	0.4505	1,752	224
452	1,723	221	0.4515	1,754	224
453	1,724	221	0.4525	1,755	224
454	1,728	221	0.4535	1,756	224

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
455	1,729	221	0.4545	1,758	224
456	1,731	221	0.4555	1,759	225
457	1,731	222	0.4565	1,761	225
458	1,731	222	0.4575	1,762	225
459	1,732	222	0.4585	1,764	225
460	1,733	222	0.4595	1,765	225
461	1,733	222	0.4605	1,767	225
462	1,733	222	0.4615	1,768	225
463	1,734	222	0.4625	1,770	225
464	1,734	222	0.4635	1,771	225
465	1,736	222	0.4645	1,772	225
466	1,736	222	0.4655	1,774	226
467	1,738	222	0.4665	1,775	226
468	1,738	222	0.4675	1,777	226
469	1,739	222	0.4685	1,778	226
470	1,740	222	0.4695	1,780	226
471	1,740	222	0.4705	1,781	226
472	1,740	222	0.4715	1,783	226
473	1,740	222	0.4725	1,784	226
474	1,741	222	0.4735	1,786	226
475	1,742	223	0.4745	1,787	226
476	1,744	223	0.4755	1,789	227
477	1,744	223	0.4765	1,790	227
478	1,746	223	0.4775	1,791	227
479	1,747	223	0.4785	1,793	227
480	1,748	223	0.4795	1,794	227
481	1,748	223	0.4805	1,796	227
482	1,749	223	0.4815	1,797	227
483	1,750	223	0.4825	1,799	227
484	1,750	223	0.4835	1,800	227
485	1,752	223	0.4845	1,802	227
486	1,753	223	0.4855	1,803	227
487	1,754	223	0.4865	1,805	228
488	1,754	223	0.4875	1,806	228
489	1,755	223	0.4885	1,808	228
490	1,755	223	0.4895	1,809	228
491	1,756	223	0.4905	1,811	228
492	1,758	224	0.4915	1,812	228

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
493	1,758	224	0.4925	1,814	228
494	1,759	224	0.4935	1,815	228
495	1,760	224	0.4945	1,817	228
496	1,760	224	0.4955	1,818	228
497	1,762	224	0.4965	1,820	229
498	1,762	224	0.4975	1,821	229
499	1,764	224	0.4985	1,823	229
500	1,764	224	0.4995	1,824	229
501	1,767	224	0.5005	1,826	229
502	1,767	224	0.5015	1,827	229
503	1,769	224	0.5025	1,829	229
504	1,769	224	0.5035	1,830	229
505	1,772	224	0.5045	1,832	229
506	1,773	224	0.5055	1,833	229
507	1,773	225	0.5065	1,835	230
508	1,774	225	0.5075	1,836	230
509	1,775	225	0.5085	1,838	230
510	1,776	225	0.5095	1,839	230
511	1,776	225	0.5105	1,841	230
512	1,776	225	0.5115	1,842	230
513	1,777	225	0.5125	1,844	230
514	1,777	225	0.5135	1,845	230
515	1,779	225	0.5145	1,847	230
516	1,779	225	0.5155	1,848	230
517	1,782	225	0.5165	1,850	231
518	1,783	225	0.5175	1,851	231
519	1,784	225	0.5185	1,853	231
520	1,784	225	0.5195	1,854	231
521	1,785	225	0.5205	1,856	231
522	1,785	225	0.5215	1,857	231
523	1,786	225	0.5225	1,859	231
524	1,786	225	0.5235	1,860	231
525	1,787	225	0.5245	1,862	231
526	1,787	225	0.5255	1,863	231
527	1,788	225	0.5265	1,865	232
528	1,788	225	0.5275	1,866	232
529	1,789	225	0.5285	1,868	232
530	1,790	225	0.5295	1,870	232

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
531	1,791	225	0.5305	1,871	232
532	1,793	226	0.5315	1,873	232
533	1,794	226	0.5325	1,874	232
534	1,795	226	0.5335	1,876	232
535	1,795	226	0.5345	1,877	232
536	1,796	226	0.5355	1,879	232
537	1,798	226	0.5365	1,880	233
538	1,800	226	0.5375	1,882	233
539	1,800	226	0.5385	1,883	233
540	1,801	226	0.5395	1,885	233
541	1,803	226	0.5405	1,887	233
542	1,804	227	0.5415	1,888	233
543	1,805	227	0.5425	1,890	233
544	1,806	227	0.5435	1,891	233
545	1,807	227	0.5445	1,893	233
546	1,807	227	0.5455	1,894	233
547	1,808	227	0.5465	1,896	234
548	1,808	227	0.5475	1,897	234
549	1,809	227	0.5485	1,899	234
550	1,809	227	0.5495	1,901	234
551	1,809	227	0.5505	1,902	234
552	1,810	227	0.5515	1,904	234
553	1,810	227	0.5525	1,905	234
554	1,810	227	0.5535	1,907	234
555	1,811	227	0.5545	1,908	234
556	1,811	227	0.5555	1,910	234
557	1,813	227	0.5565	1,912	235
558	1,813	227	0.5575	1,913	235
559	1,813	227	0.5585	1,915	235
560	1,814	227	0.5595	1,916	235
561	1,816	227	0.5605	1,918	235
562	1,817	227	0.5615	1,920	235
563	1,819	228	0.5625	1,921	235
564	1,819	228	0.5635	1,923	235
565	1,822	228	0.5645	1,924	235
566	1,822	228	0.5655	1,926	235
567	1,823	228	0.5665	1,928	236
568	1,824	228	0.5675	1,929	236

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
569	1,824	228	0.5685	1,931	236
570	1,824	228	0.5695	1,932	236
571	1,825	228	0.5705	1,934	236
572	1,826	228	0.5715	1,936	236
573	1,827	228	0.5725	1,937	236
574	1,829	228	0.5735	1,939	236
575	1,830	228	0.5745	1,940	236
576	1,830	229	0.5755	1,942	236
577	1,831	229	0.5765	1,944	237
578	1,833	229	0.5775	1,945	237
579	1,835	229	0.5785	1,947	237
580	1,836	230	0.5795	1,949	237
581	1,836	230	0.5805	1,950	237
582	1,837	230	0.5815	1,952	237
583	1,837	230	0.5825	1,953	237
584	1,837	230	0.5835	1,955	237
585	1,838	230	0.5845	1,957	237
586	1,839	230	0.5855	1,958	238
587	1,839	230	0.5865	1,960	238
588	1,840	230	0.5875	1,962	238
589	1,841	230	0.5885	1,963	238
590	1,841	230	0.5895	1,965	238
591	1,841	231	0.5905	1,967	238
592	1,844	231	0.5915	1,968	238
593	1,847	231	0.5925	1,970	238
594	1,848	231	0.5935	1,972	238
595	1,849	231	0.5945	1,973	238
596	1,850	231	0.5955	1,975	239
597	1,850	231	0.5965	1,977	239
598	1,851	231	0.5975	1,978	239
599	1,852	231	0.5985	1,980	239
600	1,854	231	0.5995	1,982	239
601	1,855	231	0.6005	1,983	239
602	1,856	232	0.6015	1,985	239
603	1,857	232	0.6025	1,987	239
604	1,860	232	0.6035	1,988	239
605	1,860	232	0.6045	1,990	240
606	1,860	232	0.6055	1,992	240

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
607	1,860	232	0.6065	1,993	240
608	1,860	232	0.6075	1,995	240
609	1,861	232	0.6085	1,997	240
610	1,862	232	0.6095	1,999	240
611	1,862	232	0.6105	2,000	240
612	1,863	232	0.6115	2,002	240
613	1,863	232	0.6125	2,004	240
614	1,863	233	0.6135	2,005	240
615	1,865	233	0.6145	2,007	241
616	1,866	233	0.6155	2,009	241
617	1,866	233	0.6165	2,010	241
618	1,867	233	0.6175	2,012	241
619	1,868	233	0.6185	2,014	241
620	1,871	233	0.6195	2,016	241
621	1,871	233	0.6205	2,017	241
622	1,876	233	0.6215	2,019	241
623	1,876	233	0.6225	2,021	241
624	1,876	233	0.6235	2,023	242
625	1,876	233	0.6245	2,024	242
626	1,877	233	0.6255	2,026	242
627	1,878	233	0.6265	2,028	242
628	1,878	233	0.6275	2,030	242
629	1,879	233	0.6285	2,031	242
630	1,884	234	0.6295	2,033	242
631	1,884	234	0.6305	2,035	242
632	1,888	234	0.6315	2,037	242
633	1,890	234	0.6325	2,038	243
634	1,890	234	0.6335	2,040	243
635	1,891	234	0.6345	2,042	243
636	1,893	234	0.6355	2,044	243
637	1,895	234	0.6365	2,046	243
638	1,895	234	0.6375	2,047	243
639	1,896	234	0.6385	2,049	243
640	1,899	234	0.6395	2,051	243
641	1,899	234	0.6405	2,053	243
642	1,901	234	0.6415	2,054	244
643	1,904	235	0.6425	2,056	244
644	1,906	235	0.6435	2,058	244

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
645	1,908	235	0.6445	2,060	244
646	1,908	235	0.6455	2,062	244
647	1,908	235	0.6465	2,063	244
648	1,909	235	0.6475	2,065	244
649	1,911	235	0.6485	2,067	244
650	1,912	235	0.6495	2,069	244
651	1,913	235	0.6505	2,071	245
652	1,913	235	0.6515	2,073	245
653	1,914	235	0.6525	2,074	245
654	1,915	235	0.6535	2,076	245
655	1,916	236	0.6545	2,078	245
656	1,916	236	0.6555	2,080	245
657	1,916	236	0.6565	2,082	245
658	1,916	236	0.6575	2,084	245
659	1,919	236	0.6585	2,086	245
660	1,919	236	0.6595	2,087	246
661	1,924	236	0.6605	2,089	246
662	1,924	236	0.6615	2,091	246
663	1,924	236	0.6625	2,093	246
664	1,925	236	0.6635	2,095	246
665	1,925	236	0.6645	2,097	246
666	1,925	236	0.6655	2,099	246
667	1,926	236	0.6665	2,101	246
668	1,926	237	0.6675	2,102	247
669	1,926	237	0.6685	2,104	247
670	1,927	237	0.6695	2,106	247
671	1,928	237	0.6705	2,108	247
672	1,930	237	0.6715	2,110	247
673	1,931	237	0.6725	2,112	247
674	1,931	237	0.6735	2,114	247
675	1,932	237	0.6745	2,116	247
676	1,933	237	0.6755	2,118	247
677	1,934	237	0.6765	2,120	248
678	1,934	237	0.6775	2,122	248
679	1,934	237	0.6785	2,123	248
680	1,936	237	0.6795	2,125	248
681	1,942	237	0.6805	2,127	248
682	1,942	237	0.6815	2,129	248

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
683	1,944	238	0.6825	2,131	248
684	1,945	238	0.6835	2,133	248
685	1,945	238	0.6845	2,135	249
686	1,948	238	0.6855	2,137	249
687	1,948	238	0.6865	2,139	249
688	1,950	238	0.6875	2,141	249
689	1,953	238	0.6885	2,143	249
690	1,955	239	0.6895	2,145	249
691	1,956	239	0.6905	2,147	249
692	1,956	239	0.6915	2,149	249
693	1,959	239	0.6925	2,151	249
694	1,959	239	0.6935	2,153	250
695	1,960	239	0.6945	2,155	250
696	1,964	239	0.6955	2,157	250
697	1,964	239	0.6965	2,159	250
698	1,964	239	0.6975	2,161	250
699	1,965	239	0.6985	2,163	250
700	1,966	239	0.6995	2,165	250
701	1,967	239	0.7005	2,167	250
702	1,968	240	0.7015	2,169	251
703	1,969	240	0.7025	2,171	251
704	1,971	240	0.7035	2,173	251
705	1,972	240	0.7045	2,175	251
706	1,972	240	0.7055	2,177	251
707	1,973	240	0.7065	2,180	251
708	1,976	240	0.7075	2,182	251
709	1,976	240	0.7085	2,184	251
710	1,976	240	0.7095	2,186	252
711	1,977	240	0.7105	2,188	252
712	1,983	241	0.7115	2,190	252
713	1,983	241	0.7125	2,192	252
714	1,985	241	0.7135	2,194	252
715	1,985	241	0.7145	2,196	252
716	1,985	241	0.7155	2,198	252
717	1,987	241	0.7165	2,200	252
718	1,988	241	0.7175	2,203	253
719	1,988	241	0.7185	2,205	253
720	1,988	241	0.7195	2,207	253

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
721	1,989	241	0.7205	2,209	253
722	1,990	242	0.7215	2,211	253
723	1,990	242	0.7225	2,213	253
724	1,990	242	0.7235	2,216	253
725	1,990	242	0.7245	2,218	253
726	1,993	242	0.7255	2,220	254
727	1,993	242	0.7265	2,222	254
728	1,994	242	0.7275	2,224	254
729	1,995	242	0.7285	2,226	254
730	1,998	242	0.7295	2,229	254
731	1,999	242	0.7305	2,231	254
732	2,000	242	0.7315	2,233	254
733	2,001	242	0.7325	2,235	255
734	2,001	242	0.7335	2,237	255
735	2,001	242	0.7345	2,240	255
736	2,002	243	0.7355	2,242	255
737	2,003	243	0.7365	2,244	255
738	2,003	243	0.7375	2,246	255
739	2,004	243	0.7385	2,249	255
740	2,005	243	0.7395	2,251	255
741	2,006	243	0.7405	2,253	256
742	2,011	244	0.7415	2,255	256
743	2,013	244	0.7425	2,258	256
744	2,014	244	0.7435	2,260	256
745	2,018	244	0.7445	2,262	256
746	2,019	244	0.7455	2,265	256
747	2,021	244	0.7465	2,267	256
748	2,024	244	0.7475	2,269	257
749	2,027	244	0.7485	2,272	257
750	2,029	244	0.7495	2,274	257
751	2,029	244	0.7505	2,276	257
752	2,034	245	0.7515	2,279	257
753	2,038	245	0.7525	2,281	257
754	2,039	245	0.7535	2,283	257
755	2,040	245	0.7545	2,286	258
756	2,041	245	0.7555	2,288	258
757	2,042	245	0.7565	2,291	258
758	2,045	245	0.7575	2,293	258

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
759	2,046	245	0.7585	2,295	258
760	2,049	245	0.7595	2,298	258
761	2,049	245	0.7605	2,300	258
762	2,052	246	0.7615	2,303	259
763	2,052	246	0.7625	2,305	259
764	2,054	246	0.7635	2,307	259
765	2,055	246	0.7645	2,310	259
766	2,056	246	0.7655	2,312	259
767	2,066	246	0.7665	2,315	259
768	2,068	246	0.7675	2,317	259
769	2,068	246	0.7685	2,320	260
770	2,070	247	0.7695	2,322	260
771	2,070	247	0.7705	2,325	260
772	2,070	247	0.7715	2,327	260
773	2,070	247	0.7725	2,330	260
774	2,070	247	0.7735	2,332	260
775	2,072	247	0.7745	2,335	260
776	2,072	247	0.7755	2,337	261
777	2,074	247	0.7765	2,340	261
778	2,077	247	0.7775	2,343	261
779	2,078	247	0.7785	2,345	261
780	2,078	247	0.7795	2,348	261
781	2,080	248	0.7805	2,350	261
782	2,081	248	0.7815	2,353	261
783	2,082	248	0.7825	2,356	262
784	2,085	248	0.7835	2,358	262
785	2,092	248	0.7845	2,361	262
786	2,095	248	0.7855	2,363	262
787	2,095	248	0.7865	2,366	262
788	2,096	248	0.7875	2,369	262
789	2,102	248	0.7885	2,371	263
790	2,105	248	0.7895	2,374	263
791	2,118	248	0.7905	2,377	263
792	2,122	248	0.7915	2,379	263
793	2,123	248	0.7925	2,382	263
794	2,127	249	0.7935	2,385	263
795	2,129	249	0.7945	2,388	263
796	2,133	249	0.7955	2,390	264

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
797	2,135	249	0.7965	2,393	264
798	2,136	250	0.7975	2,396	264
799	2,139	250	0.7985	2,399	264
800	2,143	250	0.7995	2,402	264
801	2,143	250	0.8005	2,404	264
802	2,149	250	0.8015	2,407	265
803	2,152	250	0.8025	2,410	265
804	2,155	251	0.8035	2,413	265
805	2,169	251	0.8045	2,416	265
806	2,170	251	0.8055	2,419	265
807	2,171	251	0.8065	2,421	265
808	2,174	251	0.8075	2,424	266
809	2,176	251	0.8085	2,427	266
810	2,183	251	0.8095	2,430	266
811	2,186	251	0.8105	2,433	266
812	2,186	252	0.8115	2,436	266
813	2,191	252	0.8125	2,439	266
814	2,191	252	0.8135	2,442	267
815	2,193	252	0.8145	2,445	267
816	2,194	252	0.8155	2,448	267
817	2,197	252	0.8165	2,451	267
818	2,200	253	0.8175	2,454	267
819	2,221	253	0.8185	2,457	267
820	2,222	253	0.8195	2,460	268
821	2,222	253	0.8205	2,463	268
822	2,227	253	0.8215	2,466	268
823	2,228	253	0.8225	2,469	268
824	2,228	254	0.8235	2,472	268
825	2,228	254	0.8245	2,476	269
826	2,235	254	0.8255	2,479	269
827	2,236	254	0.8265	2,482	269
828	2,240	254	0.8275	2,485	269
829	2,245	254	0.8285	2,488	269
830	2,247	254	0.8295	2,491	269
831	2,251	254	0.8305	2,495	270
832	2,257	254	0.8315	2,498	270
833	2,259	255	0.8325	2,501	270
834	2,263	255	0.8335	2,504	270

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
835	2,263	256	0.8345	2,508	270
836	2,274	256	0.8355	2,511	271
837	2,275	256	0.8365	2,514	271
838	2,275	256	0.8375	2,518	271
839	2,275	257	0.8385	2,521	271
840	2,279	257	0.8395	2,524	271
841	2,280	257	0.8405	2,528	271
842	2,280	257	0.8415	2,531	272
843	2,283	257	0.8425	2,535	272
844	2,283	257	0.8435	2,538	272
845	2,284	258	0.8445	2,542	272
846	2,284	258	0.8455	2,545	272
847	2,289	258	0.8465	2,549	273
848	2,297	258	0.8475	2,552	273
849	2,302	258	0.8485	2,556	273
850	2,304	258	0.8495	2,559	273
851	2,308	258	0.8505	2,563	273
852	2,310	259	0.8515	2,566	274
853	2,312	259	0.8525	2,570	274
854	2,314	259	0.8535	2,574	274
855	2,319	259	0.8545	2,577	274
856	2,319	259	0.8555	2,581	274
857	2,320	259	0.8565	2,585	275
858	2,321	259	0.8575	2,589	275
859	2,327	259	0.8585	2,592	275
860	2,328	260	0.8595	2,596	275
861	2,335	260	0.8605	2,600	275
862	2,338	260	0.8615	2,604	276
863	2,339	260	0.8625	2,608	276
864	2,344	260	0.8635	2,611	276
865	2,349	260	0.8645	2,615	276
866	2,350	260	0.8655	2,619	277
867	2,350	260	0.8665	2,623	277
868	2,351	260	0.8675	2,627	277
869	2,358	260	0.8685	2,631	277
870	2,359	260	0.8695	2,635	277
871	2,370	261	0.8705	2,639	278
872	2,370	261	0.8715	2,644	278

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
873	2,370	261	0.8725	2,648	278
874	2,375	261	0.8735	2,652	278
875	2,377	261	0.8745	2,656	279
876	2,379	261	0.8755	2,660	279
877	2,380	262	0.8765	2,665	279
878	2,384	262	0.8775	2,669	279
879	2,384	263	0.8785	2,673	280
880	2,394	263	0.8795	2,677	280
881	2,405	263	0.8805	2,682	280
882	2,414	263	0.8815	2,686	280
883	2,416	263	0.8825	2,691	280
884	2,426	263	0.8835	2,695	281
885	2,426	263	0.8845	2,700	281
886	2,436	263	0.8855	2,704	281
887	2,440	263	0.8865	2,709	281
888	2,446	263	0.8875	2,713	282
889	2,464	263	0.8885	2,718	282
890	2,468	263	0.8895	2,723	282
891	2,484	265	0.8905	2,728	282
892	2,491	265	0.8915	2,732	283
893	2,495	266	0.8925	2,737	283
894	2,498	266	0.8935	2,742	283
895	2,501	267	0.8945	2,747	284
896	2,507	267	0.8955	2,752	284
897	2,514	267	0.8965	2,757	284
898	2,515	267	0.8975	2,762	284
899	2,522	268	0.8985	2,767	285
900	2,532	268	0.8995	2,772	285
901	2,537	268	0.9005	2,777	285
902	2,574	268	0.9015	2,782	285
903	2,584	268	0.9025	2,788	286
904	2,584	268	0.9035	2,793	286
905	2,596	269	0.9045	2,798	286
906	2,622	269	0.9055	2,804	287
907	2,623	269	0.9065	2,809	287
908	2,623	269	0.9075	2,815	287
909	2,623	269	0.9085	2,820	287
910	2,629	270	0.9095	2,826	288

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
911	2,648	270	0.9105	2,832	288
912	2,653	271	0.9115	2,838	288
913	2,656	273	0.9125	2,843	289
914	2,668	273	0.9135	2,849	289
915	2,680	275	0.9145	2,855	289
916	2,698	275	0.9155	2,861	290
917	2,707	275	0.9165	2,867	290
918	2,727	276	0.9175	2,873	290
919	2,749	277	0.9185	2,880	291
920	2,766	277	0.9195	2,886	291
921	2,774	277	0.9205	2,892	291
922	2,804	277	0.9215	2,899	292
923	2,806	277	0.9225	2,905	292
924	2,808	278	0.9235	2,912	292
925	2,812	279	0.9245	2,918	293
926	2,820	279	0.9255	2,925	293
927	2,830	279	0.9265	2,932	293
928	2,834	279	0.9275	2,939	294
929	2,838	280	0.9285	2,946	294
930	2,848	280	0.9295	2,953	294
931	2,864	282	0.9305	2,960	295
932	2,865	282	0.9315	2,968	295
933	2,881	283	0.9325	2,975	296
934	2,884	283	0.9335	2,982	296
935	2,898	283	0.9345	2,990	296
936	2,898	285	0.9355	2,998	297
937	2,908	285	0.9365	3,006	297
938	2,908	285	0.9375	3,014	298
939	2,910	285	0.9385	3,022	298
940	2,911	286	0.9395	3,030	298
941	2,934	288	0.9405	3,038	299
942	2,951	288	0.9415	3,047	299
943	2,962	288	0.9425	3,055	300
944	2,962	288	0.9435	3,064	300
945	2,963	291	0.9445	3,073	301
946	2,978	292	0.9455	3,082	301
947	2,986	292	0.9465	3,091	302
948	2,990	292	0.9475	3,100	302

Monte Carlo Observation No.	**Total Embodied Energy (GJ)**	**Total CO_2 Emissions (tonnes)**	**Quantile**	**Lognormal Estimated Embodied Energy (GJ)**	**Lognormal Estimated CO_2 Emissions (tonnes)**
949	3,001	293	0.9485	3,110	303
950	3,003	293	0.9495	3,120	303
951	3,007	294	0.9505	3,130	304
952	3,012	294	0.9515	3,140	304
953	3,036	296	0.9525	3,150	305
954	3,056	296	0.9535	3,161	305
955	3,063	296	0.9545	3,171	306
956	3,077	297	0.9555	3,182	306
957	3,079	298	0.9565	3,193	307
958	3,091	300	0.9575	3,205	307
959	3,169	301	0.9585	3,217	308
960	3,174	301	0.9595	3,229	309
961	3,196	302	0.9605	3,241	309
962	3,201	302	0.9615	3,253	310
963	3,243	303	0.9625	3,266	310
964	3,255	304	0.9635	3,280	311
965	3,259	304	0.9645	3,293	312
966	3,277	304	0.9655	3,307	312
967	3,311	309	0.9665	3,321	313
968	3,322	310	0.9675	3,336	314
969	3,373	312	0.9685	3,352	315
970	3,387	313	0.9695	3,367	315
971	3,412	313	0.9705	3,383	316
972	3,430	314	0.9715	3,400	317
973	3,500	316	0.9725	3,418	318
974	3,533	317	0.9735	3,436	319
975	3,549	318	0.9745	3,454	320
976	3,613	321	0.9755	3,474	321
977	3,695	331	0.9765	3,494	322
978	3,724	332	0.9775	3,515	323
979	3,726	336	0.9785	3,537	324
980	3,786	337	0.9795	3,560	325
981	3,801	338	0.9805	3,584	326
982	3,802	346	0.9815	3,609	327
983	3,833	350	0.9825	3,636	328
984	3,839	351	0.9835	3,664	330
985	3,920	352	0.9845	3,694	331
986	3,962	352	0.9855	3,726	333

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
987	3,980	359	0.9865	3,761	334
988	4,084	360	0.9875	3,798	336
989	4,165	360	0.9885	3,838	338
990	4,178	363	0.9895	3,881	340
991	4,451	378	0.9905	3,929	342
992	4,537	380	0.9915	3,982	344
993	4,744	380	0.9925	4,042	347
994	4,797	385	0.9935	4,111	350
995	4,889	393	0.9945	4,191	354
996	5,849	400	0.9955	4,287	358
997	5,979	413	0.9965	4,408	363
998	7,950	514	0.9975	4,569	370
999	10,738	532	0.9985	4,816	380
1000	11,408	553	0.9995	5,352	402

M.2 PEARSON HALL RAMMED AGGREGATE COLUMNS WITH ADDED GEOGRID

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Portland Cement (U.S.)	804	164	155	18
2	Other	Aggregate: Sand and Gravel or Crushed Rock	432	625	25	36
3	Plastics	General Plastics (Average)	1,610	753	55	26
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	**2,846**	**993**	**235**	**47**
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TOTAL	**2,846**	**993**	**235**	**47**

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Cement delivery to site	3	0	0	0
2	Heavy Duty Truck	Aggregate delivery to site	91	3	7	0
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**94**	**3**	**7**	**0**
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	**0**	**0**	**0**	**0**
		MATERIALS TRANSPORTATION TOTAL	**94**	**3**	**7**	**0**

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Diesel Consumed by all Equipment	484	16	37	1
2						
3						
4						
		SITE OPERATIONS TOTAL	**484**	**16**	**37**	**1**

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Drill Spoil Disposal Trucking	111	4	8	0
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	**111**	**4**	**8**	**0**

Figure M.4 Line by line SEEAM calculations for Rammed Aggregate Columns at Pearson Hall, with added geogrid. Computations follow the analytical method described in Appendix K.

Table M.4 SEEAM results from the analytical method for the Rammed Aggregate Columns with added geogrid at Pearson Hall, showing the contribution of materials, materials transportation, site operations and waste transportation to total embodied energy and CO_2 emissions.

	Embodied Energy (GJ)			CO_2 Emissions (tonnes)		
	Mean	**St Dev**	**% of Total**	**Mean**	**St Dev**	**% of Total**
Materials	2,846	993	81%	235	47	82%
Materials Transportation	94	3	3%	7	0	2%
Site Operations	484	16	14%	37	1	13%
Waste Transportation	111	4	3%	8	0	3%
TOTAL	**3,535**	**993**	**100%**	**287**	**48**	**100%**

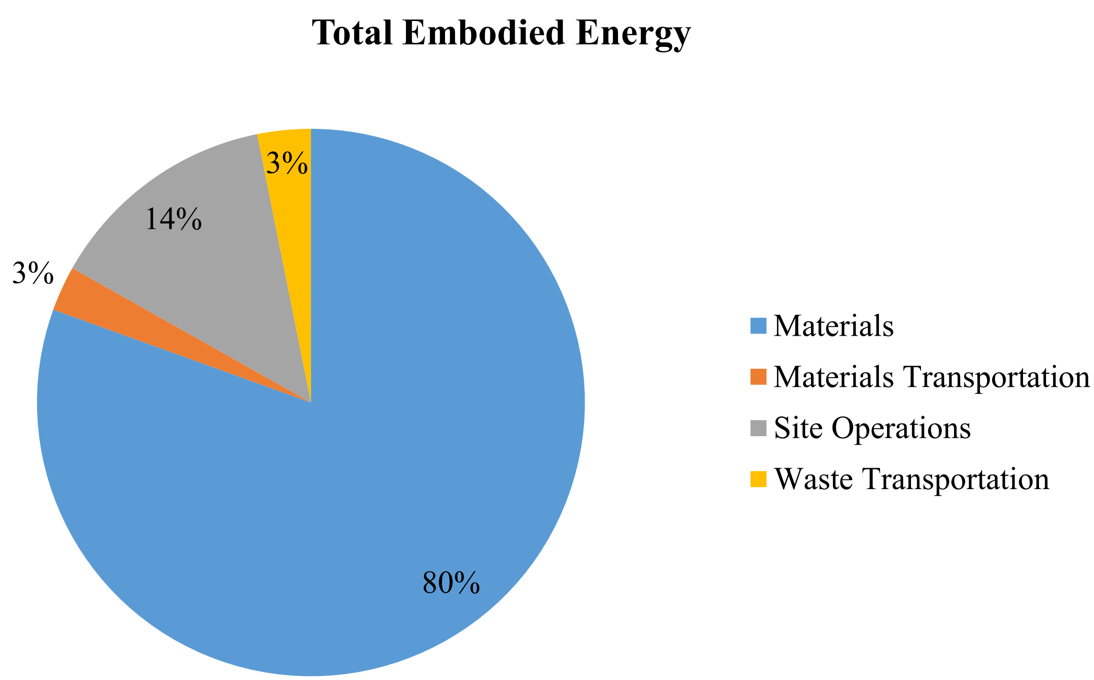

Figure M.5 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation from the analytical method of analysis for Rammed Aggregate Columns at Pearson Hall, with added geogrid.

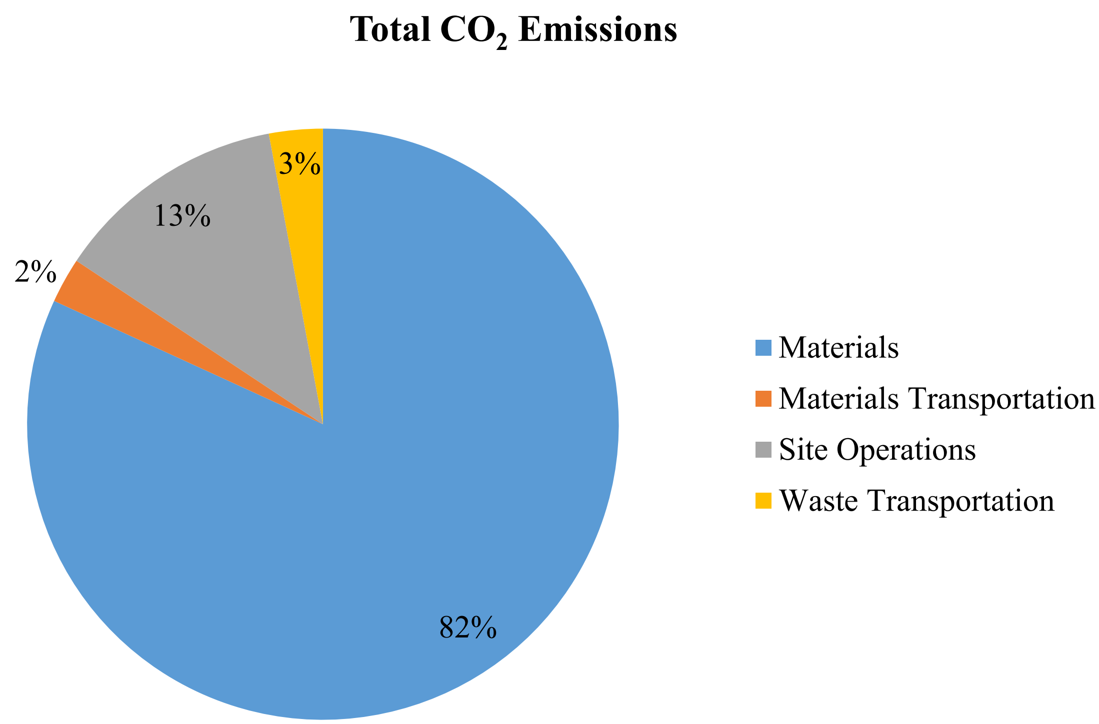

Figure M.6 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation from the analytical method of analysis for Rammed Aggregate Columns at Pearson Hall, with added geogrid.

Table M.5 Summary statistics for Monte Carlo simulated data sets of *n* = 1,000 values for total embodied energy and CO_2 emissions for Pearson Hall, with added geogrid.

Statistics	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Notes
Mean	3,531	288	
St. Dev.	906	50	
Maximum	10,620	680	
Minimum	1,886	202	
Mean Error (+/-)	47	3	90% Confidence; 1,000 Values
Mean Error % (+/-)	1.34%	0.91%	
No. of Values for +/- 2.5% Error	288	134	90% Confidence

Table M.6 Monte Carlo Simulation data, quantile, and lognormal estimates of total embodied energy and CO_2 emissions for Pearson Hall with added geogrid. Sorted in ascending numerical order.

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
1	1,886	202	0.0005	1,374	165
2	1,916	207	0.0015	1,502	174
3	1,965	207	0.0025	1,570	178
4	1,992	209	0.0035	1,619	182
5	2,003	210	0.0045	1,657	184
6	2,013	212	0.0055	1,689	186
7	2,022	213	0.0065	1,717	188
8	2,103	214	0.0075	1,741	190
9	2,163	215	0.0085	1,763	191
10	2,175	215	0.0095	1,783	192
11	2,185	216	0.0105	1,802	194
12	2,194	216	0.0115	1,819	195
13	2,194	216	0.0125	1,835	196
14	2,195	216	0.0135	1,850	197
15	2,203	217	0.0145	1,865	198
16	2,207	218	0.0155	1,878	198
17	2,213	218	0.0165	1,891	199
18	2,213	218	0.0175	1,904	200
19	2,237	220	0.0185	1,916	201
20	2,239	221	0.0195	1,927	202
21	2,275	221	0.0205	1,938	202
22	2,279	221	0.0215	1,949	203
23	2,285	222	0.0225	1,959	204
24	2,286	224	0.0235	1,969	204
25	2,289	225	0.0245	1,978	205
26	2,291	225	0.0255	1,988	205
27	2,295	226	0.0265	1,997	206
28	2,297	226	0.0275	2,006	206
29	2,309	226	0.0285	2,014	207
30	2,310	227	0.0295	2,023	207
31	2,317	227	0.0305	2,031	208
32	2,323	227	0.0315	2,039	208
33	2,323	227	0.0325	2,047	209
34	2,324	227	0.0335	2,055	209
35	2,327	229	0.0345	2,062	210
36	2,335	229	0.0355	2,069	210

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
37	2,338	229	0.0365	2,077	211
38	2,339	229	0.0375	2,084	211
39	2,344	229	0.0385	2,091	212
40	2,348	230	0.0395	2,098	212
41	2,348	230	0.0405	2,104	212
42	2,358	230	0.0415	2,111	213
43	2,363	230	0.0425	2,117	213
44	2,367	230	0.0435	2,124	214
45	2,382	230	0.0445	2,130	214
46	2,384	231	0.0455	2,136	214
47	2,384	231	0.0465	2,142	215
48	2,386	231	0.0475	2,148	215
49	2,390	231	0.0485	2,154	215
50	2,391	232	0.0495	2,160	216
51	2,393	232	0.0505	2,166	216
52	2,395	232	0.0515	2,172	216
53	2,397	232	0.0525	2,177	217
54	2,397	232	0.0535	2,183	217
55	2,401	232	0.0545	2,188	217
56	2,406	233	0.0555	2,194	218
57	2,408	233	0.0565	2,199	218
58	2,418	233	0.0575	2,204	218
59	2,422	233	0.0585	2,210	219
60	2,422	234	0.0595	2,215	219
61	2,428	234	0.0605	2,220	219
62	2,429	234	0.0615	2,225	220
63	2,431	235	0.0625	2,230	220
64	2,432	235	0.0635	2,235	220
65	2,433	235	0.0645	2,240	220
66	2,437	235	0.0655	2,245	221
67	2,444	235	0.0665	2,250	221
68	2,446	235	0.0675	2,254	221
69	2,452	235	0.0685	2,259	222
70	2,453	236	0.0695	2,264	222
71	2,454	236	0.0705	2,269	222
72	2,458	237	0.0715	2,273	222
73	2,459	237	0.0725	2,278	223
74	2,461	237	0.0735	2,282	223

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
75	2,467	237	0.0745	2,287	223
76	2,468	237	0.0755	2,291	223
77	2,477	237	0.0765	2,296	224
78	2,482	237	0.0775	2,300	224
79	2,485	237	0.0785	2,304	224
80	2,487	237	0.0795	2,309	224
81	2,501	237	0.0805	2,313	225
82	2,501	237	0.0815	2,317	225
83	2,503	237	0.0825	2,321	225
84	2,509	238	0.0835	2,326	225
85	2,512	238	0.0845	2,330	226
86	2,516	238	0.0855	2,334	226
87	2,517	238	0.0865	2,338	226
88	2,517	238	0.0875	2,342	226
89	2,522	238	0.0885	2,346	227
90	2,525	239	0.0895	2,350	227
91	2,526	239	0.0905	2,354	227
92	2,526	239	0.0915	2,358	227
93	2,526	239	0.0925	2,362	228
94	2,528	239	0.0935	2,366	228
95	2,530	240	0.0945	2,370	228
96	2,534	240	0.0955	2,374	228
97	2,539	240	0.0965	2,378	228
98	2,541	240	0.0975	2,381	229
99	2,544	240	0.0985	2,385	229
100	2,545	241	0.0995	2,389	229
101	2,545	241	0.1005	2,393	229
102	2,549	241	0.1015	2,396	230
103	2,554	241	0.1025	2,400	230
104	2,554	241	0.1035	2,404	230
105	2,556	241	0.1045	2,407	230
106	2,566	242	0.1055	2,411	230
107	2,571	242	0.1065	2,415	231
108	2,571	242	0.1075	2,418	231
109	2,579	243	0.1085	2,422	231
110	2,580	243	0.1095	2,426	231
111	2,584	243	0.1105	2,429	231
112	2,587	243	0.1115	2,433	232

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
113	2,588	243	0.1125	2,436	232
114	2,595	243	0.1135	2,440	232
115	2,600	244	0.1145	2,443	232
116	2,603	244	0.1155	2,447	232
117	2,608	244	0.1165	2,450	233
118	2,615	244	0.1175	2,454	233
119	2,616	244	0.1185	2,457	233
120	2,623	244	0.1195	2,460	233
121	2,629	244	0.1205	2,464	233
122	2,633	244	0.1215	2,467	234
123	2,634	244	0.1225	2,470	234
124	2,635	245	0.1235	2,474	234
125	2,639	245	0.1245	2,477	234
126	2,651	245	0.1255	2,480	234
127	2,656	245	0.1265	2,484	235
128	2,658	245	0.1275	2,487	235
129	2,661	245	0.1285	2,490	235
130	2,661	246	0.1295	2,494	235
131	2,663	246	0.1305	2,497	235
132	2,663	246	0.1315	2,500	235
133	2,665	246	0.1325	2,503	236
134	2,666	246	0.1335	2,507	236
135	2,670	246	0.1345	2,510	236
136	2,672	246	0.1355	2,513	236
137	2,676	246	0.1365	2,516	236
138	2,678	246	0.1375	2,519	237
139	2,681	247	0.1385	2,522	237
140	2,684	247	0.1395	2,526	237
141	2,688	247	0.1405	2,529	237
142	2,693	247	0.1415	2,532	237
143	2,693	247	0.1425	2,535	237
144	2,695	247	0.1435	2,538	238
145	2,697	247	0.1445	2,541	238
146	2,699	247	0.1455	2,544	238
147	2,714	248	0.1465	2,547	238
148	2,719	248	0.1475	2,550	238
149	2,719	248	0.1485	2,553	238
150	2,720	248	0.1495	2,556	239

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
151	2,720	248	0.1505	2,559	239
152	2,724	248	0.1515	2,562	239
153	2,724	248	0.1525	2,565	239
154	2,731	248	0.1535	2,568	239
155	2,735	248	0.1545	2,571	239
156	2,736	248	0.1555	2,574	240
157	2,739	249	0.1565	2,577	240
158	2,740	249	0.1575	2,580	240
159	2,740	249	0.1585	2,583	240
160	2,742	249	0.1595	2,586	240
161	2,746	249	0.1605	2,589	240
162	2,748	249	0.1615	2,592	241
163	2,750	249	0.1625	2,595	241
164	2,751	249	0.1635	2,598	241
165	2,751	249	0.1645	2,601	241
166	2,752	249	0.1655	2,604	241
167	2,758	250	0.1665	2,606	241
168	2,758	250	0.1675	2,609	242
169	2,759	250	0.1685	2,612	242
170	2,760	250	0.1695	2,615	242
171	2,767	250	0.1705	2,618	242
172	2,768	250	0.1715	2,621	242
173	2,770	250	0.1725	2,624	242
174	2,773	250	0.1735	2,626	242
175	2,774	250	0.1745	2,629	243
176	2,775	250	0.1755	2,632	243
177	2,780	250	0.1765	2,635	243
178	2,783	250	0.1775	2,638	243
179	2,785	251	0.1785	2,640	243
180	2,785	251	0.1795	2,643	243
181	2,786	251	0.1805	2,646	244
182	2,787	251	0.1815	2,649	244
183	2,790	251	0.1825	2,652	244
184	2,790	251	0.1835	2,654	244
185	2,790	251	0.1845	2,657	244
186	2,791	251	0.1855	2,660	244
187	2,792	251	0.1865	2,663	244
188	2,794	251	0.1875	2,665	245

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
189	2,797	251	0.1885	2,668	245
190	2,799	251	0.1895	2,671	245
191	2,802	252	0.1905	2,673	245
192	2,806	252	0.1915	2,676	245
193	2,807	252	0.1925	2,679	245
194	2,807	252	0.1935	2,682	245
195	2,811	252	0.1945	2,684	246
196	2,811	252	0.1955	2,687	246
197	2,812	252	0.1965	2,690	246
198	2,813	252	0.1975	2,692	246
199	2,815	252	0.1985	2,695	246
200	2,817	252	0.1995	2,698	246
201	2,818	252	0.2005	2,700	247
202	2,819	253	0.2015	2,703	247
203	2,822	253	0.2025	2,706	247
204	2,823	253	0.2035	2,708	247
205	2,824	253	0.2045	2,711	247
206	2,831	253	0.2055	2,713	247
207	2,832	253	0.2065	2,716	247
208	2,838	253	0.2075	2,719	248
209	2,839	254	0.2085	2,721	248
210	2,842	254	0.2095	2,724	248
211	2,842	254	0.2105	2,727	248
212	2,846	254	0.2115	2,729	248
213	2,849	254	0.2125	2,732	248
214	2,849	254	0.2135	2,734	248
215	2,850	254	0.2145	2,737	248
216	2,852	254	0.2155	2,739	249
217	2,856	254	0.2165	2,742	249
218	2,859	254	0.2175	2,745	249
219	2,860	254	0.2185	2,747	249
220	2,861	255	0.2195	2,750	249
221	2,865	255	0.2205	2,752	249
222	2,866	255	0.2215	2,755	249
223	2,866	255	0.2225	2,757	250
224	2,869	255	0.2235	2,760	250
225	2,869	255	0.2245	2,763	250
226	2,870	255	0.2255	2,765	250

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
227	2,870	256	0.2265	2,768	250
228	2,871	256	0.2275	2,770	250
229	2,871	256	0.2285	2,773	250
230	2,871	256	0.2295	2,775	251
231	2,874	256	0.2305	2,778	251
232	2,879	256	0.2315	2,780	251
233	2,880	256	0.2325	2,783	251
234	2,883	256	0.2335	2,785	251
235	2,884	256	0.2345	2,788	251
236	2,886	256	0.2355	2,790	251
237	2,889	256	0.2365	2,793	252
238	2,890	257	0.2375	2,795	252
239	2,891	257	0.2385	2,798	252
240	2,893	257	0.2395	2,800	252
241	2,894	257	0.2405	2,803	252
242	2,898	257	0.2415	2,805	252
243	2,899	257	0.2425	2,808	252
244	2,899	257	0.2435	2,810	252
245	2,900	257	0.2445	2,813	253
246	2,901	257	0.2455	2,815	253
247	2,901	257	0.2465	2,818	253
248	2,902	257	0.2475	2,820	253
249	2,904	257	0.2485	2,822	253
250	2,910	257	0.2495	2,825	253
251	2,910	258	0.2505	2,827	253
252	2,912	258	0.2515	2,830	253
253	2,914	258	0.2525	2,832	254
254	2,916	258	0.2535	2,835	254
255	2,916	258	0.2545	2,837	254
256	2,920	258	0.2555	2,840	254
257	2,922	258	0.2565	2,842	254
258	2,927	258	0.2575	2,844	254
259	2,932	258	0.2585	2,847	254
260	2,934	258	0.2595	2,849	255
261	2,934	258	0.2605	2,852	255
262	2,935	258	0.2615	2,854	255
263	2,938	259	0.2625	2,857	255
264	2,939	259	0.2635	2,859	255

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
265	2,939	259	0.2645	2,861	255
266	2,942	259	0.2655	2,864	255
267	2,947	259	0.2665	2,866	255
268	2,947	259	0.2675	2,869	256
269	2,950	259	0.2685	2,871	256
270	2,951	259	0.2695	2,873	256
271	2,957	259	0.2705	2,876	256
272	2,957	259	0.2715	2,878	256
273	2,962	259	0.2725	2,881	256
274	2,964	259	0.2735	2,883	256
275	2,968	260	0.2745	2,885	256
276	2,969	260	0.2755	2,888	257
277	2,975	260	0.2765	2,890	257
278	2,975	260	0.2775	2,892	257
279	2,978	260	0.2785	2,895	257
280	2,978	260	0.2795	2,897	257
281	2,979	260	0.2805	2,900	257
282	2,981	260	0.2815	2,902	257
283	2,985	261	0.2825	2,904	257
284	2,986	261	0.2835	2,907	258
285	2,986	261	0.2845	2,909	258
286	2,986	261	0.2855	2,911	258
287	2,987	261	0.2865	2,914	258
288	2,988	261	0.2875	2,916	258
289	2,990	261	0.2885	2,918	258
290	2,995	261	0.2895	2,921	258
291	2,997	261	0.2905	2,923	258
292	2,999	261	0.2915	2,926	259
293	3,003	261	0.2925	2,928	259
294	3,008	262	0.2935	2,930	259
295	3,009	262	0.2945	2,933	259
296	3,009	262	0.2955	2,935	259
297	3,011	262	0.2965	2,937	259
298	3,014	262	0.2975	2,940	259
299	3,014	262	0.2985	2,942	259
300	3,014	262	0.2995	2,944	260
301	3,018	263	0.3005	2,947	260
302	3,018	263	0.3015	2,949	260

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
303	3,018	263	0.3025	2,951	260
304	3,027	263	0.3035	2,954	260
305	3,027	263	0.3045	2,956	260
306	3,029	263	0.3055	2,958	260
307	3,031	263	0.3065	2,961	260
308	3,031	263	0.3075	2,963	261
309	3,033	263	0.3085	2,965	261
310	3,033	263	0.3095	2,968	261
311	3,035	263	0.3105	2,970	261
312	3,035	264	0.3115	2,972	261
313	3,035	264	0.3125	2,975	261
314	3,037	264	0.3135	2,977	261
315	3,038	264	0.3145	2,979	261
316	3,041	264	0.3155	2,981	262
317	3,044	264	0.3165	2,984	262
318	3,044	264	0.3175	2,986	262
319	3,046	264	0.3185	2,988	262
320	3,051	264	0.3195	2,991	262
321	3,052	264	0.3205	2,993	262
322	3,057	264	0.3215	2,995	262
323	3,059	264	0.3225	2,998	262
324	3,060	264	0.3235	3,000	262
325	3,061	265	0.3245	3,002	263
326	3,065	265	0.3255	3,004	263
327	3,066	265	0.3265	3,007	263
328	3,070	265	0.3275	3,009	263
329	3,071	265	0.3285	3,011	263
330	3,072	265	0.3295	3,014	263
331	3,075	265	0.3305	3,016	263
332	3,077	265	0.3315	3,018	263
333	3,080	266	0.3325	3,021	264
334	3,080	266	0.3335	3,023	264
335	3,081	266	0.3345	3,025	264
336	3,083	266	0.3355	3,027	264
337	3,084	266	0.3365	3,030	264
338	3,087	266	0.3375	3,032	264
339	3,088	266	0.3385	3,034	264
340	3,089	266	0.3395	3,037	264

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
341	3,096	266	0.3405	3,039	265
342	3,099	266	0.3415	3,041	265
343	3,102	266	0.3425	3,043	265
344	3,104	267	0.3435	3,046	265
345	3,107	267	0.3445	3,048	265
346	3,109	267	0.3455	3,050	265
347	3,110	267	0.3465	3,053	265
348	3,110	267	0.3475	3,055	265
349	3,112	267	0.3485	3,057	265
350	3,112	267	0.3495	3,059	266
351	3,114	267	0.3505	3,062	266
352	3,114	267	0.3515	3,064	266
353	3,115	267	0.3525	3,066	266
354	3,116	267	0.3535	3,068	266
355	3,118	267	0.3545	3,071	266
356	3,119	267	0.3555	3,073	266
357	3,121	267	0.3565	3,075	266
358	3,124	268	0.3575	3,078	267
359	3,130	268	0.3585	3,080	267
360	3,132	268	0.3595	3,082	267
361	3,134	268	0.3605	3,084	267
362	3,135	268	0.3615	3,087	267
363	3,140	268	0.3625	3,089	267
364	3,140	268	0.3635	3,091	267
365	3,143	268	0.3645	3,093	267
366	3,148	269	0.3655	3,096	267
367	3,148	269	0.3665	3,098	268
368	3,148	269	0.3675	3,100	268
369	3,150	269	0.3685	3,103	268
370	3,151	269	0.3695	3,105	268
371	3,151	269	0.3705	3,107	268
372	3,154	269	0.3715	3,109	268
373	3,155	269	0.3725	3,112	268
374	3,159	269	0.3735	3,114	268
375	3,160	269	0.3745	3,116	269
376	3,160	269	0.3755	3,118	269
377	3,161	269	0.3765	3,121	269
378	3,161	269	0.3775	3,123	269

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
379	3,163	270	0.3785	3,125	269
380	3,164	270	0.3795	3,127	269
381	3,166	270	0.3805	3,130	269
382	3,168	270	0.3815	3,132	269
383	3,169	270	0.3825	3,134	269
384	3,169	270	0.3835	3,137	270
385	3,169	270	0.3845	3,139	270
386	3,171	270	0.3855	3,141	270
387	3,172	270	0.3865	3,143	270
388	3,172	270	0.3875	3,146	270
389	3,176	270	0.3885	3,148	270
390	3,179	270	0.3895	3,150	270
391	3,182	270	0.3905	3,152	270
392	3,186	270	0.3915	3,155	270
393	3,190	270	0.3925	3,157	271
394	3,191	270	0.3935	3,159	271
395	3,194	271	0.3945	3,161	271
396	3,195	271	0.3955	3,164	271
397	3,196	271	0.3965	3,166	271
398	3,197	271	0.3975	3,168	271
399	3,204	271	0.3985	3,170	271
400	3,205	271	0.3995	3,173	271
401	3,205	271	0.4005	3,175	272
402	3,205	271	0.4015	3,177	272
403	3,209	271	0.4025	3,180	272
404	3,214	271	0.4035	3,182	272
405	3,216	271	0.4045	3,184	272
406	3,219	271	0.4055	3,186	272
407	3,222	271	0.4065	3,189	272
408	3,223	271	0.4075	3,191	272
409	3,225	271	0.4085	3,193	272
410	3,225	271	0.4095	3,195	273
411	3,231	271	0.4105	3,198	273
412	3,233	271	0.4115	3,200	273
413	3,234	272	0.4125	3,202	273
414	3,236	272	0.4135	3,204	273
415	3,238	272	0.4145	3,207	273
416	3,238	272	0.4155	3,209	273

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
417	3,241	272	0.4165	3,211	273
418	3,244	272	0.4175	3,214	273
419	3,245	272	0.4185	3,216	274
420	3,245	272	0.4195	3,218	274
421	3,248	272	0.4205	3,220	274
422	3,249	273	0.4215	3,223	274
423	3,251	273	0.4225	3,225	274
424	3,252	273	0.4235	3,227	274
425	3,252	273	0.4245	3,229	274
426	3,253	273	0.4255	3,232	274
427	3,253	273	0.4265	3,234	275
428	3,254	273	0.4275	3,236	275
429	3,254	273	0.4285	3,238	275
430	3,257	273	0.4295	3,241	275
431	3,258	273	0.4305	3,243	275
432	3,260	273	0.4315	3,245	275
433	3,261	273	0.4325	3,248	275
434	3,261	274	0.4335	3,250	275
435	3,261	274	0.4345	3,252	275
436	3,264	274	0.4355	3,254	276
437	3,264	274	0.4365	3,257	276
438	3,266	274	0.4375	3,259	276
439	3,267	274	0.4385	3,261	276
440	3,273	274	0.4395	3,264	276
441	3,274	274	0.4405	3,266	276
442	3,274	274	0.4415	3,268	276
443	3,278	274	0.4425	3,270	276
444	3,280	275	0.4435	3,273	276
445	3,282	275	0.4445	3,275	277
446	3,283	275	0.4455	3,277	277
447	3,284	275	0.4465	3,280	277
448	3,286	275	0.4475	3,282	277
449	3,286	275	0.4485	3,284	277
450	3,287	275	0.4495	3,286	277
451	3,287	275	0.4505	3,289	277
452	3,287	275	0.4515	3,291	277
453	3,288	275	0.4525	3,293	278
454	3,288	276	0.4535	3,296	278

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
455	3,293	276	0.4545	3,298	278
456	3,294	276	0.4555	3,300	278
457	3,299	276	0.4565	3,302	278
458	3,299	276	0.4575	3,305	278
459	3,303	276	0.4585	3,307	278
460	3,303	276	0.4595	3,309	278
461	3,305	276	0.4605	3,312	278
462	3,306	276	0.4615	3,314	279
463	3,310	276	0.4625	3,316	279
464	3,312	276	0.4635	3,319	279
465	3,316	276	0.4645	3,321	279
466	3,316	276	0.4655	3,323	279
467	3,317	276	0.4665	3,325	279
468	3,317	276	0.4675	3,328	279
469	3,318	276	0.4685	3,330	279
470	3,318	276	0.4695	3,332	279
471	3,319	277	0.4705	3,335	280
472	3,319	277	0.4715	3,337	280
473	3,321	277	0.4725	3,339	280
474	3,322	277	0.4735	3,342	280
475	3,323	277	0.4745	3,344	280
476	3,326	277	0.4755	3,346	280
477	3,327	277	0.4765	3,349	280
478	3,329	277	0.4775	3,351	280
479	3,330	277	0.4785	3,353	281
480	3,333	277	0.4795	3,355	281
481	3,333	278	0.4805	3,358	281
482	3,336	278	0.4815	3,360	281
483	3,337	278	0.4825	3,362	281
484	3,339	278	0.4835	3,365	281
485	3,339	278	0.4845	3,367	281
486	3,342	278	0.4855	3,369	281
487	3,342	278	0.4865	3,372	281
488	3,343	278	0.4875	3,374	282
489	3,344	278	0.4885	3,376	282
490	3,344	278	0.4895	3,379	282
491	3,346	278	0.4905	3,381	282
492	3,348	278	0.4915	3,383	282

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
493	3,352	278	0.4925	3,386	282
494	3,352	279	0.4935	3,388	282
495	3,354	279	0.4945	3,390	282
496	3,362	279	0.4955	3,393	282
497	3,363	279	0.4965	3,395	283
498	3,363	279	0.4975	3,397	283
499	3,365	279	0.4985	3,400	283
500	3,370	279	0.4995	3,402	283
501	3,370	279	0.5005	3,405	283
502	3,373	280	0.5015	3,407	283
503	3,379	280	0.5025	3,409	283
504	3,381	280	0.5035	3,412	283
505	3,383	280	0.5045	3,414	284
506	3,386	280	0.5055	3,416	284
507	3,389	280	0.5065	3,419	284
508	3,391	280	0.5075	3,421	284
509	3,393	280	0.5085	3,423	284
510	3,396	280	0.5095	3,426	284
511	3,396	280	0.5105	3,428	284
512	3,400	280	0.5115	3,431	284
513	3,403	280	0.5125	3,433	284
514	3,404	280	0.5135	3,435	285
515	3,405	281	0.5145	3,438	285
516	3,409	281	0.5155	3,440	285
517	3,412	281	0.5165	3,442	285
518	3,416	281	0.5175	3,445	285
519	3,416	281	0.5185	3,447	285
520	3,418	281	0.5195	3,450	285
521	3,421	281	0.5205	3,452	285
522	3,423	281	0.5215	3,454	286
523	3,426	281	0.5225	3,457	286
524	3,426	282	0.5235	3,459	286
525	3,428	282	0.5245	3,461	286
526	3,428	282	0.5255	3,464	286
527	3,429	282	0.5265	3,466	286
528	3,430	282	0.5275	3,469	286
529	3,430	282	0.5285	3,471	286
530	3,431	282	0.5295	3,473	286

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
531	3,437	282	0.5305	3,476	287
532	3,440	282	0.5315	3,478	287
533	3,442	282	0.5325	3,481	287
534	3,443	282	0.5335	3,483	287
535	3,443	282	0.5345	3,486	287
536	3,444	282	0.5355	3,488	287
537	3,446	282	0.5365	3,490	287
538	3,447	283	0.5375	3,493	287
539	3,450	283	0.5385	3,495	288
540	3,451	283	0.5395	3,498	288
541	3,451	283	0.5405	3,500	288
542	3,454	283	0.5415	3,503	288
543	3,455	283	0.5425	3,505	288
544	3,456	283	0.5435	3,507	288
545	3,456	283	0.5445	3,510	288
546	3,457	283	0.5455	3,512	288
547	3,458	284	0.5465	3,515	289
548	3,458	284	0.5475	3,517	289
549	3,463	284	0.5485	3,520	289
550	3,464	284	0.5495	3,522	289
551	3,465	284	0.5505	3,524	289
552	3,466	284	0.5515	3,527	289
553	3,467	284	0.5525	3,529	289
554	3,468	284	0.5535	3,532	289
555	3,469	284	0.5545	3,534	289
556	3,470	284	0.5555	3,537	290
557	3,476	284	0.5565	3,539	290
558	3,477	285	0.5575	3,542	290
559	3,480	285	0.5585	3,544	290
560	3,480	285	0.5595	3,547	290
561	3,482	285	0.5605	3,549	290
562	3,483	285	0.5615	3,552	290
563	3,484	285	0.5625	3,554	290
564	3,485	285	0.5635	3,557	291
565	3,487	285	0.5645	3,559	291
566	3,487	285	0.5655	3,562	291
567	3,488	285	0.5665	3,564	291
568	3,488	285	0.5675	3,567	291

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
569	3,489	285	0.5685	3,569	291
570	3,489	285	0.5695	3,572	291
571	3,491	285	0.5705	3,574	291
572	3,492	285	0.5715	3,577	292
573	3,492	285	0.5725	3,579	292
574	3,496	286	0.5735	3,582	292
575	3,497	286	0.5745	3,584	292
576	3,497	286	0.5755	3,587	292
577	3,498	286	0.5765	3,589	292
578	3,499	286	0.5775	3,592	292
579	3,504	286	0.5785	3,594	292
580	3,506	286	0.5795	3,597	293
581	3,510	286	0.5805	3,599	293
582	3,513	286	0.5815	3,602	293
583	3,516	286	0.5825	3,604	293
584	3,517	287	0.5835	3,607	293
585	3,517	287	0.5845	3,610	293
586	3,520	287	0.5855	3,612	293
587	3,520	287	0.5865	3,615	293
588	3,524	287	0.5875	3,617	294
589	3,525	287	0.5885	3,620	294
590	3,525	287	0.5895	3,622	294
591	3,530	287	0.5905	3,625	294
592	3,530	287	0.5915	3,627	294
593	3,531	287	0.5925	3,630	294
594	3,532	287	0.5935	3,633	294
595	3,535	287	0.5945	3,635	294
596	3,540	287	0.5955	3,638	294
597	3,540	287	0.5965	3,640	295
598	3,541	287	0.5975	3,643	295
599	3,541	288	0.5985	3,646	295
600	3,544	288	0.5995	3,648	295
601	3,546	288	0.6005	3,651	295
602	3,547	288	0.6015	3,653	295
603	3,547	288	0.6025	3,656	295
604	3,548	288	0.6035	3,659	296
605	3,548	288	0.6045	3,661	296
606	3,548	288	0.6055	3,664	296

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
607	3,549	288	0.6065	3,666	296
608	3,553	288	0.6075	3,669	296
609	3,553	288	0.6085	3,672	296
610	3,553	288	0.6095	3,674	296
611	3,554	288	0.6105	3,677	296
612	3,555	288	0.6115	3,680	297
613	3,559	289	0.6125	3,682	297
614	3,561	289	0.6135	3,685	297
615	3,564	289	0.6145	3,688	297
616	3,565	289	0.6155	3,690	297
617	3,565	289	0.6165	3,693	297
618	3,567	289	0.6175	3,696	297
619	3,569	289	0.6185	3,698	297
620	3,573	289	0.6195	3,701	298
621	3,573	289	0.6205	3,704	298
622	3,575	289	0.6215	3,706	298
623	3,577	290	0.6225	3,709	298
624	3,578	290	0.6235	3,712	298
625	3,582	290	0.6245	3,714	298
626	3,585	290	0.6255	3,717	298
627	3,586	290	0.6265	3,720	298
628	3,588	290	0.6275	3,722	299
629	3,595	290	0.6285	3,725	299
630	3,595	290	0.6295	3,728	299
631	3,595	290	0.6305	3,731	299
632	3,599	291	0.6315	3,733	299
633	3,600	291	0.6325	3,736	299
634	3,603	291	0.6335	3,739	299
635	3,605	291	0.6345	3,742	299
636	3,606	291	0.6355	3,744	300
637	3,606	291	0.6365	3,747	300
638	3,610	291	0.6375	3,750	300
639	3,618	291	0.6385	3,753	300
640	3,619	291	0.6395	3,755	300
641	3,620	291	0.6405	3,758	300
642	3,620	291	0.6415	3,761	300
643	3,621	291	0.6425	3,764	301
644	3,622	291	0.6435	3,766	301

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
645	3,626	291	0.6445	3,769	301
646	3,626	291	0.6455	3,772	301
647	3,627	291	0.6465	3,775	301
648	3,629	291	0.6475	3,778	301
649	3,633	292	0.6485	3,780	301
650	3,636	292	0.6495	3,783	301
651	3,637	292	0.6505	3,786	302
652	3,637	292	0.6515	3,789	302
653	3,638	292	0.6525	3,792	302
654	3,639	292	0.6535	3,794	302
655	3,640	293	0.6545	3,797	302
656	3,642	293	0.6555	3,800	302
657	3,648	293	0.6565	3,803	302
658	3,649	293	0.6575	3,806	303
659	3,649	293	0.6585	3,809	303
660	3,649	293	0.6595	3,812	303
661	3,649	293	0.6605	3,814	303
662	3,651	293	0.6615	3,817	303
663	3,651	293	0.6625	3,820	303
664	3,658	293	0.6635	3,823	303
665	3,663	293	0.6645	3,826	303
666	3,667	294	0.6655	3,829	304
667	3,675	294	0.6665	3,832	304
668	3,683	294	0.6675	3,835	304
669	3,683	294	0.6685	3,838	304
670	3,685	294	0.6695	3,840	304
671	3,689	294	0.6705	3,843	304
672	3,691	294	0.6715	3,846	304
673	3,696	294	0.6725	3,849	305
674	3,696	294	0.6735	3,852	305
675	3,701	294	0.6745	3,855	305
676	3,702	295	0.6755	3,858	305
677	3,704	295	0.6765	3,861	305
678	3,707	295	0.6775	3,864	305
679	3,709	295	0.6785	3,867	305
680	3,711	295	0.6795	3,870	306
681	3,715	295	0.6805	3,873	306
682	3,716	295	0.6815	3,876	306

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
683	3,720	295	0.6825	3,879	306
684	3,725	296	0.6835	3,882	306
685	3,726	296	0.6845	3,885	306
686	3,730	296	0.6855	3,888	306
687	3,739	296	0.6865	3,891	307
688	3,746	296	0.6875	3,894	307
689	3,748	296	0.6885	3,897	307
690	3,750	296	0.6895	3,900	307
691	3,751	297	0.6905	3,903	307
692	3,762	297	0.6915	3,906	307
693	3,762	297	0.6925	3,909	307
694	3,763	297	0.6935	3,912	308
695	3,765	297	0.6945	3,915	308
696	3,765	297	0.6955	3,918	308
697	3,767	297	0.6965	3,922	308
698	3,769	298	0.6975	3,925	308
699	3,769	298	0.6985	3,928	308
700	3,771	298	0.6995	3,931	308
701	3,771	298	0.7005	3,934	309
702	3,774	298	0.7015	3,937	309
703	3,775	298	0.7025	3,940	309
704	3,779	298	0.7035	3,943	309
705	3,784	298	0.7045	3,947	309
706	3,786	299	0.7055	3,950	309
707	3,788	299	0.7065	3,953	309
708	3,788	299	0.7075	3,956	310
709	3,790	299	0.7085	3,959	310
710	3,790	299	0.7095	3,962	310
711	3,794	299	0.7105	3,966	310
712	3,802	299	0.7115	3,969	310
713	3,804	299	0.7125	3,972	310
714	3,807	300	0.7135	3,975	311
715	3,808	300	0.7145	3,978	311
716	3,809	300	0.7155	3,982	311
717	3,814	300	0.7165	3,985	311
718	3,819	300	0.7175	3,988	311
719	3,822	300	0.7185	3,991	311
720	3,823	300	0.7195	3,995	311

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
721	3,827	300	0.7205	3,998	312
722	3,833	301	0.7215	4,001	312
723	3,833	301	0.7225	4,004	312
724	3,833	301	0.7235	4,008	312
725	3,843	301	0.7245	4,011	312
726	3,843	301	0.7255	4,014	312
727	3,845	301	0.7265	4,018	312
728	3,855	301	0.7275	4,021	313
729	3,860	301	0.7285	4,024	313
730	3,860	302	0.7295	4,028	313
731	3,876	302	0.7305	4,031	313
732	3,877	302	0.7315	4,034	313
733	3,880	302	0.7325	4,038	313
734	3,883	302	0.7335	4,041	314
735	3,889	302	0.7345	4,045	314
736	3,889	303	0.7355	4,048	314
737	3,894	303	0.7365	4,051	314
738	3,894	303	0.7375	4,055	314
739	3,896	303	0.7385	4,058	314
740	3,897	303	0.7395	4,062	315
741	3,901	303	0.7405	4,065	315
742	3,903	304	0.7415	4,069	315
743	3,923	304	0.7425	4,072	315
744	3,924	304	0.7435	4,076	315
745	3,925	304	0.7445	4,079	315
746	3,929	304	0.7455	4,083	315
747	3,934	304	0.7465	4,086	316
748	3,939	304	0.7475	4,090	316
749	3,940	305	0.7485	4,093	316
750	3,942	305	0.7495	4,097	316
751	3,944	305	0.7505	4,100	316
752	3,948	306	0.7515	4,104	316
753	3,961	306	0.7525	4,107	317
754	3,961	306	0.7535	4,111	317
755	3,962	306	0.7545	4,115	317
756	3,968	306	0.7555	4,118	317
757	3,971	306	0.7565	4,122	317
758	3,979	307	0.7575	4,125	317

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
759	3,980	307	0.7585	4,129	318
760	3,981	307	0.7595	4,133	318
761	3,983	307	0.7605	4,136	318
762	3,985	307	0.7615	4,140	318
763	3,987	308	0.7625	4,144	318
764	4,014	308	0.7635	4,147	318
765	4,018	308	0.7645	4,151	319
766	4,019	308	0.7655	4,155	319
767	4,024	308	0.7665	4,159	319
768	4,025	308	0.7675	4,162	319
769	4,031	309	0.7685	4,166	319
770	4,034	309	0.7695	4,170	320
771	4,036	309	0.7705	4,174	320
772	4,045	309	0.7715	4,178	320
773	4,051	310	0.7725	4,181	320
774	4,055	310	0.7735	4,185	320
775	4,055	310	0.7745	4,189	320
776	4,057	310	0.7755	4,193	321
777	4,062	310	0.7765	4,197	321
778	4,063	311	0.7775	4,201	321
779	4,064	311	0.7785	4,204	321
780	4,071	311	0.7795	4,208	321
781	4,080	311	0.7805	4,212	321
782	4,081	311	0.7815	4,216	322
783	4,088	311	0.7825	4,220	322
784	4,091	311	0.7835	4,224	322
785	4,093	311	0.7845	4,228	322
786	4,095	312	0.7855	4,232	322
787	4,098	312	0.7865	4,236	323
788	4,098	312	0.7875	4,240	323
789	4,099	312	0.7885	4,244	323
790	4,104	312	0.7895	4,248	323
791	4,104	312	0.7905	4,252	323
792	4,109	312	0.7915	4,256	323
793	4,120	313	0.7925	4,260	324
794	4,130	313	0.7935	4,265	324
795	4,133	313	0.7945	4,269	324
796	4,137	313	0.7955	4,273	324

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
797	4,140	313	0.7965	4,277	324
798	4,142	313	0.7975	4,281	325
799	4,144	313	0.7985	4,285	325
800	4,151	314	0.7995	4,290	325
801	4,154	314	0.8005	4,294	325
802	4,155	314	0.8015	4,298	325
803	4,160	314	0.8025	4,302	326
804	4,168	315	0.8035	4,307	326
805	4,179	315	0.8045	4,311	326
806	4,185	315	0.8055	4,315	326
807	4,188	315	0.8065	4,319	326
808	4,192	315	0.8075	4,324	326
809	4,194	316	0.8085	4,328	327
810	4,202	316	0.8095	4,333	327
811	4,211	316	0.8105	4,337	327
812	4,218	316	0.8115	4,341	327
813	4,218	317	0.8125	4,346	327
814	4,219	317	0.8135	4,350	328
815	4,225	317	0.8145	4,355	328
816	4,227	317	0.8155	4,359	328
817	4,227	317	0.8165	4,364	328
818	4,228	317	0.8175	4,368	328
819	4,237	318	0.8185	4,373	329
820	4,243	319	0.8195	4,377	329
821	4,245	319	0.8205	4,382	329
822	4,247	319	0.8215	4,387	329
823	4,249	319	0.8225	4,391	330
824	4,258	319	0.8235	4,396	330
825	4,261	319	0.8245	4,401	330
826	4,265	320	0.8255	4,405	330
827	4,269	320	0.8265	4,410	330
828	4,275	320	0.8275	4,415	331
829	4,275	320	0.8285	4,420	331
830	4,284	320	0.8295	4,424	331
831	4,306	320	0.8305	4,429	331
832	4,306	321	0.8315	4,434	331
833	4,306	321	0.8325	4,439	332
834	4,307	321	0.8335	4,444	332

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
835	4,310	322	0.8345	4,449	332
836	4,311	322	0.8355	4,454	332
837	4,313	322	0.8365	4,459	333
838	4,315	322	0.8375	4,464	333
839	4,321	323	0.8385	4,469	333
840	4,322	323	0.8395	4,474	333
841	4,323	323	0.8405	4,479	333
842	4,329	323	0.8415	4,484	334
843	4,334	324	0.8425	4,489	334
844	4,345	324	0.8435	4,494	334
845	4,346	324	0.8445	4,499	334
846	4,347	325	0.8455	4,505	335
847	4,347	325	0.8465	4,510	335
848	4,349	325	0.8475	4,515	335
849	4,353	325	0.8485	4,520	335
850	4,353	325	0.8495	4,526	336
851	4,355	325	0.8505	4,531	336
852	4,360	326	0.8515	4,536	336
853	4,363	326	0.8525	4,542	336
854	4,367	326	0.8535	4,547	336
855	4,380	326	0.8545	4,553	337
856	4,382	326	0.8555	4,558	337
857	4,382	326	0.8565	4,564	337
858	4,384	326	0.8575	4,569	337
859	4,385	327	0.8585	4,575	338
860	4,386	327	0.8595	4,581	338
861	4,401	328	0.8605	4,586	338
862	4,403	328	0.8615	4,592	338
863	4,419	328	0.8625	4,598	339
864	4,427	328	0.8635	4,603	339
865	4,435	329	0.8645	4,609	339
866	4,461	329	0.8655	4,615	339
867	4,464	329	0.8665	4,621	340
868	4,467	329	0.8675	4,627	340
869	4,469	330	0.8685	4,633	340
870	4,475	330	0.8695	4,639	340
871	4,483	331	0.8705	4,645	341
872	4,484	331	0.8715	4,651	341

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
873	4,489	331	0.8725	4,657	341
874	4,492	332	0.8735	4,663	342
875	4,496	332	0.8745	4,670	342
876	4,505	333	0.8755	4,676	342
877	4,510	333	0.8765	4,682	342
878	4,510	333	0.8775	4,688	343
879	4,511	333	0.8785	4,695	343
880	4,536	333	0.8795	4,701	343
881	4,538	334	0.8805	4,708	343
882	4,553	334	0.8815	4,714	344
883	4,555	334	0.8825	4,721	344
884	4,556	335	0.8835	4,728	344
885	4,563	335	0.8845	4,734	345
886	4,564	335	0.8855	4,741	345
887	4,584	336	0.8865	4,748	345
888	4,588	336	0.8875	4,755	346
889	4,588	336	0.8885	4,761	346
890	4,589	336	0.8895	4,768	346
891	4,596	336	0.8905	4,775	346
892	4,598	336	0.8915	4,782	347
893	4,600	337	0.8925	4,789	347
894	4,608	337	0.8935	4,797	347
895	4,612	337	0.8945	4,804	348
896	4,617	337	0.8955	4,811	348
897	4,619	337	0.8965	4,819	348
898	4,627	338	0.8975	4,826	349
899	4,641	338	0.8985	4,833	349
900	4,676	338	0.8995	4,841	349
901	4,691	339	0.9005	4,849	350
902	4,694	339	0.9015	4,856	350
903	4,696	339	0.9025	4,864	350
904	4,738	340	0.9035	4,872	351
905	4,743	342	0.9045	4,880	351
906	4,750	342	0.9055	4,888	351
907	4,755	342	0.9065	4,896	352
908	4,758	342	0.9075	4,904	352
909	4,760	342	0.9085	4,912	352
910	4,765	343	0.9095	4,920	353

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
911	4,766	343	0.9105	4,929	353
912	4,774	344	0.9115	4,937	353
913	4,774	344	0.9125	4,946	354
914	4,775	344	0.9135	4,954	354
915	4,782	345	0.9145	4,963	354
916	4,798	347	0.9155	4,972	355
917	4,813	347	0.9165	4,981	355
918	4,846	347	0.9175	4,990	356
919	4,855	348	0.9185	4,999	356
920	4,863	348	0.9195	5,008	356
921	4,883	348	0.9205	5,017	357
922	4,888	349	0.9215	5,027	357
923	4,895	349	0.9225	5,036	358
924	4,910	350	0.9235	5,046	358
925	4,922	350	0.9245	5,055	358
926	4,923	351	0.9255	5,065	359
927	4,937	352	0.9265	5,075	359
928	4,938	352	0.9275	5,085	360
929	4,950	352	0.9285	5,096	360
930	4,951	353	0.9295	5,106	361
931	4,977	354	0.9305	5,116	361
932	5,002	354	0.9315	5,127	361
933	5,004	355	0.9325	5,138	362
934	5,004	356	0.9335	5,149	362
935	5,044	358	0.9345	5,160	363
936	5,046	358	0.9355	5,171	363
937	5,050	359	0.9365	5,182	364
938	5,052	360	0.9375	5,194	364
939	5,054	360	0.9385	5,206	365
940	5,077	360	0.9395	5,218	365
941	5,092	361	0.9405	5,230	366
942	5,126	362	0.9415	5,242	366
943	5,130	362	0.9425	5,254	367
944	5,167	363	0.9435	5,267	367
945	5,168	364	0.9445	5,280	368
946	5,177	364	0.9455	5,293	368
947	5,195	364	0.9465	5,306	369
948	5,209	365	0.9475	5,320	369

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
949	5,216	365	0.9485	5,334	370
950	5,245	366	0.9495	5,348	371
951	5,247	366	0.9505	5,362	371
952	5,264	366	0.9515	5,377	372
953	5,282	367	0.9525	5,391	372
954	5,307	367	0.9535	5,407	373
955	5,321	371	0.9545	5,422	374
956	5,325	371	0.9555	5,438	374
957	5,339	373	0.9565	5,454	375
958	5,369	375	0.9575	5,470	376
959	5,432	376	0.9585	5,487	376
960	5,432	378	0.9595	5,505	377
961	5,487	378	0.9605	5,522	378
962	5,532	379	0.9615	5,540	379
963	5,578	380	0.9625	5,559	379
964	5,580	380	0.9635	5,578	380
965	5,586	384	0.9645	5,597	381
966	5,607	385	0.9655	5,617	382
967	5,610	387	0.9665	5,638	383
968	5,622	389	0.9675	5,659	383
969	5,685	389	0.9685	5,681	384
970	5,712	390	0.9695	5,703	385
971	5,714	390	0.9705	5,726	386
972	5,726	393	0.9715	5,750	387
973	5,845	394	0.9725	5,775	388
974	5,854	399	0.9735	5,800	389
975	5,880	400	0.9745	5,827	390
976	5,892	400	0.9755	5,854	391
977	5,909	401	0.9765	5,883	392
978	5,925	408	0.9775	5,913	394
979	5,937	408	0.9785	5,944	395
980	5,994	419	0.9795	5,977	396
981	5,995	420	0.9805	6,011	397
982	6,020	423	0.9815	6,047	399
983	6,027	424	0.9825	6,084	400
984	6,061	434	0.9835	6,124	402
985	6,066	435	0.9845	6,167	404
986	6,138	440	0.9855	6,212	405

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
987	6,225	450	0.9865	6,260	407
988	6,254	474	0.9875	6,312	409
989	6,344	476	0.9885	6,367	411
990	6,459	487	0.9895	6,428	414
991	6,600	488	0.9905	6,495	416
992	6,693	491	0.9915	6,569	419
993	6,790	525	0.9925	6,653	422
994	6,902	535	0.9935	6,747	426
995	6,973	570	0.9945	6,858	430
996	7,052	574	0.9955	6,990	435
997	7,130	639	0.9965	7,155	441
998	7,140	653	0.9975	7,376	449
999	7,242	662	0.9985	7,710	461
1000	10,620	680	0.9995	8,427	486

M.3 PEARSON HALL RAMMED AGGREGATE COLUMNS WITH THE AGGREGATE COEFFICIENTS' COEFFICIENT OF VARIATION (COV) SET TO 0.5

Materials

Material No.	Material Category	Material Sub-Type/Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Cementitious Materials	Portland Cement (U.S.)	804	164	155	18
2	Other	Aggregate: Sand and Gravel or Crushed Rock	432	216	25	13
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS SUBTOTAL	1,236	271	180	22
RM 1	Recycled or Reused					
RM 2	Recycled or Reused					
RM 3	Recycled or Reused					
		RECYCLED/REUSED MATERIALS SUBTOTAL	0	0	0	0
		MATERIALS TOTAL	1,236	271	180	22

Materials Transportation

Material No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Cement delivery to site	3	0	0	0
2	Heavy Duty Truck	Aggregate delivery to site	91	3	7	0
3						
4						
5						
6						
7						
8						
9						
10						
		NON-RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	94	3	7	0
RM 1						
RM 2						
RM 2						
		RECYCLED/REUSED MATERIALS TRANSPORTATION SUBTOTAL	0	0	0	0
		MATERIALS TRANSPORTATION TOTAL	94	3	7	0

Construction Site Operations (Site Energy and Emissions)

Energy Source No.	Fuel Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Diesel	Diesel Consumed by all Equipment	484	16	37	1
2						
3						
4						
		SITE OPERATIONS TOTAL	484	16	37	1

Waste Transportation

Waste Material/Stream No.	Transportation Vehicle Type	Description	Embodied Energy (GJ)		CO_2 Emissions (tonnes)	
			Mean	St Dev	Mean	St Dev
1	Heavy Duty Truck	Drill Spoil Disposal Trucking	111	4	8	0
2						
3						
4						
		WASTE TRANSPORTATION TOTAL	111	4	8	0

Figure M.7 Line by line SEEAM calculations for Rammed Aggregate Columns at Pearson Hall, with the aggregate coefficients' COV = 0.5. Computations follow the analytical method described in Appendix K.

Table M.7 SEEAM results from the analytical method for the Rammed Aggregate Columns with the aggregate coefficients' COV = 0.5 at Pearson Hall, showing the contribution of materials, materials transportation, site operations and waste transportation to total embodied energy and CO_2 emissions.

	Embodied Energy (GJ)			CO_2 Emissions (tonnes)		
	Mean	**St Dev**	**% of Total**	**Mean**	**St Dev**	**% of Total**
Materials	1,236	271	64%	180	22	78%
Materials Transportation	94	3	5%	7	0	3%
Site Operations	484	16	25%	37	1	16%
Waste Transportation	111	4	6%	8	0	4%
TOTAL	**1,925**	**272**	**100%**	**232**	**22**	**100%**

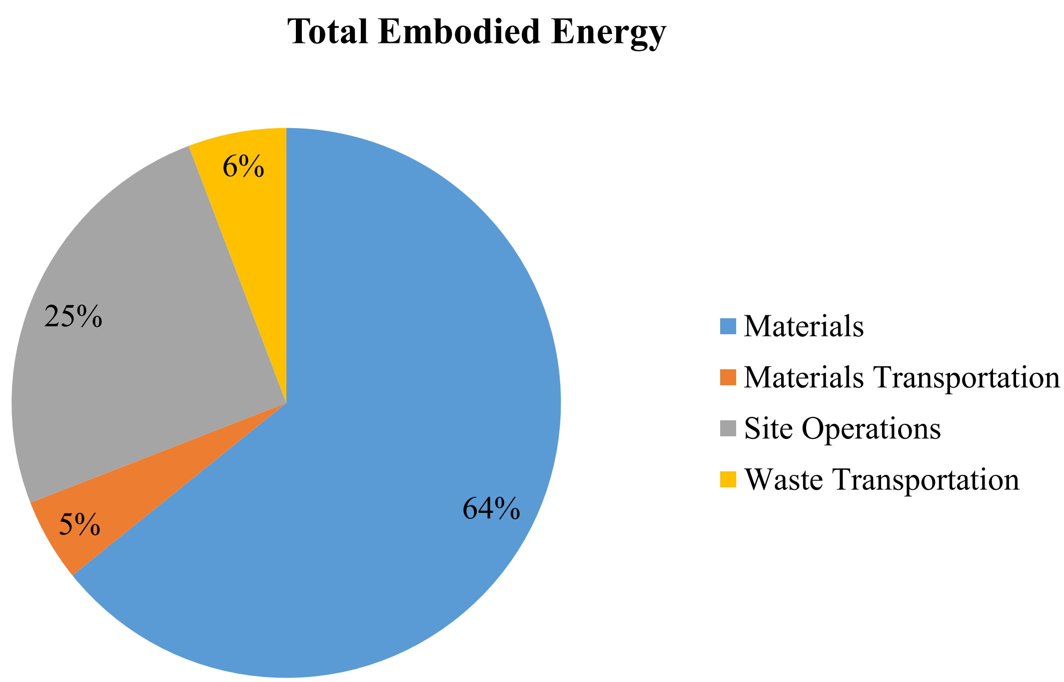

Figure M.8 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation from the analytical method of analysis for Rammed Aggregate Columns at Pearson Hall, with the aggregate coefficients' COV = 0.5.

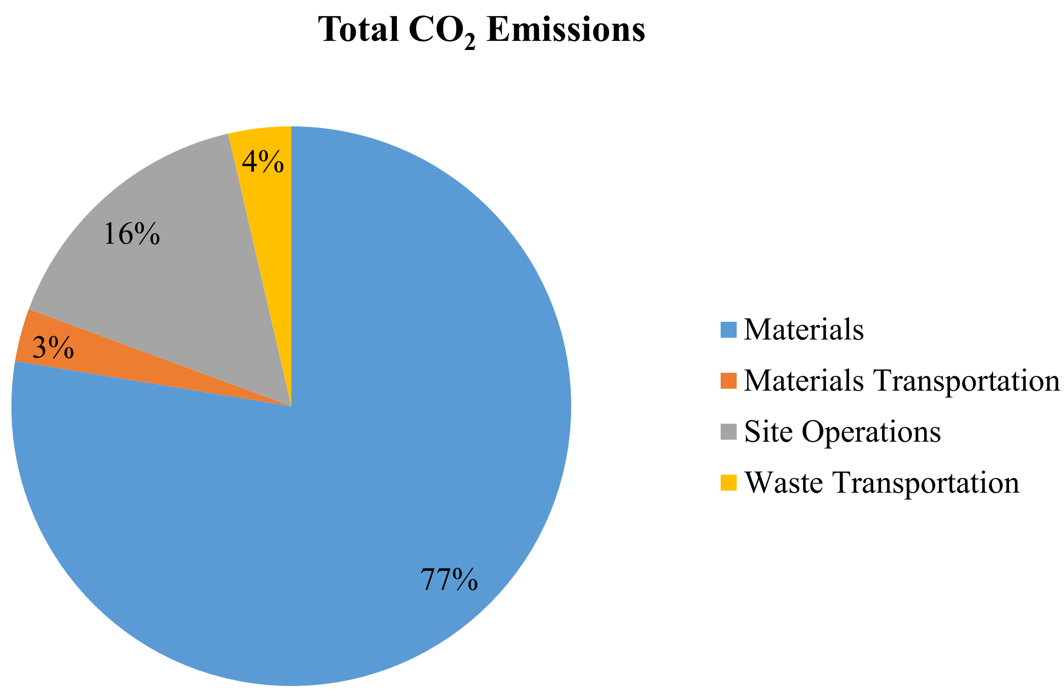

Figure M.9 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation from the analytical method of analysis for Rammed Aggregate Columns at Pearson Hall, with the aggregate coefficients' COV = 0.5.

Table M.8 Summary statistics for Monte Carlo simulated data sets of n = 1,000 values for total embodied energy and CO_2 emissions for Pearson Hall, with the aggregate coefficients' COV = 0.5.

Statistics	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Notes
Mean	1,919	232	
St. Dev.	277	22	
Maximum	3,340	315	
Minimum	1,227	180	
Mean Error (+/-)	14	1	90% Confidence; 1,000 Values
Mean Error % (+/-)	0.75%	0.49%	
No. of Values for +/- 2.5% Error	93	41	90% Confidence

Table M.9 Monte Carlo Simulation data, quantile, and lognormal estimates of total embodied energy and CO_2 emissions for Pearson Hall with the aggregate coefficients' COV = 0.5. Sorted in ascending numerical order.

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
1	1,227	180	0.0005	1,200	170
2	1,335	182	0.0015	1,256	176
3	1,358	185	0.0025	1,285	178
4	1,373	185	0.0035	1,305	180
5	1,380	185	0.0045	1,320	181
6	1,390	186	0.0055	1,333	183
7	1,390	186	0.0065	1,344	184
8	1,403	186	0.0075	1,354	185
9	1,416	188	0.0085	1,363	185
10	1,417	189	0.0095	1,371	186
11	1,420	190	0.0105	1,378	187
12	1,423	191	0.0115	1,385	187
13	1,427	191	0.0125	1,391	188
14	1,430	192	0.0135	1,397	188
15	1,433	192	0.0145	1,402	189
16	1,434	192	0.0155	1,408	189
17	1,442	192	0.0165	1,412	190
18	1,452	193	0.0175	1,417	190
19	1,457	193	0.0185	1,422	191
20	1,457	193	0.0195	1,426	191
21	1,464	194	0.0205	1,430	191
22	1,471	194	0.0215	1,434	192
23	1,473	194	0.0225	1,438	192
24	1,477	194	0.0235	1,442	192
25	1,485	194	0.0245	1,445	193
26	1,488	194	0.0255	1,449	193
27	1,491	195	0.0265	1,452	193
28	1,492	195	0.0275	1,455	194
29	1,493	196	0.0285	1,459	194
30	1,499	196	0.0295	1,462	194
31	1,500	196	0.0305	1,465	194
32	1,501	197	0.0315	1,468	195
33	1,504	197	0.0325	1,471	195
34	1,504	197	0.0335	1,473	195
35	1,509	197	0.0345	1,476	195

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
36	1,509	197	0.0355	1,479	196
37	1,511	197	0.0365	1,481	196
38	1,515	197	0.0375	1,484	196
39	1,522	197	0.0385	1,487	196
40	1,527	197	0.0395	1,489	196
41	1,530	197	0.0405	1,492	197
42	1,530	197	0.0415	1,494	197
43	1,530	198	0.0425	1,496	197
44	1,535	198	0.0435	1,499	197
45	1,536	198	0.0445	1,501	197
46	1,537	198	0.0455	1,503	198
47	1,538	199	0.0465	1,505	198
48	1,539	199	0.0475	1,507	198
49	1,539	199	0.0485	1,510	198
50	1,543	200	0.0495	1,512	198
51	1,551	200	0.0505	1,514	199
52	1,552	200	0.0515	1,516	199
53	1,553	200	0.0525	1,518	199
54	1,555	200	0.0535	1,520	199
55	1,556	200	0.0545	1,522	199
56	1,559	201	0.0555	1,524	199
57	1,559	201	0.0565	1,525	200
58	1,559	201	0.0575	1,527	200
59	1,559	201	0.0585	1,529	200
60	1,560	201	0.0595	1,531	200
61	1,560	201	0.0605	1,533	200
62	1,560	201	0.0615	1,535	200
63	1,561	201	0.0625	1,536	201
64	1,561	201	0.0635	1,538	201
65	1,561	202	0.0645	1,540	201
66	1,562	202	0.0655	1,542	201
67	1,562	202	0.0665	1,543	201
68	1,563	202	0.0675	1,545	201
69	1,567	202	0.0685	1,547	201
70	1,567	203	0.0695	1,548	202
71	1,568	203	0.0705	1,550	202
72	1,571	203	0.0715	1,551	202
73	1,573	203	0.0725	1,553	202

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
74	1,573	203	0.0735	1,555	202
75	1,574	203	0.0745	1,556	202
76	1,574	203	0.0755	1,558	202
77	1,576	203	0.0765	1,559	203
78	1,576	203	0.0775	1,561	203
79	1,576	203	0.0785	1,562	203
80	1,578	203	0.0795	1,564	203
81	1,579	203	0.0805	1,565	203
82	1,582	203	0.0815	1,567	203
83	1,582	204	0.0825	1,568	203
84	1,582	204	0.0835	1,570	203
85	1,583	204	0.0845	1,571	204
86	1,586	204	0.0855	1,572	204
87	1,586	204	0.0865	1,574	204
88	1,588	204	0.0875	1,575	204
89	1,590	204	0.0885	1,577	204
90	1,591	204	0.0895	1,578	204
91	1,595	204	0.0905	1,579	204
92	1,595	204	0.0915	1,581	204
93	1,596	204	0.0925	1,582	204
94	1,596	204	0.0935	1,583	205
95	1,596	204	0.0945	1,585	205
96	1,597	204	0.0955	1,586	205
97	1,598	205	0.0965	1,587	205
98	1,598	205	0.0975	1,589	205
99	1,599	205	0.0985	1,590	205
100	1,601	205	0.0995	1,591	205
101	1,602	205	0.1005	1,593	205
102	1,603	205	0.1015	1,594	205
103	1,604	205	0.1025	1,595	206
104	1,606	205	0.1035	1,596	206
105	1,606	205	0.1045	1,598	206
106	1,607	205	0.1055	1,599	206
107	1,609	206	0.1065	1,600	206
108	1,612	206	0.1075	1,601	206
109	1,614	206	0.1085	1,602	206
110	1,614	206	0.1095	1,604	206
111	1,614	206	0.1105	1,605	206

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
112	1,616	206	0.1115	1,606	207
113	1,617	206	0.1125	1,607	207
114	1,618	206	0.1135	1,608	207
115	1,620	206	0.1145	1,610	207
116	1,620	206	0.1155	1,611	207
117	1,621	206	0.1165	1,612	207
118	1,621	206	0.1175	1,613	207
119	1,623	206	0.1185	1,614	207
120	1,623	207	0.1195	1,615	207
121	1,625	207	0.1205	1,616	207
122	1,625	207	0.1215	1,618	208
123	1,625	207	0.1225	1,619	208
124	1,628	207	0.1235	1,620	208
125	1,630	208	0.1245	1,621	208
126	1,631	208	0.1255	1,622	208
127	1,632	208	0.1265	1,623	208
128	1,632	208	0.1275	1,624	208
129	1,633	208	0.1285	1,625	208
130	1,634	208	0.1295	1,626	208
131	1,636	208	0.1305	1,628	208
132	1,636	209	0.1315	1,629	208
133	1,637	209	0.1325	1,630	209
134	1,642	209	0.1335	1,631	209
135	1,643	209	0.1345	1,632	209
136	1,644	209	0.1355	1,633	209
137	1,644	209	0.1365	1,634	209
138	1,644	209	0.1375	1,635	209
139	1,645	209	0.1385	1,636	209
140	1,645	209	0.1395	1,637	209
141	1,648	209	0.1405	1,638	209
142	1,649	209	0.1415	1,639	209
143	1,652	209	0.1425	1,640	209
144	1,654	209	0.1435	1,641	210
145	1,654	210	0.1445	1,642	210
146	1,655	210	0.1455	1,643	210
147	1,656	210	0.1465	1,644	210
148	1,656	210	0.1475	1,645	210
149	1,657	210	0.1485	1,646	210

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
150	1,657	210	0.1495	1,647	210
151	1,657	210	0.1505	1,648	210
152	1,658	210	0.1515	1,649	210
153	1,658	210	0.1525	1,650	210
154	1,658	210	0.1535	1,651	210
155	1,658	210	0.1545	1,652	210
156	1,660	210	0.1555	1,653	211
157	1,661	211	0.1565	1,654	211
158	1,661	211	0.1575	1,655	211
159	1,661	211	0.1585	1,656	211
160	1,662	211	0.1595	1,657	211
161	1,662	211	0.1605	1,658	211
162	1,664	211	0.1615	1,659	211
163	1,665	211	0.1625	1,660	211
164	1,665	211	0.1635	1,661	211
165	1,666	211	0.1645	1,662	211
166	1,667	211	0.1655	1,663	211
167	1,668	212	0.1665	1,664	211
168	1,670	212	0.1675	1,665	211
169	1,671	212	0.1685	1,665	212
170	1,671	212	0.1695	1,666	212
171	1,672	212	0.1705	1,667	212
172	1,672	212	0.1715	1,668	212
173	1,673	212	0.1725	1,669	212
174	1,674	212	0.1735	1,670	212
175	1,674	212	0.1745	1,671	212
176	1,675	212	0.1755	1,672	212
177	1,675	212	0.1765	1,673	212
178	1,676	213	0.1775	1,674	212
179	1,676	213	0.1785	1,675	212
180	1,676	213	0.1795	1,676	212
181	1,677	213	0.1805	1,676	212
182	1,677	213	0.1815	1,677	213
183	1,677	213	0.1825	1,678	213
184	1,678	213	0.1835	1,679	213
185	1,678	213	0.1845	1,680	213
186	1,678	213	0.1855	1,681	213
187	1,680	213	0.1865	1,682	213

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
188	1,680	213	0.1875	1,683	213
189	1,680	213	0.1885	1,684	213
190	1,682	213	0.1895	1,684	213
191	1,683	214	0.1905	1,685	213
192	1,684	214	0.1915	1,686	213
193	1,684	214	0.1925	1,687	213
194	1,684	214	0.1935	1,688	213
195	1,684	214	0.1945	1,689	213
196	1,685	214	0.1955	1,690	214
197	1,689	214	0.1965	1,690	214
198	1,689	214	0.1975	1,691	214
199	1,690	214	0.1985	1,692	214
200	1,690	214	0.1995	1,693	214
201	1,691	214	0.2005	1,694	214
202	1,691	214	0.2015	1,695	214
203	1,692	214	0.2025	1,696	214
204	1,692	214	0.2035	1,696	214
205	1,692	214	0.2045	1,697	214
206	1,694	215	0.2055	1,698	214
207	1,695	215	0.2065	1,699	214
208	1,696	215	0.2075	1,700	214
209	1,696	215	0.2085	1,701	214
210	1,697	215	0.2095	1,701	215
211	1,698	215	0.2105	1,702	215
212	1,698	215	0.2115	1,703	215
213	1,699	215	0.2125	1,704	215
214	1,699	215	0.2135	1,705	215
215	1,700	215	0.2145	1,706	215
216	1,700	215	0.2155	1,706	215
217	1,701	215	0.2165	1,707	215
218	1,703	215	0.2175	1,708	215
219	1,704	215	0.2185	1,709	215
220	1,706	215	0.2195	1,710	215
221	1,707	216	0.2205	1,710	215
222	1,708	216	0.2215	1,711	215
223	1,709	216	0.2225	1,712	215
224	1,709	216	0.2235	1,713	216
225	1,709	216	0.2245	1,714	216

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
226	1,709	216	0.2255	1,714	216
227	1,710	216	0.2265	1,715	216
228	1,712	216	0.2275	1,716	216
229	1,713	216	0.2285	1,717	216
230	1,714	216	0.2295	1,718	216
231	1,714	216	0.2305	1,718	216
232	1,715	216	0.2315	1,719	216
233	1,717	216	0.2325	1,720	216
234	1,718	216	0.2335	1,721	216
235	1,719	216	0.2345	1,722	216
236	1,720	216	0.2355	1,722	216
237	1,720	216	0.2365	1,723	216
238	1,721	217	0.2375	1,724	216
239	1,721	217	0.2385	1,725	216
240	1,721	217	0.2395	1,726	217
241	1,721	217	0.2405	1,726	217
242	1,722	217	0.2415	1,727	217
243	1,722	217	0.2425	1,728	217
244	1,722	217	0.2435	1,729	217
245	1,723	217	0.2445	1,729	217
246	1,724	217	0.2455	1,730	217
247	1,724	217	0.2465	1,731	217
248	1,724	217	0.2475	1,732	217
249	1,725	217	0.2485	1,733	217
250	1,725	217	0.2495	1,733	217
251	1,725	217	0.2505	1,734	217
252	1,726	217	0.2515	1,735	217
253	1,727	217	0.2525	1,736	217
254	1,727	218	0.2535	1,736	217
255	1,727	218	0.2545	1,737	218
256	1,728	218	0.2555	1,738	218
257	1,729	218	0.2565	1,739	218
258	1,729	218	0.2575	1,739	218
259	1,729	218	0.2585	1,740	218
260	1,731	218	0.2595	1,741	218
261	1,731	218	0.2605	1,742	218
262	1,733	218	0.2615	1,742	218
263	1,734	218	0.2625	1,743	218

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
264	1,734	218	0.2635	1,744	218
265	1,734	218	0.2645	1,745	218
266	1,734	218	0.2655	1,745	218
267	1,735	218	0.2665	1,746	218
268	1,736	218	0.2675	1,747	218
269	1,736	218	0.2685	1,748	218
270	1,737	218	0.2695	1,748	218
271	1,738	218	0.2705	1,749	219
272	1,738	219	0.2715	1,750	219
273	1,738	219	0.2725	1,751	219
274	1,739	219	0.2735	1,751	219
275	1,739	219	0.2745	1,752	219
276	1,739	219	0.2755	1,753	219
277	1,740	219	0.2765	1,754	219
278	1,740	219	0.2775	1,754	219
279	1,741	219	0.2785	1,755	219
280	1,741	219	0.2795	1,756	219
281	1,741	219	0.2805	1,757	219
282	1,741	219	0.2815	1,757	219
283	1,743	219	0.2825	1,758	219
284	1,743	219	0.2835	1,759	219
285	1,743	219	0.2845	1,759	219
286	1,744	219	0.2855	1,760	219
287	1,745	219	0.2865	1,761	219
288	1,745	219	0.2875	1,762	220
289	1,745	219	0.2885	1,762	220
290	1,746	219	0.2895	1,763	220
291	1,746	219	0.2905	1,764	220
292	1,746	219	0.2915	1,765	220
293	1,747	219	0.2925	1,765	220
294	1,747	219	0.2935	1,766	220
295	1,748	219	0.2945	1,767	220
296	1,748	219	0.2955	1,767	220
297	1,752	219	0.2965	1,768	220
298	1,752	219	0.2975	1,769	220
299	1,752	220	0.2985	1,770	220
300	1,753	220	0.2995	1,770	220
301	1,753	220	0.3005	1,771	220

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
302	1,755	220	0.3015	1,772	220
303	1,757	220	0.3025	1,772	220
304	1,758	220	0.3035	1,773	220
305	1,758	220	0.3045	1,774	221
306	1,760	220	0.3055	1,775	221
307	1,760	220	0.3065	1,775	221
308	1,761	220	0.3075	1,776	221
309	1,762	220	0.3085	1,777	221
310	1,762	220	0.3095	1,777	221
311	1,762	220	0.3105	1,778	221
312	1,763	220	0.3115	1,779	221
313	1,763	220	0.3125	1,780	221
314	1,763	220	0.3135	1,780	221
315	1,764	220	0.3145	1,781	221
316	1,764	220	0.3155	1,782	221
317	1,764	220	0.3165	1,782	221
318	1,764	220	0.3175	1,783	221
319	1,764	220	0.3185	1,784	221
320	1,765	220	0.3195	1,784	221
321	1,765	220	0.3205	1,785	221
322	1,766	221	0.3215	1,786	222
323	1,766	221	0.3225	1,787	222
324	1,767	221	0.3235	1,787	222
325	1,767	221	0.3245	1,788	222
326	1,768	221	0.3255	1,789	222
327	1,769	221	0.3265	1,789	222
328	1,769	221	0.3275	1,790	222
329	1,770	221	0.3285	1,791	222
330	1,770	221	0.3295	1,791	222
331	1,770	221	0.3305	1,792	222
332	1,772	221	0.3315	1,793	222
333	1,773	221	0.3325	1,794	222
334	1,774	221	0.3335	1,794	222
335	1,775	221	0.3345	1,795	222
336	1,775	221	0.3355	1,796	222
337	1,776	221	0.3365	1,796	222
338	1,777	221	0.3375	1,797	222
339	1,778	221	0.3385	1,798	223

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
340	1,779	221	0.3395	1,798	223
341	1,780	221	0.3405	1,799	223
342	1,781	221	0.3415	1,800	223
343	1,782	221	0.3425	1,800	223
344	1,783	221	0.3435	1,801	223
345	1,783	222	0.3445	1,802	223
346	1,784	222	0.3455	1,803	223
347	1,784	222	0.3465	1,803	223
348	1,786	222	0.3475	1,804	223
349	1,786	222	0.3485	1,805	223
350	1,786	222	0.3495	1,805	223
351	1,787	222	0.3505	1,806	223
352	1,788	222	0.3515	1,807	223
353	1,788	222	0.3525	1,807	223
354	1,788	222	0.3535	1,808	223
355	1,788	222	0.3545	1,809	223
356	1,788	222	0.3555	1,809	223
357	1,789	222	0.3565	1,810	224
358	1,790	222	0.3575	1,811	224
359	1,790	222	0.3585	1,811	224
360	1,790	222	0.3595	1,812	224
361	1,791	223	0.3605	1,813	224
362	1,791	223	0.3615	1,813	224
363	1,792	223	0.3625	1,814	224
364	1,792	223	0.3635	1,815	224
365	1,792	223	0.3645	1,816	224
366	1,793	223	0.3655	1,816	224
367	1,793	223	0.3665	1,817	224
368	1,793	223	0.3675	1,818	224
369	1,794	223	0.3685	1,818	224
370	1,794	223	0.3695	1,819	224
371	1,794	223	0.3705	1,820	224
372	1,796	223	0.3715	1,820	224
373	1,796	223	0.3725	1,821	224
374	1,796	223	0.3735	1,822	224
375	1,797	223	0.3745	1,822	225
376	1,799	223	0.3755	1,823	225
377	1,800	223	0.3765	1,824	225

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
378	1,800	223	0.3775	1,824	225
379	1,800	223	0.3785	1,825	225
380	1,801	223	0.3795	1,826	225
381	1,804	224	0.3805	1,826	225
382	1,805	224	0.3815	1,827	225
383	1,805	224	0.3825	1,828	225
384	1,805	224	0.3835	1,828	225
385	1,806	224	0.3845	1,829	225
386	1,806	224	0.3855	1,830	225
387	1,806	224	0.3865	1,830	225
388	1,809	224	0.3875	1,831	225
389	1,809	224	0.3885	1,832	225
390	1,809	224	0.3895	1,832	225
391	1,809	224	0.3905	1,833	225
392	1,810	224	0.3915	1,834	225
393	1,811	224	0.3925	1,834	225
394	1,813	224	0.3935	1,835	226
395	1,813	224	0.3945	1,836	226
396	1,814	224	0.3955	1,836	226
397	1,816	224	0.3965	1,837	226
398	1,816	225	0.3975	1,838	226
399	1,817	225	0.3985	1,838	226
400	1,817	225	0.3995	1,839	226
401	1,818	225	0.4005	1,840	226
402	1,818	225	0.4015	1,840	226
403	1,818	225	0.4025	1,841	226
404	1,819	225	0.4035	1,842	226
405	1,819	225	0.4045	1,842	226
406	1,819	225	0.4055	1,843	226
407	1,820	225	0.4065	1,844	226
408	1,820	225	0.4075	1,844	226
409	1,820	225	0.4085	1,845	226
410	1,820	225	0.4095	1,846	226
411	1,821	225	0.4105	1,846	226
412	1,822	225	0.4115	1,847	227
413	1,822	225	0.4125	1,848	227
414	1,823	225	0.4135	1,848	227
415	1,823	225	0.4145	1,849	227

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
416	1,824	225	0.4155	1,850	227
417	1,824	225	0.4165	1,850	227
418	1,825	225	0.4175	1,851	227
419	1,828	225	0.4185	1,852	227
420	1,828	226	0.4195	1,852	227
421	1,829	226	0.4205	1,853	227
422	1,829	226	0.4215	1,854	227
423	1,829	226	0.4225	1,854	227
424	1,830	226	0.4235	1,855	227
425	1,830	226	0.4245	1,856	227
426	1,830	226	0.4255	1,856	227
427	1,831	226	0.4265	1,857	227
428	1,831	226	0.4275	1,858	227
429	1,833	226	0.4285	1,858	227
430	1,834	226	0.4295	1,859	227
431	1,835	226	0.4305	1,860	228
432	1,836	226	0.4315	1,860	228
433	1,837	226	0.4325	1,861	228
434	1,837	226	0.4335	1,862	228
435	1,837	226	0.4345	1,862	228
436	1,837	226	0.4355	1,863	228
437	1,837	226	0.4365	1,864	228
438	1,838	226	0.4375	1,864	228
439	1,838	226	0.4385	1,865	228
440	1,838	227	0.4395	1,866	228
441	1,839	227	0.4405	1,866	228
442	1,839	227	0.4415	1,867	228
443	1,839	227	0.4425	1,868	228
444	1,841	227	0.4435	1,868	228
445	1,842	227	0.4445	1,869	228
446	1,842	227	0.4455	1,870	228
447	1,843	227	0.4465	1,870	228
448	1,843	227	0.4475	1,871	228
449	1,843	227	0.4485	1,872	229
450	1,844	227	0.4495	1,872	229
451	1,845	227	0.4505	1,873	229
452	1,845	227	0.4515	1,874	229
453	1,845	227	0.4525	1,874	229

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
454	1,846	227	0.4535	1,875	229
455	1,846	227	0.4545	1,876	229
456	1,847	227	0.4555	1,876	229
457	1,847	227	0.4565	1,877	229
458	1,847	228	0.4575	1,878	229
459	1,847	228	0.4585	1,878	229
460	1,848	228	0.4595	1,879	229
461	1,849	228	0.4605	1,880	229
462	1,850	228	0.4615	1,880	229
463	1,851	228	0.4625	1,881	229
464	1,851	228	0.4635	1,882	229
465	1,851	228	0.4645	1,882	229
466	1,851	228	0.4655	1,883	229
467	1,851	228	0.4665	1,884	229
468	1,852	228	0.4675	1,884	230
469	1,853	228	0.4685	1,885	230
470	1,853	228	0.4695	1,886	230
471	1,855	228	0.4705	1,886	230
472	1,856	228	0.4715	1,887	230
473	1,856	228	0.4725	1,888	230
474	1,856	228	0.4735	1,888	230
475	1,856	228	0.4745	1,889	230
476	1,857	228	0.4755	1,890	230
477	1,857	228	0.4765	1,890	230
478	1,857	228	0.4775	1,891	230
479	1,858	229	0.4785	1,892	230
480	1,859	229	0.4795	1,892	230
481	1,859	229	0.4805	1,893	230
482	1,860	229	0.4815	1,894	230
483	1,861	229	0.4825	1,894	230
484	1,861	229	0.4835	1,895	230
485	1,863	229	0.4845	1,896	230
486	1,865	229	0.4855	1,896	230
487	1,865	229	0.4865	1,897	231
488	1,866	229	0.4875	1,898	231
489	1,867	229	0.4885	1,898	231
490	1,868	229	0.4895	1,899	231
491	1,868	229	0.4905	1,900	231

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
492	1,869	229	0.4915	1,900	231
493	1,870	229	0.4925	1,901	231
494	1,870	230	0.4935	1,902	231
495	1,872	230	0.4945	1,902	231
496	1,873	230	0.4955	1,903	231
497	1,875	230	0.4965	1,904	231
498	1,875	230	0.4975	1,904	231
499	1,876	230	0.4985	1,905	231
500	1,877	230	0.4995	1,906	231
501	1,878	230	0.5005	1,906	231
502	1,878	230	0.5015	1,907	231
503	1,879	230	0.5025	1,908	231
504	1,879	230	0.5035	1,908	231
505	1,879	230	0.5045	1,909	232
506	1,880	230	0.5055	1,910	232
507	1,880	230	0.5065	1,910	232
508	1,881	230	0.5075	1,911	232
509	1,881	230	0.5085	1,912	232
510	1,882	230	0.5095	1,913	232
511	1,882	230	0.5105	1,913	232
512	1,883	231	0.5115	1,914	232
513	1,884	231	0.5125	1,915	232
514	1,884	231	0.5135	1,915	232
515	1,884	231	0.5145	1,916	232
516	1,887	231	0.5155	1,917	232
517	1,887	231	0.5165	1,917	232
518	1,887	231	0.5175	1,918	232
519	1,889	231	0.5185	1,919	232
520	1,889	231	0.5195	1,919	232
521	1,890	231	0.5205	1,920	232
522	1,891	231	0.5215	1,921	232
523	1,895	232	0.5225	1,921	232
524	1,895	232	0.5235	1,922	233
525	1,895	232	0.5245	1,923	233
526	1,896	232	0.5255	1,923	233
527	1,896	232	0.5265	1,924	233
528	1,896	232	0.5275	1,925	233
529	1,897	232	0.5285	1,925	233

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
530	1,899	232	0.5295	1,926	233
531	1,901	232	0.5305	1,927	233
532	1,902	232	0.5315	1,927	233
533	1,902	232	0.5325	1,928	233
534	1,904	232	0.5335	1,929	233
535	1,904	232	0.5345	1,929	233
536	1,905	232	0.5355	1,930	233
537	1,905	232	0.5365	1,931	233
538	1,906	232	0.5375	1,932	233
539	1,906	232	0.5385	1,932	233
540	1,907	232	0.5395	1,933	233
541	1,908	232	0.5405	1,934	233
542	1,908	232	0.5415	1,934	234
543	1,910	232	0.5425	1,935	234
544	1,910	232	0.5435	1,936	234
545	1,911	232	0.5445	1,936	234
546	1,911	232	0.5455	1,937	234
547	1,911	233	0.5465	1,938	234
548	1,912	233	0.5475	1,938	234
549	1,912	233	0.5485	1,939	234
550	1,913	233	0.5495	1,940	234
551	1,913	233	0.5505	1,940	234
552	1,913	233	0.5515	1,941	234
553	1,914	233	0.5525	1,942	234
554	1,915	233	0.5535	1,943	234
555	1,916	233	0.5545	1,943	234
556	1,918	233	0.5555	1,944	234
557	1,918	233	0.5565	1,945	234
558	1,920	233	0.5575	1,945	234
559	1,920	233	0.5585	1,946	234
560	1,920	233	0.5595	1,947	235
561	1,921	233	0.5605	1,947	235
562	1,922	233	0.5615	1,948	235
563	1,925	233	0.5625	1,949	235
564	1,926	233	0.5635	1,949	235
565	1,926	233	0.5645	1,950	235
566	1,926	233	0.5655	1,951	235
567	1,928	233	0.5665	1,952	235

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
568	1,929	233	0.5675	1,952	235
569	1,930	234	0.5685	1,953	235
570	1,932	234	0.5695	1,954	235
571	1,932	234	0.5705	1,954	235
572	1,933	234	0.5715	1,955	235
573	1,934	234	0.5725	1,956	235
574	1,934	234	0.5735	1,956	235
575	1,935	234	0.5745	1,957	235
576	1,935	234	0.5755	1,958	235
577	1,936	234	0.5765	1,959	235
578	1,936	234	0.5775	1,959	236
579	1,936	234	0.5785	1,960	236
580	1,936	234	0.5795	1,961	236
581	1,937	234	0.5805	1,961	236
582	1,938	234	0.5815	1,962	236
583	1,939	234	0.5825	1,963	236
584	1,939	234	0.5835	1,963	236
585	1,940	234	0.5845	1,964	236
586	1,943	234	0.5855	1,965	236
587	1,943	234	0.5865	1,966	236
588	1,943	234	0.5875	1,966	236
589	1,943	234	0.5885	1,967	236
590	1,943	234	0.5895	1,968	236
591	1,945	234	0.5905	1,968	236
592	1,945	234	0.5915	1,969	236
593	1,945	234	0.5925	1,970	236
594	1,945	234	0.5935	1,971	236
595	1,945	234	0.5945	1,971	236
596	1,946	235	0.5955	1,972	237
597	1,946	235	0.5965	1,973	237
598	1,947	235	0.5975	1,973	237
599	1,948	235	0.5985	1,974	237
600	1,948	235	0.5995	1,975	237
601	1,949	235	0.6005	1,976	237
602	1,949	235	0.6015	1,976	237
603	1,951	235	0.6025	1,977	237
604	1,951	235	0.6035	1,978	237
605	1,952	235	0.6045	1,978	237

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
606	1,953	235	0.6055	1,979	237
607	1,954	235	0.6065	1,980	237
608	1,954	235	0.6075	1,981	237
609	1,955	236	0.6085	1,981	237
610	1,955	236	0.6095	1,982	237
611	1,955	236	0.6105	1,983	237
612	1,957	236	0.6115	1,984	237
613	1,958	236	0.6125	1,984	237
614	1,960	236	0.6135	1,985	238
615	1,961	236	0.6145	1,986	238
616	1,961	236	0.6155	1,986	238
617	1,962	236	0.6165	1,987	238
618	1,962	236	0.6175	1,988	238
619	1,964	236	0.6185	1,989	238
620	1,964	236	0.6195	1,989	238
621	1,966	236	0.6205	1,990	238
622	1,970	236	0.6215	1,991	238
623	1,971	236	0.6225	1,992	238
624	1,971	236	0.6235	1,992	238
625	1,971	236	0.6245	1,993	238
626	1,972	236	0.6255	1,994	238
627	1,973	236	0.6265	1,995	238
628	1,974	237	0.6275	1,995	238
629	1,974	237	0.6285	1,996	238
630	1,975	237	0.6295	1,997	238
631	1,977	237	0.6305	1,998	239
632	1,978	237	0.6315	1,998	239
633	1,978	237	0.6325	1,999	239
634	1,979	237	0.6335	2,000	239
635	1,980	237	0.6345	2,001	239
636	1,981	237	0.6355	2,001	239
637	1,981	237	0.6365	2,002	239
638	1,982	237	0.6375	2,003	239
639	1,982	237	0.6385	2,003	239
640	1,984	237	0.6395	2,004	239
641	1,988	237	0.6405	2,005	239
642	1,988	237	0.6415	2,006	239
643	1,989	237	0.6425	2,007	239

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
644	1,990	238	0.6435	2,007	239
645	1,990	238	0.6445	2,008	239
646	1,991	238	0.6455	2,009	239
647	1,991	238	0.6465	2,010	239
648	1,992	238	0.6475	2,010	240
649	1,992	238	0.6485	2,011	240
650	1,995	238	0.6495	2,012	240
651	1,995	238	0.6505	2,013	240
652	1,996	238	0.6515	2,013	240
653	1,996	238	0.6525	2,014	240
654	1,996	238	0.6535	2,015	240
655	1,997	238	0.6545	2,016	240
656	2,000	238	0.6555	2,016	240
657	2,000	239	0.6565	2,017	240
658	2,001	239	0.6575	2,018	240
659	2,001	239	0.6585	2,019	240
660	2,002	239	0.6595	2,020	240
661	2,003	239	0.6605	2,020	240
662	2,003	239	0.6615	2,021	240
663	2,005	239	0.6625	2,022	240
664	2,007	239	0.6635	2,023	241
665	2,008	239	0.6645	2,023	241
666	2,008	240	0.6655	2,024	241
667	2,009	240	0.6665	2,025	241
668	2,010	240	0.6675	2,026	241
669	2,010	240	0.6685	2,027	241
670	2,011	240	0.6695	2,027	241
671	2,012	240	0.6705	2,028	241
672	2,012	240	0.6715	2,029	241
673	2,012	240	0.6725	2,030	241
674	2,016	240	0.6735	2,030	241
675	2,018	240	0.6745	2,031	241
676	2,019	240	0.6755	2,032	241
677	2,021	240	0.6765	2,033	241
678	2,024	240	0.6775	2,034	241
679	2,025	240	0.6785	2,034	241
680	2,027	240	0.6795	2,035	242
681	2,027	240	0.6805	2,036	242

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
682	2,028	240	0.6815	2,037	242
683	2,028	241	0.6825	2,038	242
684	2,028	241	0.6835	2,038	242
685	2,030	241	0.6845	2,039	242
686	2,030	241	0.6855	2,040	242
687	2,031	241	0.6865	2,041	242
688	2,031	241	0.6875	2,042	242
689	2,031	241	0.6885	2,043	242
690	2,031	241	0.6895	2,043	242
691	2,032	241	0.6905	2,044	242
692	2,033	241	0.6915	2,045	242
693	2,033	241	0.6925	2,046	242
694	2,033	241	0.6935	2,047	242
695	2,035	241	0.6945	2,047	242
696	2,036	241	0.6955	2,048	243
697	2,039	242	0.6965	2,049	243
698	2,039	242	0.6975	2,050	243
699	2,039	242	0.6985	2,051	243
700	2,041	242	0.6995	2,052	243
701	2,041	242	0.7005	2,052	243
702	2,041	242	0.7015	2,053	243
703	2,043	242	0.7025	2,054	243
704	2,044	242	0.7035	2,055	243
705	2,044	242	0.7045	2,056	243
706	2,044	242	0.7055	2,057	243
707	2,045	242	0.7065	2,057	243
708	2,045	242	0.7075	2,058	243
709	2,045	242	0.7085	2,059	243
710	2,046	242	0.7095	2,060	243
711	2,046	242	0.7105	2,061	243
712	2,047	242	0.7115	2,062	244
713	2,048	242	0.7125	2,062	244
714	2,051	242	0.7135	2,063	244
715	2,052	243	0.7145	2,064	244
716	2,052	243	0.7155	2,065	244
717	2,052	243	0.7165	2,066	244
718	2,054	243	0.7175	2,067	244
719	2,054	243	0.7185	2,068	244

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
720	2,056	243	0.7195	2,068	244
721	2,056	243	0.7205	2,069	244
722	2,056	243	0.7215	2,070	244
723	2,056	243	0.7225	2,071	244
724	2,058	243	0.7235	2,072	244
725	2,059	243	0.7245	2,073	244
726	2,059	243	0.7255	2,074	245
727	2,060	243	0.7265	2,075	245
728	2,062	243	0.7275	2,075	245
729	2,062	243	0.7285	2,076	245
730	2,063	243	0.7295	2,077	245
731	2,063	243	0.7305	2,078	245
732	2,064	243	0.7315	2,079	245
733	2,064	243	0.7325	2,080	245
734	2,064	243	0.7335	2,081	245
735	2,066	244	0.7345	2,082	245
736	2,067	244	0.7355	2,082	245
737	2,068	244	0.7365	2,083	245
738	2,068	244	0.7375	2,084	245
739	2,069	244	0.7385	2,085	245
740	2,069	244	0.7395	2,086	245
741	2,069	244	0.7405	2,087	246
742	2,070	244	0.7415	2,088	246
743	2,070	244	0.7425	2,089	246
744	2,071	244	0.7435	2,090	246
745	2,072	244	0.7445	2,091	246
746	2,072	244	0.7455	2,092	246
747	2,072	244	0.7465	2,092	246
748	2,073	244	0.7475	2,093	246
749	2,074	244	0.7485	2,094	246
750	2,076	245	0.7495	2,095	246
751	2,081	245	0.7505	2,096	246
752	2,083	245	0.7515	2,097	246
753	2,084	245	0.7525	2,098	246
754	2,088	245	0.7535	2,099	246
755	2,089	245	0.7545	2,100	247
756	2,089	245	0.7555	2,101	247
757	2,090	245	0.7565	2,102	247

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
758	2,090	245	0.7575	2,103	247
759	2,091	245	0.7585	2,104	247
760	2,091	245	0.7595	2,105	247
761	2,092	245	0.7605	2,106	247
762	2,094	246	0.7615	2,107	247
763	2,095	246	0.7625	2,107	247
764	2,095	246	0.7635	2,108	247
765	2,098	246	0.7645	2,109	247
766	2,099	246	0.7655	2,110	247
767	2,100	246	0.7665	2,111	247
768	2,100	246	0.7675	2,112	248
769	2,102	246	0.7685	2,113	248
770	2,102	246	0.7695	2,114	248
771	2,102	246	0.7705	2,115	248
772	2,105	246	0.7715	2,116	248
773	2,105	246	0.7725	2,117	248
774	2,105	246	0.7735	2,118	248
775	2,106	246	0.7745	2,119	248
776	2,106	246	0.7755	2,120	248
777	2,106	246	0.7765	2,121	248
778	2,110	247	0.7775	2,122	248
779	2,112	247	0.7785	2,123	248
780	2,112	247	0.7795	2,124	248
781	2,112	247	0.7805	2,125	249
782	2,115	247	0.7815	2,126	249
783	2,115	247	0.7825	2,127	249
784	2,117	247	0.7835	2,128	249
785	2,117	247	0.7845	2,129	249
786	2,118	247	0.7855	2,130	249
787	2,118	248	0.7865	2,131	249
788	2,119	248	0.7875	2,132	249
789	2,120	248	0.7885	2,133	249
790	2,120	248	0.7895	2,134	249
791	2,120	248	0.7905	2,135	249
792	2,121	248	0.7915	2,136	249
793	2,121	248	0.7925	2,138	249
794	2,121	248	0.7935	2,139	250
795	2,121	248	0.7945	2,140	250

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
796	2,122	248	0.7955	2,141	250
797	2,123	248	0.7965	2,142	250
798	2,124	249	0.7975	2,143	250
799	2,126	249	0.7985	2,144	250
800	2,127	249	0.7995	2,145	250
801	2,130	249	0.8005	2,146	250
802	2,131	249	0.8015	2,147	250
803	2,133	249	0.8025	2,148	250
804	2,134	249	0.8035	2,149	250
805	2,135	249	0.8045	2,150	250
806	2,137	250	0.8055	2,151	251
807	2,138	250	0.8065	2,153	251
808	2,138	250	0.8075	2,154	251
809	2,141	250	0.8085	2,155	251
810	2,142	250	0.8095	2,156	251
811	2,142	250	0.8105	2,157	251
812	2,143	250	0.8115	2,158	251
813	2,143	250	0.8125	2,159	251
814	2,144	250	0.8135	2,160	251
815	2,146	250	0.8145	2,162	251
816	2,146	250	0.8155	2,163	251
817	2,149	250	0.8165	2,164	251
818	2,149	250	0.8175	2,165	252
819	2,150	250	0.8185	2,166	252
820	2,150	251	0.8195	2,167	252
821	2,155	251	0.8205	2,168	252
822	2,155	251	0.8215	2,170	252
823	2,156	251	0.8225	2,171	252
824	2,160	251	0.8235	2,172	252
825	2,163	251	0.8245	2,173	252
826	2,163	251	0.8255	2,174	252
827	2,163	251	0.8265	2,176	252
828	2,163	252	0.8275	2,177	252
829	2,164	252	0.8285	2,178	253
830	2,165	252	0.8295	2,179	253
831	2,166	252	0.8305	2,180	253
832	2,167	252	0.8315	2,182	253
833	2,169	252	0.8325	2,183	253

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
834	2,169	252	0.8335	2,184	253
835	2,169	252	0.8345	2,185	253
836	2,171	252	0.8355	2,186	253
837	2,171	252	0.8365	2,188	253
838	2,173	253	0.8375	2,189	253
839	2,174	253	0.8385	2,190	253
840	2,176	253	0.8395	2,191	254
841	2,177	254	0.8405	2,193	254
842	2,179	254	0.8415	2,194	254
843	2,181	254	0.8425	2,195	254
844	2,182	254	0.8435	2,197	254
845	2,182	254	0.8445	2,198	254
846	2,186	254	0.8455	2,199	254
847	2,190	254	0.8465	2,200	254
848	2,191	254	0.8475	2,202	254
849	2,192	254	0.8485	2,203	254
850	2,192	254	0.8495	2,204	255
851	2,192	255	0.8505	2,206	255
852	2,194	255	0.8515	2,207	255
853	2,198	255	0.8525	2,208	255
854	2,199	255	0.8535	2,210	255
855	2,200	255	0.8545	2,211	255
856	2,200	255	0.8555	2,212	255
857	2,201	255	0.8565	2,214	255
858	2,204	255	0.8575	2,215	255
859	2,205	255	0.8585	2,217	256
860	2,205	255	0.8595	2,218	256
861	2,206	255	0.8605	2,219	256
862	2,208	256	0.8615	2,221	256
863	2,209	256	0.8625	2,222	256
864	2,212	256	0.8635	2,224	256
865	2,215	256	0.8645	2,225	256
866	2,221	256	0.8655	2,227	256
867	2,223	256	0.8665	2,228	256
868	2,224	256	0.8675	2,229	256
869	2,224	256	0.8685	2,231	257
870	2,226	256	0.8695	2,232	257
871	2,226	256	0.8705	2,234	257

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
872	2,226	257	0.8715	2,235	257
873	2,228	257	0.8725	2,237	257
874	2,229	257	0.8735	2,238	257
875	2,230	257	0.8745	2,240	257
876	2,231	257	0.8755	2,241	257
877	2,231	257	0.8765	2,243	258
878	2,234	257	0.8775	2,245	258
879	2,236	257	0.8785	2,246	258
880	2,236	257	0.8795	2,248	258
881	2,237	257	0.8805	2,249	258
882	2,237	258	0.8815	2,251	258
883	2,237	258	0.8825	2,252	258
884	2,238	258	0.8835	2,254	258
885	2,239	258	0.8845	2,256	258
886	2,240	258	0.8855	2,257	259
887	2,240	258	0.8865	2,259	259
888	2,241	258	0.8875	2,261	259
889	2,244	258	0.8885	2,262	259
890	2,245	259	0.8895	2,264	259
891	2,246	259	0.8905	2,266	259
892	2,249	259	0.8915	2,267	259
893	2,252	259	0.8925	2,269	259
894	2,254	259	0.8935	2,271	260
895	2,254	259	0.8945	2,273	260
896	2,260	260	0.8955	2,274	260
897	2,260	260	0.8965	2,276	260
898	2,261	260	0.8975	2,278	260
899	2,262	260	0.8985	2,280	260
900	2,265	260	0.8995	2,281	260
901	2,268	260	0.9005	2,283	261
902	2,268	260	0.9015	2,285	261
903	2,269	260	0.9025	2,287	261
904	2,269	261	0.9035	2,289	261
905	2,270	261	0.9045	2,291	261
906	2,273	261	0.9055	2,293	261
907	2,274	261	0.9065	2,295	261
908	2,277	261	0.9075	2,297	262
909	2,278	261	0.9085	2,298	262

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
910	2,282	261	0.9095	2,300	262
911	2,291	261	0.9105	2,302	262
912	2,291	262	0.9115	2,304	262
913	2,296	262	0.9125	2,306	262
914	2,297	262	0.9135	2,309	262
915	2,298	263	0.9145	2,311	263
916	2,299	263	0.9155	2,313	263
917	2,305	263	0.9165	2,315	263
918	2,306	263	0.9175	2,317	263
919	2,306	263	0.9185	2,319	263
920	2,309	263	0.9195	2,321	263
921	2,316	263	0.9205	2,323	264
922	2,319	263	0.9215	2,326	264
923	2,319	264	0.9225	2,328	264
924	2,320	264	0.9235	2,330	264
925	2,322	265	0.9245	2,332	264
926	2,325	265	0.9255	2,335	264
927	2,326	265	0.9265	2,337	265
928	2,327	265	0.9275	2,340	265
929	2,329	266	0.9285	2,342	265
930	2,330	266	0.9295	2,344	265
931	2,330	267	0.9305	2,347	265
932	2,334	267	0.9315	2,349	266
933	2,340	267	0.9325	2,352	266
934	2,340	268	0.9335	2,354	266
935	2,341	268	0.9345	2,357	266
936	2,345	269	0.9355	2,360	266
937	2,349	269	0.9365	2,362	266
938	2,349	269	0.9375	2,365	267
939	2,358	269	0.9385	2,368	267
940	2,360	270	0.9395	2,370	267
941	2,361	270	0.9405	2,373	267
942	2,364	270	0.9415	2,376	268
943	2,368	270	0.9425	2,379	268
944	2,370	270	0.9435	2,382	268
945	2,370	270	0.9445	2,385	268
946	2,371	270	0.9455	2,388	268
947	2,376	271	0.9465	2,391	269

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
948	2,378	272	0.9475	2,394	269
949	2,378	272	0.9485	2,397	269
950	2,380	272	0.9495	2,400	269
951	2,390	273	0.9505	2,404	270
952	2,391	273	0.9515	2,407	270
953	2,392	273	0.9525	2,410	270
954	2,394	273	0.9535	2,414	270
955	2,400	274	0.9545	2,417	271
956	2,411	274	0.9555	2,421	271
957	2,411	274	0.9565	2,425	271
958	2,412	275	0.9575	2,428	271
959	2,418	275	0.9585	2,432	272
960	2,420	276	0.9595	2,436	272
961	2,424	277	0.9605	2,440	272
962	2,429	277	0.9615	2,444	273
963	2,437	277	0.9625	2,448	273
964	2,439	278	0.9635	2,452	273
965	2,444	279	0.9645	2,457	273
966	2,448	279	0.9655	2,461	274
967	2,449	279	0.9665	2,466	274
968	2,467	279	0.9675	2,471	274
969	2,469	279	0.9685	2,475	275
970	2,503	280	0.9695	2,480	275
971	2,505	280	0.9705	2,486	276
972	2,510	280	0.9715	2,491	276
973	2,519	282	0.9725	2,496	276
974	2,529	283	0.9735	2,502	277
975	2,571	283	0.9745	2,508	277
976	2,573	283	0.9755	2,514	278
977	2,580	283	0.9765	2,520	278
978	2,586	284	0.9775	2,527	279
979	2,620	284	0.9785	2,533	279
980	2,653	285	0.9795	2,540	280
981	2,656	288	0.9805	2,548	280
982	2,657	288	0.9815	2,556	281
983	2,692	288	0.9825	2,564	281
984	2,692	289	0.9835	2,572	282
985	2,698	289	0.9845	2,581	283

Monte Carlo Observation No.	Total Embodied Energy (GJ)	Total CO_2 Emissions (tonnes)	Quantile	Lognormal Estimated Embodied Energy (GJ)	Lognormal Estimated CO_2 Emissions (tonnes)
986	2,706	290	0.9855	2,591	283
987	2,711	290	0.9865	2,601	284
988	2,748	290	0.9875	2,612	285
989	2,805	294	0.9885	2,624	286
990	2,856	294	0.9895	2,637	287
991	2,859	295	0.9905	2,651	288
992	2,868	295	0.9915	2,666	289
993	2,874	298	0.9925	2,683	290
994	2,879	300	0.9935	2,703	291
995	2,894	300	0.9945	2,725	293
996	2,990	300	0.9955	2,752	295
997	3,034	305	0.9965	2,785	297
998	3,094	308	0.9975	2,828	300
999	3,103	314	0.9985	2,893	305
1000	3,340	315	0.9995	3,027	314

Appendix N: Kriging to Estimate the Top of Rock Elevation at the Pearson Hall Construction Site

N.1 KRIGING BACKGROUND

Kriging is a geostatistical method that may be used to provide a best estimate of a parameter between known data based on spatial correlation and a known function describing any variation or trend in the mean (Fenton and Griffiths 2008). Typically, spatial correlation structure is represented by a semivariogram.

The semivariogram is a plot showing the dissimilarity in values of a spatially varying parameter between locations separated by certain separation distance intervals (Goovaerts 1997). As the separation distance increases, the correlation between the values of a parameter decreases, such that the value at one location provides less information regarding the possible value at the other. As a result, there is greater dissimilarity with increasing separation distance and the semivariogram increases. The separation distance at which the correlation between data reaches zero is known as the range; at separation distances equal to or greater than the range, dissimilarity stops increasing and the semivariogram reaches a sill value (Goovaerts 1997). There should be no dissimilarity with zero separation distance (i.e., the semivariogram should pass through the origin). However, the empirical semivariogram developed based on field observations may not tend to zero as separation distance approaches zero. This discontinuity is known as the nugget effect and is due to either measurement error, or spatial variation occurring at distances smaller than the shortest sampling interval (Journel and Huijbregts (1978) as cited in Goovaerts (1997)). For Kriging, a theoretical semivariogram model is fit to the data in the empirical semivariogram. The theoretical model is then used for determining the spatial relationship between points separated by any distance. Common basic semivariogram models include the Gaussian model, exponential model and spherical model (Goovaerts 1997).

Commercially available software applications can perform Kriging based on input data. For the analyses presented here and in Ch. 6, ArcGIS software has been used (Esri 2013). Within ArcGIS, the Kriging algorithm works to assign weights to measured values in order to derive an estimate at an unmeasured location (Esri 2011). The user must provide the input data, generate an empirical semivariogram, and then fit a theoretical model to the empirical semivariogram. The fitted theoretical semivariogram model is used by the program to generate weights that are applied to each known value in the input data set in order to estimate the value of the parameter at the desired location where a measurement was not obtained. Weights are used to make the estimate following Eq. N.1 (Esri 2011):

$$\hat{Z}(s_o) = \sum_{i=1}^{n} w_i Z(s_i) \tag{N.1}$$

where $\hat{Z}$ is the estimated value, s_o is the location for the estimate, w_i is the weight for the measured value at the i^{th} location, $Z(s_i)$ is the measured value at the i^{th} location, and n is the number of measured values.

The estimated value from ArcGIS is the expected value, or mean of the parameter at the estimation location. ArcGIS also generates a standard deviation for the estimate, which indicates the degree of uncertainty surrounding the estimated value.

There are different types of Kriging that may be used depending on the nature of the problem and the input data. ArcGIS can conduct two common types of Kriging: 1) ordinary Kriging, and 2) universal Kriging. Ordinary Kriging is the most general and widely used method, which assumes the estimated parameter has a constant and unknown mean (Esri 2011). In contrast, universal Kriging is based on the assumption that there is an overall trend in the data that can be modeled by a deterministic function (Esri 2011). For example, the trend of increasing undrained shear strength with depth. Universal Kriging should only be used when it is known that a trend exists in the data and there is a physical or scientific explanation/justification for it (Esri 2011).

While Kriging is computationally efficient and very useful for interpolation and the development of contour plots for the estimated parameter, it can be unstable and should therefore be used with care (Rodriguez-Marek 2013). For example, when making an estimate, Kriging may produce negative weights for some observed data at great distance from the estimation location. However, negative weights are not physically meaningful and could have a detrimental effect, such that an estimated value may be outside the range of observed data (Deutsch 1996). To overcome this issue, Deutsch (1996) has proposed setting negative and near zero weights equal to zero, and then rebalancing the remaining weights such that they sum to 1. Other issues with Kriging can arise, such as having an insufficient number of appropriately spaced field observations for identifying spatial correlation (see discussion about the nugget effect on the first page of this Appendix), and fitting an inappropriate theoretical semivariogram model to observed field data.

N.2 ESTIMATING TOP OF ROCK ELEVATION AT PEARSON HALL

N.2.1 Assumptions

In using ArcGIS to perform Kriging for top of rock (TOR) elevation across the Pearson Hall construction site, the following assumptions were made:

1) TOR elevation is a stationary random field, with mean and variance spatially constant (Fenton and Griffiths 2008). This means that only the separation vector (distance and direction) is important for spatial correlations (Goovaerts 1997). This assumption also means that ordinary Kriging is the appropriate method to use in ArcGIS software.

2) The random field is isotropic, which means that only the separation distance between points (not distance and direction) is sufficient to describe the spatial correlation (Goovaerts 1997). In other words, the TOR elevation is assumed to vary in the same manner in all directions.
3) The theoretical semivariogram fit is forced to have a nugget = 0 (i.e., the theoretical semivariogram passes through the origin).

N.2.2 Input Data

The input boring data for Kriging is shown in Table L.3, where the listed TOR elevations are the known values of the parameter Z, and the X and Y coordinates define the spatial position. Note that the TOR elevation at each boring was determined based on an estimated ground surface elevation from a contour map of the site, and the depth at which rock was encountered as listed in the boring logs. Using the contour map to determine surface elevations at the borings induces some error in the observed TOR elevation data. Unfortunately, survey data for the ground surface elevation at the boring locations was not available. The estimation locations for TOR elevation are the locations of each cement treated aggregate column, defined by the X and Y coordinates in Table L.1.

N.2.3 Results

During the Kriging process, the results using two different theoretical semivariogram models were compared. These included the Gaussian model and the exponential model.

The Gaussian semivariogram plot, as generated by ArcGIS, is shown in Figure N.1. The theoretical Gaussian model (blue line) fit to the empirical data in Figure N.1 has a range of 168.2 ft and a sill of 192.6 ft. The exponential semivariogram plot, as generated in ArcGIS, is shown in Figure N.2. The theoretical exponential model (blue line) fit to the empirical data in Figure N.2

has a range of 168.2 ft and a sill of 172.8 ft. Notably, the range is the same for both theoretical semivariogram models, and the sill values are very similar.

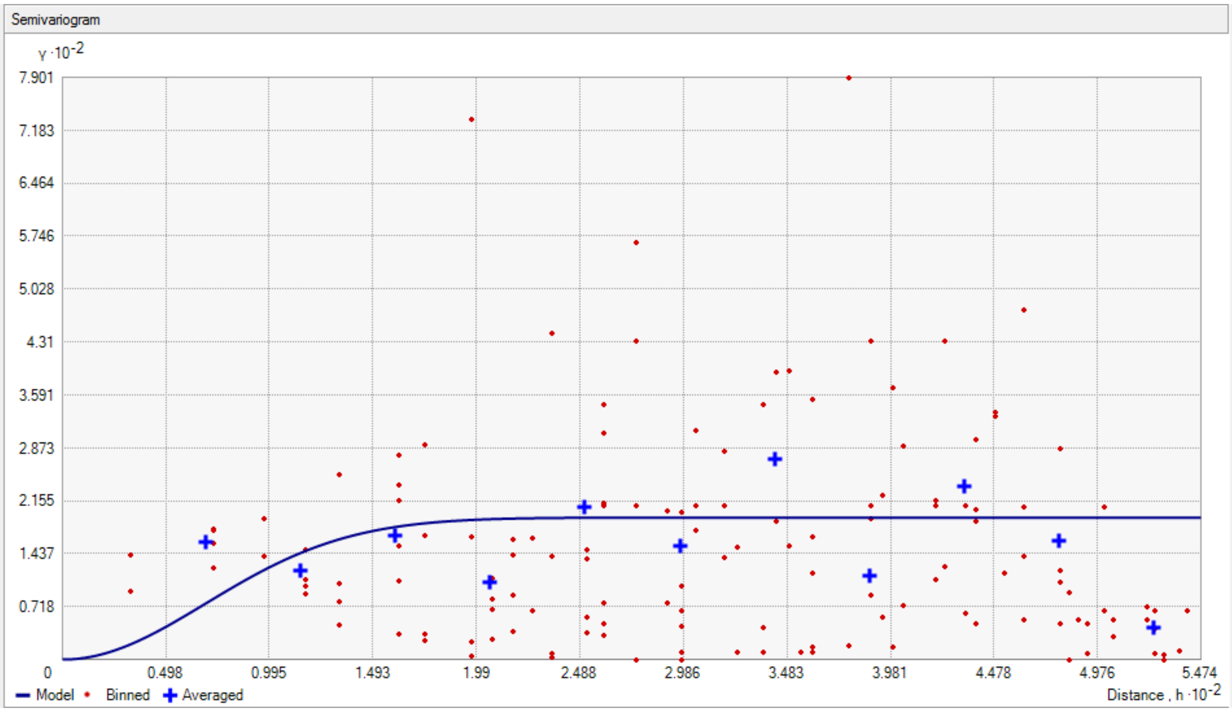

Figure N.1 Gaussian semivariogram model for top of rock elevation at Pearson Hall for Kriging in ArcGIS.

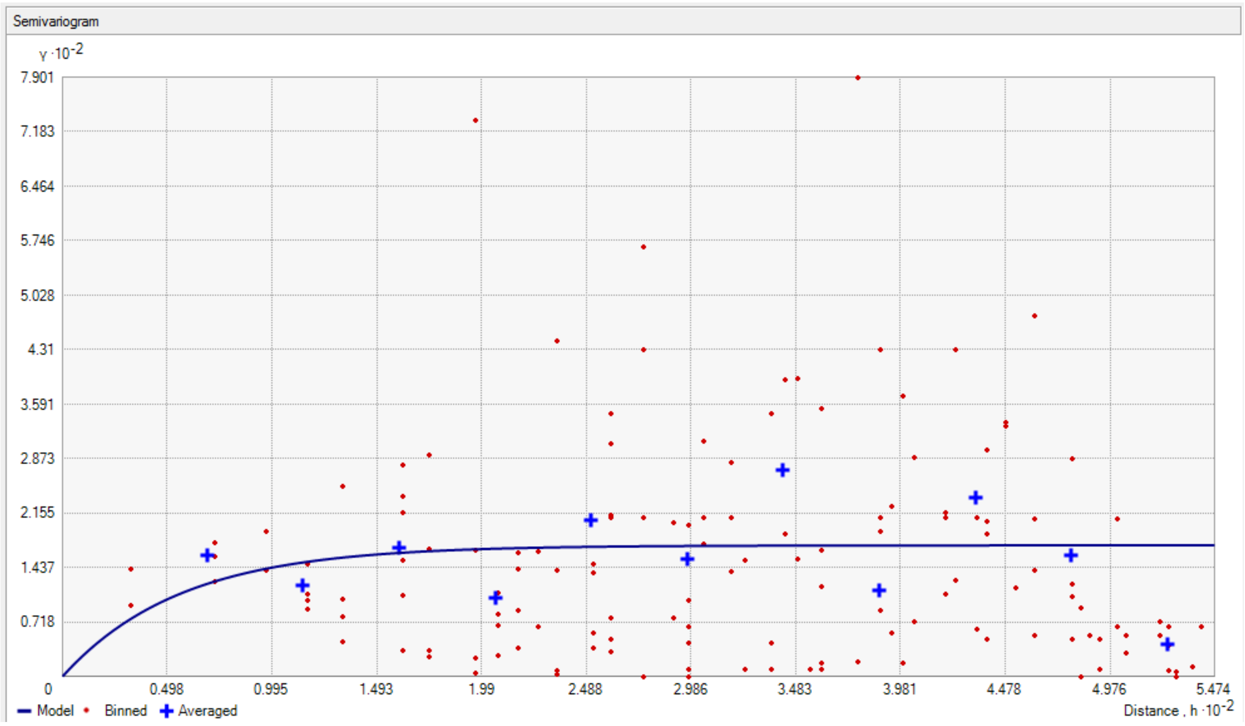

Figure N.2 Exponential semivariogram model for top of rock elevation at Pearson Hall for Kriging in ArcGIS.

Note that the empirical semivariogram shown in these plots (the plotted points) has significant scatter; it is difficult to observe any spatial correlation trend and the empirical semivariogram in actuality appears to have a significant nugget effect. Therefore, if the nugget in the theoretical models was not forced to be zero, it may be significant. The scatter and nugget effect that appears in the empirical semivariogram most likely indicates that spatial correlation is primarily observed at distances that are less than the shortest separation distance between borings in the geotechnical investigation program. Since the theoretical semivariogram models were forced to have no nugget effect, they are essentially each making an assumption about the spatial correlation behavior at shorter separation distances.

The theoretical semivariogram curves with no nugget effect in Figures N.1 and N.2 (blue lines) exhibit significantly different shapes, particularly for small values of separation distance. The Gaussian model shows almost perfect correlation (semivariogram = 0) for some non-zero separation distances, while the exponential model shows an immediate increase in the semivariogram with separation distance. Up to a separation distance of approximately 100 ft, the exponential model shows greater dissimilarity (lower correlation) than the Gaussian model. The differences between these models for estimating the values of TOR elevation at locations with small separation distances from the geotechnical borings may result in significantly different estimates of TOR elevation.

Estimated TOR elevations at the Pearson Hall site from Kriging are shown in Tables N.1 (9 pages) and N.2 (9 pages), with a comparison to the actual TOR elevation as observed during construction. The column numbers in these tables denote the number designation of the cement treated rammed aggregate column at that location. Note that the column numbers are not continuous, as untreated aggregate columns do not extend to rock, and are not included in these tables.

Table N.1 ArcGIS Kriging results for top of rock elevation at Pearson Hall with the Gaussian semivariogram model, compared to observed top of rock elevation.

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
1	462.4	235.0	2046.3	2043.5	8.2	2.8
2	466.8	237.6	2043.3	2044.2	7.5	0.9
3	471.2	235.0	2043.3	2044.6	7.2	1.3
5	469.6	225.0	2043.5	2045.2	8.0	1.7
6	462.6	218.9	2045.5	2040.2	8.7	5.3
9	462.6	203.3	2056.5	2038.4	8.8	18.1
12	490.0	171.0	2057.3	2046.9	6.8	10.4
13	490.0	160.5	2056.3	2046.6	5.2	9.7
14	511.6	136.5	2041.6	2052.8	2.3	11.2
15	483.6	128.7	2047.3	2042.1	2.5	5.2
16	493.0	128.7	2044.3	2045.9	1.8	1.6
17	488.5	124.1	2046.3	2043.8	2.0	2.5
18	483.6	119.5	2046.3	2041.7	2.5	4.6
19	493.0	119.5	2047.3	2045.2	1.6	2.1
20	456.3	114.8	2057.5	2033.2	3.3	24.3
21	462.6	114.8	2054.5	2034.9	3.4	19.6
22	456.3	106.5	2048.5	2034.1	3.8	14.4
23	462.6	106.5	2044.5	2035.5	3.8	9.0
24	456.3	98.2	2048.5	2034.9	4.3	13.6
25	462.6	98.2	2046.5	2035.9	4.2	10.6
26	483.6	94.1	2038.3	2039.9	3.1	1.6
27	493.0	94.1	2043.3	2042.5	2.0	0.8
28	488.5	88.9	2043.3	2040.6	2.6	2.7
29	483.6	84.3	2043.3	2038.9	3.2	4.4
30	493.0	84.3	2043.3	2041.1	2.1	2.2
64	367.7	14.5	2057.2	2039.2	2.9	18.0
65	377.1	14.5	2044.2	2037.0	2.3	7.2
66	372.2	9.7	2046	2036.7	2.5	9.3
67	367.7	4.8	2052.2	2037.1	2.7	15.1
68	377.1	4.8	2058	2033.8	2.0	24.2
69	402.5	14.5	2044	2029.5	1.9	14.5
70	414.2	14.5	2049	2027.1	3.1	21.9
71	405.5	9.7	2053	2027.2	1.8	25.8
72	411.5	9.7	2050	2026.0	2.5	24.0
73	402.5	4.8	2046	2026.3	1.2	19.7
74	414.2	4.8	2040	2024.0	2.6	16.0
79	425.8	221.4	2054.5	2035.0	11.3	19.5
80	433.2	221.4	2057.5	2035.6	10.9	21.9

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
81	440.6	221.4	2046.5	2036.8	10.3	9.7
82	447.9	221.4	2052.5	2038.1	9.8	14.4
83	455.2	221.4	2054.5	2039.6	9.2	14.9
84	425.8	215.3	2056.5	2033.5	11.1	23.0
85	433.2	215.3	2057.5	2034.5	10.7	23.0
86	440.6	215.3	2058.5	2035.8	10.2	22.7
87	447.9	215.3	2060.5	2037.2	9.8	23.3
88	455.2	215.3	2060.3	2038.0	9.3	22.3
89	446.7	209.2	2059.5	2036.1	9.8	23.4
90	438.2	209.2	2062.5	2034.3	10.2	28.2
91	429.7	209.2	2066.5	2032.9	10.7	33.6
92	455.2	209.2	2063.5	2037.1	9.2	26.4
93	448.5	203.1	2062.5	2034.5	9.4	28.0
94	441.9	203.1	2064.5	2032.9	9.7	31.6
95	435.3	203.1	2046.5	2032.7	10.1	13.8
96	455.2	203.1	2047.7	2036.3	9.1	11.4
97	441.2	64.3	2050	2034.7	5.5	15.3
98	447.4	64.3	2047	2034.3	5.6	12.7
99	424.0	56.0	2048.6	2036.1	4.6	12.5
100	430.8	59.0	2048.6	2035.4	5.1	13.2
101	436.7	59.0	2033.6	2034.6	5.4	1.0
102	444.2	59.0	2041.6	2034.0	5.7	7.6
103	424.0	50.5	2047.6	2035.3	4.7	12.3
104	430.8	52.0	2048.6	2034.5	5.2	14.1
105	436.7	52.0	2040.6	2033.7	5.5	6.9
106	444.2	52.0	2048.6	2033.2	5.8	15.4
107	451.0	52.0	2047.6	2032.9	5.8	14.7
108	457.8	52.0	2048.6	2032.9	5.7	15.7
109	464.7	52.0	2039.6	2033.2	5.3	6.4
110	430.8	45.0	2038.6	2033.2	5.3	5.4
111	436.7	45.0	2041.6	2032.6	5.6	9.0
112	444.2	45.0	2042	2032.0	5.8	10.0
113	451.0	45.0	2038.5	2031.8	5.9	6.7
114	457.8	45.0	2038	2031.9	5.7	6.1
115	464.7	45.0	2040	2032.2	5.4	7.8
116	430.8	38.0	2038	2031.7	5.3	6.3
117	436.7	38.0	2040	2031.0	5.6	9.0
118	444.2	38.0	2045	2030.6	5.8	14.4

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
119	451.0	38.0	2044	2030.5	5.9	13.5
120	457.8	38.0	2041	2030.7	5.7	10.3
121	464.7	38.0	2046.5	2031.1	5.4	15.4
122	430.8	31.0	2044	2029.8	5.2	14.2
123	436.7	31.0	2043.5	2029.3	5.5	14.2
124	444.2	31.0	2041.5	2029.1	5.8	12.4
125	296.9	59.8	2050.7	2035.2	1.1	15.5
126	303.4	59.8	2046.7	2036.4	0.5	10.3
127	310.0	59.8	2046.7	2037.8	1.0	8.9
128	316.5	59.8	2051.7	2039.2	1.6	12.5
129	323.1	59.8	2054.7	2040.6	2.2	14.1
130	329.6	59.8	2049.7	2041.9	2.7	7.8
131	296.9	53.1	2047.7	2037.0	1.6	10.7
132	303.4	53.1	2050.7	2038.3	1.2	12.4
133	310.0	53.1	2050.7	2039.6	1.4	11.1
134	316.5	53.1	2045.7	2041.0	1.9	4.7
135	323.1	53.1	2054.7	2042.3	2.4	12.4
136	329.6	53.1	2049.7	2043.4	2.8	6.3
137	296.9	46.5	2053.7	2038.9	2.0	14.8
138	303.4	46.5	2044.7	2040.2	1.7	4.5
139	310.0	46.5	2044.7	2041.5	1.8	3.2
140	316.5	46.5	2049.7	2042.7	2.1	7.0
141	293.0	39.9	2054.7	2040.1	2.7	14.6
142	299.7	39.9	2054.7	2041.4	2.2	13.3
143	306.4	39.9	2046.7	2042.7	2.0	4.0
144	313.0	39.9	2042.7	2043.9	2.1	1.2
145	293.0	33.2	2049.7	2042.0	2.9	7.7
146	299.7	33.2	2046.7	2043.3	2.4	3.4
147	306.4	33.2	2055.7	2044.5	2.1	11.2
148	313.0	33.2	2042.7	2045.7	2.2	3.0
149	293.0	26.6	2051.7	2043.7	2.8	8.0
150	299.7	26.6	2055.7	2045.2	2.4	10.5
151	295.2	20.5	2052.7	2046.1	2.6	6.6
152	301.3	20.5	2052.7	2047.1	2.1	5.6
153	295.2	14.1	2059.7	2048.0	2.4	11.7
154	301.3	14.1	2050.7	2048.7	1.8	2.0
155	300.8	8.3	2050.7	2050.2	1.7	0.5
156	321.8	8.3	2055	2051.0	1.5	4.0

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
157	327.3	11.1	2061.8	2050.4	2.1	11.4
158	336.4	11.1	2061.7	2048.0	2.7	13.7
159	347.5	11.1	2072.4	2045.3	3.2	27.1
160	358.9	11.1	2052.4	2041.8	3.1	10.6
161	382.2	7.7	2044	2033.3	1.6	10.7
162	389.9	7.7	2044	2030.8	0.9	13.2
163	397.6	7.7	2046	2028.5	0.9	17.5
164	419.8	11.1	2047	2025.2	3.5	21.8
165	441.2	11.1	2041.9	2024.4	5.2	17.5
166	450.9	11.1	2046.6	2025.2	5.4	21.4
167	459.7	9.7	2052.6	2026.2	5.3	26.4
168	459.7	3.3	2048.6	2026.4	5.2	22.2
169	465.4	3.3	2057.6	2027.4	5.0	30.2
170	471.4	3.3	2049.6	2028.6	4.6	21.0
171	474.8	5.2	2047.6	2029.4	4.3	18.2
172	481.0	5.2	2045.6	2032.4	3.9	13.2
173	484.5	3.3	2058.6	2032.9	3.5	25.7
174	490.3	3.3	2053.6	2033.8	2.6	19.8
175	496.5	3.3	2046.6	2034.7	1.6	11.9
176	497.0	9.2	2043.6	2034.8	1.6	8.8
177	497.0	15.0	2053.6	2034.8	1.8	18.8
178	494.0	19.0	2049.6	2034.5	2.4	15.1
179	493.6	25.0	2048.6	2034.7	2.5	13.9
180	497.0	29.0	2046.6	2035.3	2.1	11.3
181	497.0	34.5	2054.6	2035.7	2.1	18.9
182	497.0	40.2	2045.6	2036.2	2.0	9.4
183	491.7	40.2	2039.6	2035.5	2.7	4.1
184	486.7	40.2	2049.6	2034.9	3.4	14.7
185	486.6	48.7	2039.6	2035.7	3.3	3.9
186	486.6	57.9	2048.6	2036.7	3.2	11.9
187	486.6	67.7	2053.6	2037.6	3.0	16.0
188	486.6	77.4	2043.6	2038.8	2.9	4.8
189	490.0	99.4	2041.3	2042.2	2.3	0.9
190	490.0	106.5	2043.3	2043.0	2.1	0.3
191	490.0	114.0	2037.3	2043.7	2.0	6.4
192	486.6	135.9	2051.3	2043.6	2.7	7.7
193	486.6	144.2	2057.3	2044.8	3.5	12.5
194	490.0	152.7	2056.3	2046.4	4.3	9.9

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
195	490.0	177.1	2054.3	2046.2	7.2	8.1
196	486.6	183.2	2051.3	2045.0	7.7	6.3
197	486.6	193.1	2050.3	2045.4	8.0	4.9
198	486.6	203.1	2054.3	2045.5	8.0	8.8
199	486.6	213.4	2050.3	2047.7	7.6	2.6
200	486.6	223.4	2053.3	2047.5	6.8	5.8
201	512.7	144.2	2047.6	2053.5	3.2	5.9
202	512.7	153.8	2047.6	2053.7	4.4	6.1
203	512.7	163.8	2049.7	2053.7	5.6	4.0
204	512.7	173.8	2049.7	2053.6	7.2	3.9
205	512.7	183.7	2053.7	2053.0	7.8	0.7
206	512.7	193.7	2049.7	2052.4	8.1	2.7
207	512.7	203.1	2049.7	2051.0	8.0	1.3
208	512.7	209.2	2046.7	2050.6	7.8	3.9
209	512.7	217.2	2045.7	2050.4	7.3	4.7
210	512.7	225.7	2048.6	2049.8	6.5	1.2
211	512.7	231.3	2046.7	2049.5	5.8	2.8
212	507.2	234.1	2050.3	2049.0	5.2	1.3
213	501.1	231.3	2054.3	2048.8	5.4	5.5
214	495.6	234.1	2052.3	2048.2	5.1	4.1
215	489.5	231.3	2050.3	2047.7	5.8	2.6
216	489.5	236.9	2052.3	2046.5	5.2	5.8
217	493.4	242.9	2060.3	2046.9	4.1	13.4
218	489.5	249.0	2058.3	2046.8	3.5	11.5
219	493.4	254.6	2059.3	2047.1	2.2	12.2
220	487.1	258.2	2058.3	2046.8	2.9	11.5
221	481.2	254.6	2060.3	2046.4	4.2	13.9
222	475.4	258.2	2061.3	2046.0	5.1	15.3
223	469.9	254.6	2061.3	2045.5	6.1	15.8
224	469.0	263.2	2061.3	2046.2	6.1	15.1
225	463.7	258.2	2065.3	2045.7	7.0	19.6
226	457.4	254.6	2061.3	2045.1	8.1	16.2
227	457.9	263.2	2070.3	2045.8	7.9	24.5
228	451.9	258.2	2068.3	2045.2	8.8	23.1
229	445.8	254.6	2061.3	2044.6	9.6	16.7
230	440.2	258.2	2068.5	2044.7	10.3	23.8
231	440.2	247.0	2065.5	2043.6	10.3	21.9
232	444.1	241.3	2051.5	2042.0	10.0	9.5

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
233	444.1	229.4	2057.5	2038.4	10.1	19.1
234	440.2	235.2	2058.5	2040.9	10.5	17.6
235	435.3	230.8	2057.5	2037.7	10.8	19.8
236	430.3	226.3	2056.5	2036.4	11.1	20.1
237	447.4	198.1	2058.5	2033.4	9.2	25.1
238	443.3	192.6	2055.5	2031.5	9.0	24.0
239	447.4	187.0	2058.3	2031.8	8.5	26.5
240	443.3	182.6	2057.5	2030.1	8.1	27.4
241	443.3	175.7	2047.5	2029.2	7.3	18.3
242	440.2	170.2	2045.5	2027.8	6.7	17.7
243	443.3	165.2	2040.5	2028.3	6.0	12.2
244	440.2	159.5	2044.5	2023.4	4.9	21.1
245	443.3	154.5	2045.5	2025.1	4.2	20.4
246	440.2	148.8	2054.5	2024.6	3.3	29.9
247	443.3	143.8	2046.5	2025.9	2.8	20.6
248	446.1	138.7	2040.5	2027.5	2.5	13.0
249	443.3	133.1	2040	2027.5	1.9	12.5
250	462.6	122.4	2058.5	2033.9	3.1	24.6
251	457.1	125.9	2063.5	2032.3	2.8	31.2
252	451.6	122.4	2056.5	2031.1	2.7	25.4
253	446.1	128.0	2045	2028.9	2.1	16.1
254	443.3	122.4	2044	2029.2	2.1	14.8
255	436.7	125.2	2044.5	2027.6	1.3	16.9
256	433.3	121.4	2038.5	2028.0	1.2	10.5
257	436.7	117.7	2048.5	2029.1	1.9	19.4
258	433.3	114.0	2046.5	2029.7	2.0	16.8
259	436.7	110.3	2049.5	2030.7	2.6	18.8
260	433.3	106.5	2053.5	2031.4	2.7	22.1
261	436.7	102.8	2049.5	2032.2	3.2	17.3
262	433.3	99.1	2044.5	2032.9	3.3	11.6
263	436.7	95.4	2048.5	2033.5	3.8	15.0
264	433.3	91.6	2046.5	2034.2	3.8	12.3
265	436.7	87.9	2053.5	2034.5	4.3	19.0
266	459.9	87.2	2051	2036.0	4.7	15.0
267	455.7	90.6	2054.5	2035.4	4.6	19.1
268	451.6	87.2	2049.5	2034.6	4.8	14.9
269	447.4	89.9	2051.5	2034.3	4.6	17.2
270	444.7	83.7	2051.5	2034.6	4.8	16.9

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
271	447.4	80.2	2051.5	2034.7	5.1	16.8
272	444.7	74.7	2049.5	2034.8	5.2	14.7
273	447.4	70.5	2049	2034.7	5.4	14.3
274	420.3	51.5	2044.3	2036.1	4.4	8.2
275	415.3	54.2	2044.3	2037.6	3.9	6.7
276	405.4	39.8	2041.3	2036.8	3.0	4.5
277	410.3	43.7	2046.3	2036.7	3.5	9.6
278	405.4	47.6	2056.3	2038.6	3.0	17.7
279	410.3	51.5	2048.3	2038.2	3.4	10.1
280	405.4	54.2	2048.3	2039.7	2.8	8.6
281	408.7	60.9	2043	2039.7	3.0	3.3
282	404.8	64.2	2054.3	2040.6	2.4	13.7
283	401.2	60.9	2052.3	2041.2	2.1	11.1
284	397.3	64.2	2057.3	2042.1	1.5	15.2
285	393.8	60.9	2055.4	2042.7	1.3	12.7
286	389.9	64.2	2046.3	2043.5	0.7	2.8
287	386.3	60.9	2056.3	2044.1	0.9	12.2
288	382.4	64.2	2053.3	2044.6	0.8	8.7
289	378.9	60.9	2057.3	2045.1	1.2	12.2
290	374.9	64.2	2054.3	2045.7	1.5	8.6
291	371.4	60.9	2056.3	2046.2	1.8	10.1
292	374.2	38.7	2036.3	2043.7	2.6	7.4
293	370.5	41.5	2043.3	2044.8	2.7	1.5
294	374.2	44.8	2043.3	2044.7	2.4	1.4
295	373.8	50.9	2054.5	2045.4	2.1	9.1
296	368.6	54.8	2061.5	2046.0	2.3	15.5
297	364.1	50.9	2057.5	2046.3	2.8	11.2
298	358.9	54.8	2053.5	2047.2	2.8	6.3
299	354.4	50.9	2049.5	2047.4	3.1	2.1
300	349.2	54.8	2054.5	2047.1	3.1	7.4
301	344.7	50.9	2055.5	2045.6	3.3	9.9
302	339.5	54.8	2057.5	2044.1	3.2	13.4
303	335.1	50.9	2054.5	2044.7	3.1	9.8
304	321.8	41.5	2051.5	2044.8	2.6	6.7
305	319.0	34.9	2056.5	2046.0	2.5	10.5
306	325.7	34.9	2062.5	2046.7	2.9	15.8
307	336.7	34.9	2070.3	2047.2	3.4	23.1
308	349.5	34.9	2072.3	2046.2	3.6	26.1

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
309	360.5	41.5	2051.5	2046.2	3.3	5.3
310	359.5	34.9	2074	2045.7	3.4	28.3
311	369.6	34.9	2047	2043.9	2.9	3.1
312	379.9	34.9	2036	2041.7	2.4	5.7
313	389.9	34.9	2039	2039.3	2.1	0.3
314	400.4	34.9	2045	2036.7	2.6	8.3
315	325.7	28.4	2064	2047.9	2.8	16.1
316	335.4	28.4	2072	2048.1	3.3	23.9
317	348.4	28.4	2065	2046.2	3.5	18.8
318	357.4	28.4	2071	2044.6	3.4	26.4
319	366.9	28.4	2055	2043.3	3.1	11.7
320	376.0	28.4	2051	2041.1	2.6	9.9
321	385.1	28.4	2031	2038.7	2.2	7.7
322	394.6	28.4	2039	2036.2	2.2	2.8
323	406.7	28.4	2046	2033.2	3.0	12.8
324	432.2	28.4	2049.5	2029.0	5.2	20.5
325	441.2	28.4	2047.5	2028.5	5.6	19.0
326	450.2	28.4	2050.6	2028.5	5.8	22.1
327	459.7	28.4	2045.5	2029.1	5.6	16.4
328	459.7	18.0	2040.6	2027.4	5.5	13.2
329	466.1	22.8	2049.6	2028.7	5.2	20.9
330	475.9	27.7	2045.6	2030.7	4.5	14.9
331	485.6	29.0	2046.6	2033.9	3.6	12.7
332	477.0	34.3	2047.6	2031.4	4.4	16.2
333	477.0	40.7	2048.6	2033.8	4.7	14.8
334	469.6	40.0	2046	2030.8	5.1	15.2
335	469.6	49.8	2044	2033.3	5.0	10.7
336	469.6	59.5	2041	2034.6	4.9	6.4
337	469.6	69.2	2039.5	2037.1	4.7	2.4
338	469.6	78.9	2040.5	2037.6	4.6	2.9
339	469.6	89.0	2046	2036.1	4.4	9.9
340	469.6	98.3	2043.5	2036.4	4.1	7.1
341	469.6	108.5	2049.5	2036.5	3.6	13.0
342	469.6	118.0	2044.5	2036.4	3.2	8.1
343	469.6	128.8	2055.5	2036.4	3.0	19.1
344	469.6	137.2	2064.5	2036.3	3.3	28.2
345	469.6	147.0	2064.5	2036.3	4.0	28.2

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
346	469.6	156.7	2060.5	2037.9	5.1	22.6
347	469.6	166.5	2064.5	2038.2	6.1	26.3
348	469.6	176.3	2054.5	2038.6	7.4	15.9
349	469.6	186.1	2053.5	2039.2	8.1	14.3
350	469.6	195.9	2051.5	2039.9	8.5	11.6
351	476.8	203.7	2053.5	2042.7	8.3	10.8
352	479.5	210.3	2049.3	2043.8	8.0	5.5
353	462.6	57.4	2040.6	2033.8	5.4	6.8
354	462.6	71.3	2042.5	2035.3	5.1	7.2
355	462.6	81.6	2041.5	2036.4	4.8	5.1
356	462.6	91.3	2048.5	2036.2	4.5	12.3
357	462.6	133.4	2066.5	2033.6	3.0	32.9
358	462.6	142.2	2066.5	2033.4	3.5	33.1
359	462.6	150.9	2058.5	2032.8	4.3	25.7
360	462.6	159.7	2053.5	2035.1	5.4	18.4
361	462.6	168.4	2063.5	2035.4	6.6	28.1
362	462.6	177.2	2063.5	2036.0	7.5	27.5
363	462.6	185.9	2047.5	2036.7	8.2	10.8
364	455.7	186.7	2044.5	2034.4	8.3	10.1

Table N.2 ArcGIS Kriging results for top of rock elevation at Pearson Hall with the exponential semivariogram model, compared to observed top of rock elevation.

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
1	462.4	235.0	2046.3	2042.8	12.1	3.5
2	466.8	237.6	2043.3	2043.2	11.9	0.1
3	471.2	235.0	2043.3	2043.4	11.7	0.1
5	469.6	225.0	2043.5	2043.4	12.1	0.1
6	462.6	218.9	2045.5	2043.1	12.4	2.4
9	462.6	203.3	2056.5	2042.2	12.6	14.3
12	490.0	171.0	2057.3	2042.6	12.2	14.7
13	490.0	160.5	2056.3	2042.4	11.7	13.9
14	511.6	136.5	2041.6	2046.0	9.7	4.4
15	483.6	128.7	2047.3	2042.5	9.7	4.8
16	493.0	128.7	2044.3	2044.6	8.8	0.3
17	488.5	124.1	2046.3	2044.0	8.9	2.3
18	483.6	119.5	2046.3	2042.9	9.3	3.4
19	493.0	119.5	2047.3	2045.4	7.7	1.9
20	456.3	114.8	2057.5	2036.0	10.1	21.5
21	462.6	114.8	2054.5	2037.6	10.2	16.9
22	456.3	106.5	2048.5	2036.5	10.3	12.0
23	462.6	106.5	2044.5	2037.9	10.4	6.6
24	456.3	98.2	2048.5	2037.0	10.5	11.5
25	462.6	98.2	2046.5	2038.1	10.5	8.4
26	483.6	94.1	2038.3	2041.8	9.6	3.5
27	493.0	94.1	2043.3	2043.2	8.9	0.1
28	488.5	88.9	2043.3	2042.1	9.2	1.2
29	483.6	84.3	2043.3	2041.0	9.6	2.3
30	493.0	84.3	2043.3	2042.1	8.7	1.2
64	367.7	14.5	2057.2	2036.3	10.0	20.9
65	377.1	14.5	2044.2	2034.3	9.3	9.9
66	372.2	9.7	2046.0	2034.8	9.5	11.2
67	367.7	4.8	2052.2	2035.6	9.8	16.6
68	377.1	4.8	2058.0	2033.0	8.8	25.0
69	402.5	14.5	2044.0	2031.1	8.4	12.9
70	414.2	14.5	2049.0	2032.1	9.7	16.9
71	405.5	9.7	2053.0	2030.3	8.1	22.7
72	411.5	9.7	2050.0	2031.1	9.0	18.9
73	402.5	4.8	2046.0	2029.1	6.7	16.9
74	414.2	4.8	2040.0	2030.9	9.2	9.1
79	425.8	221.4	2054.5	2041.0	13.2	13.5
80	433.2	221.4	2057.5	2041.3	13.0	16.2

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
81	440.6	221.4	2046.5	2041.4	12.9	5.1
82	447.9	221.4	2052.5	2041.7	12.7	10.8
83	455.2	221.4	2054.5	2042.1	12.6	12.4
84	425.8	215.3	2056.5	2040.5	13.1	16.0
85	433.2	215.3	2057.5	2040.7	13.0	16.8
86	440.6	215.3	2058.5	2041.0	12.9	17.5
87	447.9	215.3	2060.5	2041.3	12.8	19.2
88	455.2	215.3	2060.3	2042.5	12.6	17.8
89	446.7	209.2	2059.5	2040.9	12.8	18.6
90	438.2	209.2	2062.5	2040.5	12.9	22.0
91	429.7	209.2	2066.5	2040.2	13.0	26.3
92	455.2	209.2	2063.5	2042.1	12.6	21.4
93	448.5	203.1	2062.5	2041.4	12.7	21.1
94	441.9	203.1	2064.5	2041.1	12.8	23.4
95	435.3	203.1	2046.5	2040.0	12.9	6.5
96	455.2	203.1	2047.7	2041.8	12.6	5.9
97	441.2	64.3	2050.0	2037.3	11.2	12.7
98	447.4	64.3	2047.0	2037.4	11.2	9.6
99	424.0	56.0	2048.6	2037.4	10.8	11.2
100	430.8	59.0	2048.6	2037.3	11.0	11.3
101	436.7	59.0	2033.6	2037.2	11.2	3.6
102	444.2	59.0	2041.6	2037.3	11.3	4.3
103	424.0	50.5	2047.6	2037.1	10.8	10.5
104	430.8	52.0	2048.6	2037.0	11.1	11.6
105	436.7	52.0	2040.6	2037.0	11.2	3.6
106	444.2	52.0	2048.6	2036.9	11.3	11.7
107	451.0	52.0	2047.6	2037.1	11.3	10.5
108	457.8	52.0	2048.6	2037.3	11.2	11.3
109	464.7	52.0	2039.6	2037.6	11.0	2.0
110	430.8	45.0	2038.6	2036.6	11.1	2.0
111	436.7	45.0	2041.6	2036.4	11.3	5.2
112	444.2	45.0	2042.0	2036.5	11.4	5.5
113	451.0	45.0	2038.5	2036.7	11.4	1.8
114	457.8	45.0	2038.0	2037.0	11.3	1.0
115	464.7	45.0	2040.0	2037.3	11.1	2.7
116	430.8	38.0	2038.0	2035.8	11.2	2.2
117	436.7	38.0	2040.0	2035.9	11.3	4.1
118	444.2	38.0	2045.0	2036.1	11.4	8.9

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
119	451.0	38.0	2044.0	2036.3	11.4	7.7
120	457.8	38.0	2041.0	2036.6	11.3	4.4
121	464.7	38.0	2046.5	2036.9	11.1	9.6
122	430.8	31.0	2044.0	2035.1	11.1	8.9
123	436.7	31.0	2043.5	2035.3	11.3	8.2
124	444.2	31.0	2041.5	2035.6	11.4	5.9
125	296.9	59.8	2050.7	2036.4	6.4	14.3
126	303.4	59.8	2046.7	2036.1	5.1	10.6
127	310.0	59.8	2046.7	2036.7	6.6	10.0
128	316.5	59.8	2051.7	2037.5	8.1	14.2
129	323.1	59.8	2054.7	2038.2	9.1	16.5
130	329.6	59.8	2049.7	2038.7	9.8	11.0
131	296.9	53.1	2047.7	2037.8	7.8	9.9
132	303.4	53.1	2050.7	2037.7	7.3	13.0
133	310.0	53.1	2050.7	2038.0	7.8	12.7
134	316.5	53.1	2045.7	2038.5	8.6	7.2
135	323.1	53.1	2054.7	2039.0	9.3	15.7
136	329.6	53.1	2049.7	2039.3	9.9	10.4
137	296.9	46.5	2053.7	2039.1	8.8	14.6
138	303.4	46.5	2044.7	2039.2	8.6	5.5
139	310.0	46.5	2044.7	2039.4	8.7	5.3
140	316.5	46.5	2049.7	2039.7	9.1	10.0
141	293.0	39.9	2054.7	2040.6	9.6	14.1
142	299.7	39.9	2054.7	2040.7	9.3	14.0
143	306.4	39.9	2046.7	2040.8	9.2	5.9
144	313.0	39.9	2042.7	2041.0	9.3	1.7
145	293.0	33.2	2049.7	2042.0	9.8	7.7
146	299.7	33.2	2046.7	2042.3	9.6	4.4
147	306.4	33.2	2055.7	2042.5	9.4	13.2
148	313.0	33.2	2042.7	2042.5	9.4	0.2
149	293.0	26.6	2051.7	2043.2	9.9	8.5
150	299.7	26.6	2055.7	2043.8	9.5	11.9
151	295.2	20.5	2052.7	2044.7	9.6	8.0
152	301.3	20.5	2052.7	2045.4	9.1	7.3
153	295.2	14.1	2059.7	2046.1	9.2	13.6
154	301.3	14.1	2050.7	2046.9	8.5	3.8
155	300.8	8.3	2050.7	2048.2	8.0	2.5
156	321.8	8.3	2055.0	2047.8	7.5	7.2

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
157	327.3	11.1	2061.8	2045.9	8.7	15.9
158	336.4	11.1	2061.7	2043.4	9.7	18.3
159	347.5	11.1	2072.4	2040.7	10.3	31.7
160	358.9	11.1	2052.4	2038.0	10.3	14.4
161	382.2	7.7	2044.0	2032.0	8.1	12.0
162	389.9	7.7	2044.0	2030.0	6.7	14.0
163	397.6	7.7	2046.0	2029.2	6.3	16.8
164	419.8	11.1	2047.0	2032.2	10.1	14.8
165	441.2	11.1	2041.9	2034.2	11.3	7.7
166	450.9	11.1	2046.6	2034.9	11.4	11.7
167	459.7	9.7	2052.6	2035.3	11.3	17.3
168	459.7	3.3	2048.6	2035.3	11.3	13.3
169	465.4	3.3	2057.6	2035.6	11.1	22.0
170	471.4	3.3	2049.6	2035.8	10.8	13.8
171	474.8	5.2	2047.6	2036.0	10.5	11.6
172	481.0	5.2	2045.6	2035.7	9.9	9.9
173	484.5	3.3	2058.6	2035.7	9.4	22.9
174	490.3	3.3	2053.6	2035.8	8.4	17.8
175	496.5	3.3	2046.6	2035.9	6.9	10.7
176	497.0	9.2	2043.6	2036.2	7.4	7.4
177	497.0	15.0	2053.6	2036.5	8.3	17.1
178	494.0	19.0	2049.6	2036.7	9.0	12.9
179	493.6	25.0	2048.6	2037.0	9.5	11.6
180	497.0	29.0	2046.6	2037.4	9.6	9.2
181	497.0	34.5	2054.6	2037.7	9.7	16.9
182	497.0	40.2	2045.6	2038.2	9.6	7.4
183	491.7	40.2	2039.6	2038.0	9.8	1.6
184	486.7	40.2	2049.6	2037.8	10.1	11.8
185	486.6	48.7	2039.6	2038.4	9.8	1.2
186	486.6	57.9	2048.6	2039.1	9.3	9.5
187	486.6	67.7	2053.6	2040.0	8.9	13.6
188	486.6	77.4	2043.6	2040.8	9.1	2.8
189	490.0	99.4	2041.3	2043.4	8.9	2.1
190	490.0	106.5	2043.3	2044.1	8.6	0.8
191	490.0	114.0	2037.3	2044.6	8.2	7.3
192	486.6	135.9	2051.3	2042.6	10.1	8.7
193	486.6	144.2	2057.3	2042.6	10.8	14.7
194	490.0	152.7	2056.3	2042.7	11.3	13.6

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
195	490.0	177.1	2054.3	2042.1	12.3	12.2
196	486.6	183.2	2051.3	2041.9	12.4	9.4
197	486.6	193.1	2050.3	2043.2	12.4	7.1
198	486.6	203.1	2054.3	2043.6	12.3	10.7
199	486.6	213.4	2050.3	2043.7	12.1	6.6
200	486.6	223.4	2053.3	2044.2	11.7	9.1
201	512.7	144.2	2047.6	2045.2	10.7	2.4
202	512.7	153.8	2047.6	2044.4	11.5	3.2
203	512.7	163.8	2049.7	2043.9	12.0	5.8
204	512.7	173.8	2049.7	2044.0	12.4	5.7
205	512.7	183.7	2053.7	2043.9	12.6	9.8
206	512.7	193.7	2049.7	2043.9	12.7	5.8
207	512.7	203.1	2049.7	2042.9	12.5	6.8
208	512.7	209.2	2046.7	2043.1	12.4	3.6
209	512.7	217.2	2045.7	2044.6	12.0	1.1
210	512.7	225.7	2048.6	2044.9	11.5	3.7
211	512.7	231.3	2046.7	2045.2	11.1	1.5
212	507.2	234.1	2050.3	2045.3	10.7	5.0
213	501.1	231.3	2054.3	2045.1	10.9	9.2
214	495.6	234.1	2052.3	2045.1	10.7	7.2
215	489.5	231.3	2050.3	2044.7	11.1	5.6
216	489.5	236.9	2052.3	2045.2	10.6	7.1
217	493.4	242.9	2060.3	2045.7	9.7	14.6
218	489.5	249.0	2058.3	2045.9	9.2	12.4
219	493.4	254.6	2059.3	2046.4	7.6	12.9
220	487.1	258.2	2058.3	2045.8	8.5	12.5
221	481.2	254.6	2060.3	2045.1	9.8	15.2
222	475.4	258.2	2061.3	2044.7	10.4	16.6
223	469.9	254.6	2061.3	2044.1	11.1	17.2
224	469.0	263.2	2061.3	2046.7	11.1	14.6
225	463.7	258.2	2065.3	2046.5	11.6	18.8
226	457.4	254.6	2061.3	2046.3	12.1	15.0
227	457.9	263.2	2070.3	2046.5	12.0	23.8
228	451.9	258.2	2068.3	2046.3	12.4	22.0
229	445.8	254.6	2061.3	2046.1	12.6	15.2
230	440.2	258.2	2068.5	2046.1	12.9	22.4
231	440.2	247.0	2065.5	2045.7	12.9	19.8
232	444.1	241.3	2051.5	2042.0	12.8	9.5

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
233	444.1	229.4	2057.5	2042.1	12.8	15.4
234	440.2	235.2	2058.5	2041.6	12.9	16.9
235	435.3	230.8	2057.5	2041.8	13.0	15.7
236	430.3	226.3	2056.5	2041.4	13.1	15.1
237	447.4	198.1	2058.5	2041.0	12.7	17.5
238	443.3	192.6	2055.5	2040.3	12.6	15.2
239	447.4	187.0	2058.3	2040.0	12.5	18.3
240	443.3	182.6	2057.5	2039.3	12.4	18.2
241	443.3	175.7	2047.5	2038.6	12.1	8.9
242	440.2	170.2	2045.5	2037.7	11.9	7.8
243	443.3	165.2	2040.5	2037.3	11.6	3.2
244	440.2	159.5	2044.5	2035.6	11.2	8.9
245	443.3	154.5	2045.5	2035.2	10.9	10.3
246	440.2	148.8	2054.5	2033.9	10.3	20.6
247	443.3	143.8	2046.5	2033.7	10.0	12.8
248	446.1	138.7	2040.5	2033.3	9.8	7.2
249	443.3	133.1	2040.0	2032.2	9.0	7.8
250	462.6	122.4	2058.5	2037.4	10.2	21.1
251	457.1	125.9	2063.5	2035.8	10.1	27.7
252	451.6	122.4	2056.5	2034.4	9.7	22.1
253	446.1	128.0	2045.0	2032.8	9.2	12.2
254	443.3	122.4	2044.0	2032.1	8.7	11.9
255	436.7	125.2	2044.5	2030.0	7.4	14.5
256	433.3	121.4	2038.5	2029.4	6.7	9.1
257	436.7	117.7	2048.5	2030.9	7.9	17.6
258	433.3	114.0	2046.5	2031.0	8.0	15.5
259	436.7	110.3	2049.5	2032.3	8.9	17.2
260	433.3	106.5	2053.5	2032.6	9.1	20.9
261	436.7	102.8	2049.5	2033.7	9.7	15.8
262	433.3	99.1	2044.5	2034.1	9.8	10.4
263	436.7	95.4	2048.5	2035.0	10.2	13.5
264	433.3	91.6	2046.5	2035.4	10.3	11.1
265	436.7	87.9	2053.5	2036.0	10.6	17.5
266	459.9	87.2	2051.0	2038.0	10.8	13.0
267	455.7	90.6	2054.5	2037.3	10.7	17.2
268	451.6	87.2	2049.5	2037.1	10.8	12.4
269	447.4	89.9	2051.5	2036.5	10.7	15.0
270	444.7	83.7	2051.5	2036.8	10.9	14.7

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
271	447.4	80.2	2051.5	2037.1	11.0	14.4
272	444.7	74.7	2049.5	2037.2	11.1	12.3
273	447.4	70.5	2049.0	2037.4	11.1	11.6
274	420.3	51.5	2044.3	2037.3	10.7	7.0
275	415.3	54.2	2044.3	2037.8	10.3	6.5
276	405.4	39.8	2041.3	2036.4	10.1	4.9
277	410.3	43.7	2046.3	2036.8	10.3	9.5
278	405.4	47.6	2056.3	2037.7	9.9	18.6
279	410.3	51.5	2048.3	2038.0	10.0	10.3
280	405.4	54.2	2048.3	2038.7	9.5	9.6
281	408.7	60.9	2043.0	2039.0	9.5	4.0
282	404.8	64.2	2054.3	2039.7	8.8	14.6
283	401.2	60.9	2052.3	2040.0	8.5	12.3
284	397.3	64.2	2057.3	2041.0	7.4	16.3
285	393.8	60.9	2055.4	2041.0	7.4	14.4
286	389.9	64.2	2046.3	2042.0	6.0	4.3
287	386.3	60.9	2056.3	2041.5	7.1	14.8
288	382.4	64.2	2053.3	2042.0	6.7	11.3
289	378.9	60.9	2057.3	2041.3	7.9	16.0
290	374.9	64.2	2054.3	2041.3	8.2	13.0
291	371.4	60.9	2056.3	2040.8	9.0	15.5
292	374.2	38.7	2036.3	2038.3	10.1	2.0
293	370.5	41.5	2043.3	2038.9	10.1	4.4
294	374.2	44.8	2043.3	2039.1	9.9	4.2
295	373.8	50.9	2054.5	2039.9	9.5	14.6
296	368.6	54.8	2061.5	2040.4	9.6	21.1
297	364.1	50.9	2057.5	2040.0	10.1	17.5
298	358.9	54.8	2053.5	2040.0	10.2	13.5
299	354.4	50.9	2049.5	2039.9	10.4	9.6
300	349.2	54.8	2054.5	2039.8	10.5	14.7
301	344.7	50.9	2055.5	2039.7	10.5	15.8
302	339.5	54.8	2057.5	2039.6	10.4	17.9
303	335.1	50.9	2054.5	2039.7	10.2	14.8
304	321.8	41.5	2051.5	2040.8	9.7	10.7
305	319.0	34.9	2056.5	2042.1	9.6	14.4
306	325.7	34.9	2062.5	2041.9	9.9	20.6
307	336.7	34.9	2070.3	2041.3	10.3	29.0
308	349.5	34.9	2072.3	2040.1	10.6	32.2

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
309	360.5	41.5	2051.5	2039.4	10.4	12.1
310	359.5	34.9	2074.0	2039.2	10.5	34.8
311	369.6	34.9	2047.0	2038.2	10.3	8.8
312	379.9	34.9	2036.0	2037.2	9.9	1.2
313	389.9	34.9	2039.0	2036.4	9.8	2.6
314	400.4	34.9	2045.0	2035.7	9.9	9.3
315	325.7	28.4	2064.0	2043.1	9.7	20.9
316	335.4	28.4	2072.0	2042.0	10.2	30.0
317	348.4	28.4	2065.0	2040.2	10.5	24.8
318	357.4	28.4	2071.0	2038.9	10.5	32.1
319	366.9	28.4	2055.0	2037.8	10.3	17.2
320	376.0	28.4	2051.0	2036.6	10.0	14.4
321	385.1	28.4	2031.0	2035.5	9.7	4.5
322	394.6	28.4	2039.0	2034.6	9.6	4.4
323	406.7	28.4	2046.0	2034.2	10.0	11.8
324	432.2	28.4	2049.5	2034.9	11.1	14.6
325	441.2	28.4	2047.5	2035.3	11.4	12.2
326	450.2	28.4	2050.6	2035.7	11.4	14.9
327	459.7	28.4	2045.5	2036.2	11.3	9.3
328	459.7	18.0	2040.6	2035.6	11.3	5.0
329	466.1	22.8	2049.6	2036.3	11.1	13.3
330	475.9	27.7	2045.6	2036.9	10.7	8.7
331	485.6	29.0	2046.6	2037.0	10.1	9.6
332	477.0	34.3	2047.6	2037.3	10.6	10.3
333	477.0	40.7	2048.6	2037.4	10.6	11.2
334	469.6	40.0	2046.0	2037.3	11.0	8.7
335	469.6	49.8	2044.0	2037.8	10.8	6.2
336	469.6	59.5	2041.0	2038.3	10.7	2.7
337	469.6	69.2	2039.5	2038.6	10.6	0.9
338	469.6	78.9	2040.5	2038.9	10.5	1.6
339	469.6	89.0	2046.0	2039.3	10.5	6.7
340	469.6	98.3	2043.5	2039.4	10.3	4.1
341	469.6	108.5	2049.5	2039.4	10.2	10.1
342	469.6	118.0	2044.5	2039.3	10.2	5.2
343	469.6	128.8	2055.5	2039.0	10.4	16.5
344	469.6	137.2	2064.5	2038.9	10.7	25.6
345	469.6	147.0	2064.5	2038.9	11.1	25.6

Column No.	x-coordinate (ft)	y-coordinate (ft)	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
				Estimated Mean TOR Elevation (ft)	Std. Dev. TOR Elevation (ft)	Difference from Actual TOR (ft)
346	469.6	156.7	2060.5	2039.3	11.6	21.2
347	469.6	166.5	2064.5	2039.5	12.0	25.0
348	469.6	176.3	2054.5	2041.2	12.2	13.3
349	469.6	186.1	2053.5	2041.7	12.4	11.8
350	469.6	195.9	2051.5	2042.2	12.5	9.3
351	476.8	203.7	2053.5	2043.1	12.4	10.4
352	479.5	210.3	2049.3	2043.5	12.3	5.8
353	462.6	57.4	2040.6	2037.8	11.0	2.8
354	462.6	71.3	2042.5	2038.2	10.9	4.3
355	462.6	81.6	2041.5	2038.3	10.8	3.2
356	462.6	91.3	2048.5	2038.3	10.6	10.2
357	462.6	133.4	2066.5	2037.3	10.5	29.2
358	462.6	142.2	2066.5	2037.4	10.8	29.1
359	462.6	150.9	2058.5	2037.5	11.2	21.0
360	462.6	159.7	2053.5	2038.3	11.6	15.2
361	462.6	168.4	2063.5	2039.9	12.0	23.6
362	462.6	177.2	2063.5	2040.5	12.2	23.0
363	462.6	185.9	2047.5	2041.1	12.4	6.4
364	455.7	186.7	2044.5	2040.6	12.5	3.9

Tables N.3 and N.4 present summary statistics regarding the mean and standard deviation of TOR elevation at the Pearson Hall site as estimated by Kriging, and the difference between the actual TOR elevation and the estimated TOR elevation at each rammed aggregate column location.

Table N.3 Summary statistics for estimated vs. actual top of rock elevation at Pearson Hall Rammed Aggregate Column locations, using the Gaussian semivariogram model.

	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Gaussian		
		Estimated Mean TOR Elevation (ft)	Estimated Std. Dev. TOR Elevation (ft)	Difference Between Actual and Estimated Mean TOR (ft)
Mean	2,050.7	2,038.3	4.5	13.0
Std. Dev.	7.7	6.8	2.6	7.6
Maximum	2,074.0	2,053.7	11.3	33.6
Minimum	2,031.0	2,023.4	0.5	0.3

Table N.4 Summary statistics for estimated vs. actual top of rock elevation at Pearson Hall Rammed Aggregate Column locations, using the exponential semivariogram model.

	Actual Top of Rock (TOR) Elevation (ft)	ArcGIS Kriging - Exponential		
		Estimated Mean TOR Elevation (ft)	Estimated Std. Dev. TOR Elevation (ft)	Difference between Actual and Estimated Mean TOR (ft)
Mean	2,050.7	2,039.2	10.4	11.7
Std. Dev.	7.7	3.8	1.6	6.9
Maximum	2,074.0	2,048.2	13.2	34.8
Minimum	2,031.0	2,029.1	5.1	0.1

The mean and standard deviation of the difference between the estimated and actual TOR elevations are both smaller with the exponential semivariogram model than with the Gaussian semivariogram model. In addition, the minimum difference between the estimated and the actual TOR elevations is also smaller with the exponential semivariogram model. However, the maximum difference between the estimated and actual TOR elevations is slightly greater for the exponential model than for the Gaussian model.

Overall, using the exponential semivariogram model generally results in higher estimated TOR elevations than the Gaussian model, as the mean, maximum and minimum TOR elevation are all greater for the exponential model than the Gaussian model. However, Kriging with the exponential semivariogram model still results in a lower mean, maximum and minimum TOR elevation than were actually observed during construction. This is also shown clearly in Figure 6.2 (reproduced here as Figure N.3), which compares 3D surfaces for TOR based on Kriging estimated values with the exponential semivariogram model and actual observed values. The figure clearly shows that Kriging not only tended to underestimate the actual TOR elevation, but also failed to capture the significant irregularity in TOR elevation across the site. The irregularity in TOR elevation is not unexpected given the limestone/dolomite bedrock underlying the site is known to be highly variable in other locations.

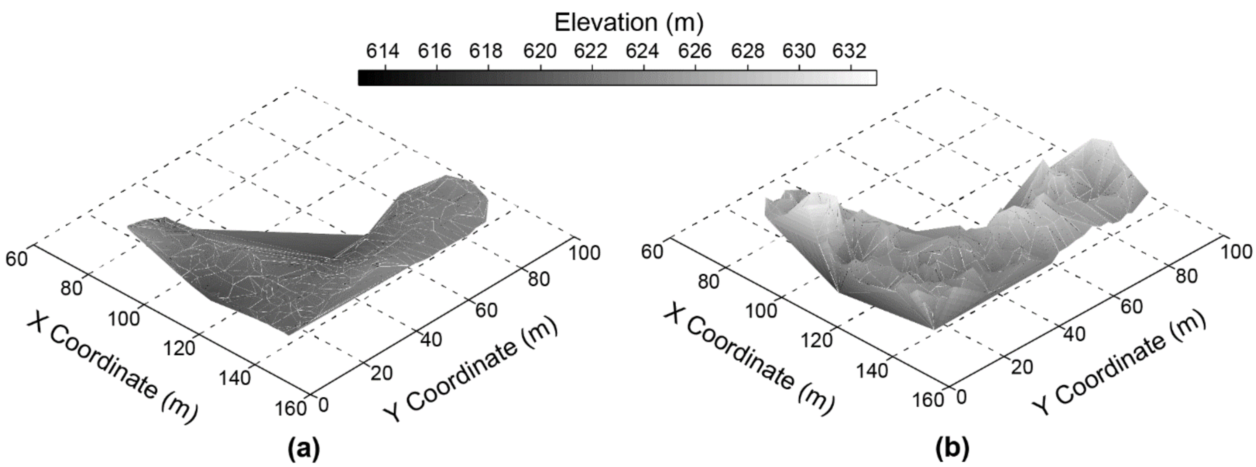

Figure N.3 Reproduction of Figure 6.2. (a) Estimated top of rock surface generated using boring data and Kriging with an exponential semivariogram fit. (b) Actual top of rock surface generated based on the top of rock elevation observed by the contractor at each column location during construction.

N.2.4 Conclusions

Since the Pearson Hall site is small, there are few input data values, and there is no input data within the building footprint, Kriging may not be an appropriate method for interpolating TOR elevation. This is especially the case given the scatter in the semivariogram and the potential lack of data at short enough separation distances to observe spatial correlation without significant nugget effect in the empirical semivariogram.

When Kriging is used to interpolate TOR elevation at Pearson Hall, the exponential semivariogram model is better than the Gaussian model because it shows an immediate increase in the semivariogram (decrease in correlation) with increasing separation distance. It makes sense that correlation would decrease rapidly with separation distance given the significant variability in the limestone/dolomite bedrock surface observed in other nearby locations. The conclusion that the exponential semivariogram model leads to a better estimate of TOR elevation than the Gaussian model for the Pearson Hall site is further supported by generally better agreement between the TOR elevations estimated by Kriging using the exponential semivariogram model and the observed TOR elevations during construction. Despite this, without initial input data with smaller separation distance, it is impossible to conclude with certainty which theoretical semivariogram model is the best fit for TOR elevation at Pearson Hall.

Kriging with the exponential model was used for the analysis presented in Ch. 6.

N.3 REFERENCES

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Appendix O: Comparison of Methods for Accounting for Subsurface Variability in SEEAM Analyses

This Appendix describes how the Monte Carlo simulation to determine total embodied energy and CO_2 emissions was conducted following the five different methods of accounting for subsurface variability, which are described in Ch. 6. In order to compare the methods of accounting for subsurface variability, each of the five methods was applied to the Pearson Hall case history project, which is described in Ch. 6 and Appendix L. The results from the Monte Carlo simulation for each method of accounting for subsurface variability are presented in this Appendix, and were compared using statistical methods to determine which one leads to the best estimates of actual embodied energy and CO_2 emissions.

At this time, the SEEAM Spreadsheet Calculator (Appendices A and B) cannot account for variable material quantities (as dictated by uncertainty in the key geotechnical parameter – see Ch. 6). Therefore, the Monte Carlo simulation to determine total embodied energy and CO_2 emissions with each method of accounting for subsurface variability was completed manually, following the SEEAM methodology.

O.1 GENERAL METHODS FOR ANALYSIS

O.1.1 Estimating Total Embodied Energy and CO_2 Emissions

In order to estimate total embodied energy and CO_2 emissions with varying subsurface conditions, a Microsoft Excel spreadsheet was developed with two worksheets for completing the calculations (henceforward called the *calculations workbook*). The first worksheet generated estimated values for the key geotechnical parameter. The second worksheet determined material quantities based on the values of the key geotechnical parameter, and then conducted a Monte Carlo simulation following the SEEAM methodology (see Ch. 4, Ch. 6 and Appendix K) for total embodied energy and CO_2 emissions. The embodied energy and CO_2 emissions coefficients were assumed to follow a lognormal distribution (see Ch. 6 and Appendices J and K). The Monte Carlo simulation generated simulated data sets consisting of n = 1,000 values each for total embodied energy and total CO_2 emissions. Note that the worksheet responsible for generating the values of the key geotechnical parameter in the *calculations workbook* must perform different procedures (i.e., be set up differently) depending on the method of accounting for subsurface variability being implemented (Methods 1 – 5; see Ch. 6).

Since Microsoft Excel automatically recalculates a workbook every time it is saved (regardless of whether or not it is set to automatic or manual calculation mode), in order to save a Monte Carlo realization for future reference, a separate Microsoft Excel workbook was made for the results (henceforward called the *results workbook*). The *results workbook* had a worksheet identical to the Monte Carlo simulation worksheet in the *calculations workbook*; the values from the Monte Carlo worksheet in the *calculations workbook* were copied and pasted into the blank worksheet in the *results workbook*. Only the values were pasted into the new workbook, not formulas or links to the *calculations workbook*. Following this step allowed a single Monte Carlo realization of n = 1,000 simulated values to be preserved for subsequent analysis in summarizing the results.

The *results workbook* also contained two other worksheets. One conducted calculations for generating plots of the distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation, and determined the 90% confidence intervals (CIs) for embodied energy and CO_2 emissions. The other simply presented the results of the Monte Carlo simulation in an identical table to those included on the results worksheet of the SEEAM Spreadsheet Calculator (Appendices A and B). The worksheet also contained pie graphs of the proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation, and plots of the empirical distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulated data set. The mean error shown in the table on the results worksheet was computed from the following equation (derived from information in Fenton and Griffiths (2008)):

$$\frac{t_{\frac{\alpha}{2},n-1}\frac{\hat{\sigma}_g}{\sqrt{n}}}{\hat{\mu}_g}(100\%) \tag{O.1}$$

where n is the number of values in the simulated data set (1,000 in this case), $\hat{\mu}_g$ and $\hat{\sigma}_g$ are the estimated mean and standard deviation of the simulated data set, t is the statistic from the t-distribution and α is the desired significance level. For 90% confidence, α = 0.1. Eq. O.1 assumes the results are approximately normally distributed (see Ch. 6 and Appendix K). This assumption was not applied when conducting statistical hypothesis testing. (Note: the computed mean error following Eq. O.1 is less than +/-2.5% for the analysis of all five methods of accounting for subsurface variability presented in this Appendix when n = 1,000 in the Monte Carlo simulated data set).

O.1.2 Comparing Methods of Accounting for Subsurface Variability with Statistical Inference

Since the actual distribution of the total embodied energy and CO_2 emissions is unknown, nonparametric statistical hypothesis testing was used with a significance level, α = 0.1 to evaluate differences between the embodied energy and CO_2 emissions estimates made using the SEEAM and Monte Carlo simulation with each of the five methods of accounting for subsurface variability (see Ch. 6 and Section O.4). Statistical hypothesis tests to detect differences between the methods of accounting for subsurface variability were conducted on the Monte Carlo simulated data sets using the null hypothesis that the different methods result in the same estimated total embodied energy and CO_2 emissions. The alternative hypothesis may be different depending on the type and goal of the test. The statistical tests were conducted by comparing the *p*-value generated by the test method to the significance level, *α*. See Ch. 6 for a definition of the *p*-value. When the *p*-value was less than *α*, the statistical test indicated there was significant evidence to suggest the null hypothesis was false and the alternative hypothesis was true. All statistical analyses were performed using the software package JMP Pro (SAS Institute 2013).

Statistical hypothesis testing was performed by first conducting the Kruskal-Wallis test (Kruskal and Wallis 1952), which is analogous to the parametric ANOVA test, using the Monte Carlo simulated data from each of the methods of accounting for subsurface variability. The alternative hypothesis for the Kruskal-Wallis test is that at least one of the methods results in a different estimated total embodied energy and CO_2 emissions. However, the Kruskal-Wallis test does not indicate which method results in a different estimate. Therefore, when the Kruskal-Wallis test detected differences, the nonparametric Steel-Dwass method was used to compare each method of accounting for subsurface variability in the EE and CO_2 emissions estimates to every other method. The Steel-Dwass method was originally proposed independently by Steel (1960) and Dwass (1960), and was further elaborated on by Critchlow and Fligner (1991). All methods were also compared to a Monte Carlo simulated data set for total embodied energy and CO_2 emissions that used the as-built quantities. The analysis with as-built quantities only involved variability in the embodied energy and CO_2 emissions coefficients. If the methods of accounting for subsurface variability result in good estimates of total embodied energy and CO_2 emissions, statistical hypothesis tests will conclude that the estimated total embodied energy and CO_2 emissions are not significantly different from the as-built embodied energy and CO_2 emissions.

O.2 CASE HISTORY FOR ANALYSIS

As mentioned in the opening paragraph of this Appendix, the case history project used for comparing the five methods of accounting for subsurface variability is the construction of rammed aggregate columns at Pearson Hall on the Virginia Tech campus. Additional details about this case history are included in Ch. 6 and Appendix L. In this case, the top of rock (TOR) elevation is the key geotechnical parameter, as the design calls for the cement treated aggregate (CTA) columns to extend to bedrock. Therefore, depending on the elevation of bedrock, the length of the CTA columns varies; length dictates how much material is required to complete a column. The lengths of untreated aggregate (UA) columns were specified in the design; the UA columns did not extend to bedrock. Therefore, when estimating total embodied energy and CO_2 emissions there is no variability in the length of these columns. Thus, it was assumed there is no variability in the material quantities for the UA columns.

Additional details that are important to this analysis include: 1) the average working pad elevation for installation of the rammed aggregate columns is 2,089 ft, and 2) the top portion of all of the CTA columns is filled with an average of 5.5 ft of UA. The purpose of the UA at the top of each CTA column was to provide a break between the column and the building footings, and backfill the holes from the design top elevation for the CTA column up to the working pad elevation.

O.3 RESULTS FROM MONTE CARLO SIMULATION FOR EACH METHOD OF ACCOUNTING FOR SUBSURFACE VARIABILITY

O.3.1 Method 1

Method 1 involved performing Kriging with data from the geotechnical test program in order to estimate the mean and standard deviation of TOR elevation at each CTA column location across the site. Kriging results are included in Appendix N. Figure O.1 shows the top section of the worksheet which generates values of TOR elevation (the key geotechnical parameter) at each CTA column location in the *calculations workbook*.

In this case, the Kriging generated mean and standard deviation at each CTA column location were assumed to define a normal distribution; the TOR elevation at each column location was generated from each normal distribution at each CTA column location by randomly generating a number between 0 and 1, and using it in the inverse cumulative distribution function for the normal distribution to determine a value for TOR elevation. CTA column length was determined by subtracting the generated TOR elevation from the working pad elevation at each CTA column location. The calculations were performed for all CTA column locations, and the total length of CTA columns was determined. This total length became the input for the Monte Carlo worksheet in the *calculations workbook*.

Pearson Hall - Rammed Aggregate Columns for Shallow Foundation Support									
Column Location Data			Kriging Results - TOR Elevation		Estimated (from Normal Dist)	Design			
Column No.	X coordinate (ft)	Y coordinate (ft)	Mean Estimate TOR Elevation (ft)	Standard Deviation (ft)	Top of Rock Elev. (ft)	Avg. Working Pad Elev. (ft)	Avg. Untreated Length CTA (ft)	CTA Length (ft)	UTA Length (ft)
1	462.4	235.0	2042.8	12.1	2027.3	2089.0	5.5	56.2	11.0
2	466.8	237.6	2043.2	11.9	2048.1	2089.0	5.5	35.4	13.0
3	471.2	235.0	2043.4	11.7	2041.4	2089.0	5.5	42.1	13.0
5	469.6	225.0	2043.4	12.1	2040.0	2089.0	5.5	43.5	8.0
6	462.6	218.9	2043.1	12.4	2009.8	2089.0	5.5	73.7	9.0
9	462.6	203.3	2042.2	12.6	2036.2	2089.0	5.5	47.3	8.0
12	490.0	171.0	2042.6	12.2	2059.2	2089.0	5.5	24.3	11.0
13	490.0	160.5	2042.4	11.7	2034.3	2089.0	5.5	49.2	11.0
14	511.6	136.5	2046.0	9.7	2065.6	2089.0	5.5	17.9	11.0
15	483.6	128.7	2042.5	9.7	2047.8	2089.0	5.5	35.7	11.0
16	493.0	128.7	2044.6	8.8	2048.0	2089.0	5.5	35.5	13.0
17	488.5	124.1	2044.0	8.9	2037.1	2089.0	5.5	46.4	13.0
18	483.6	119.5	2042.9	9.3	2052.0	2089.0	5.5	31.5	13.0
19	493.0	119.5	2045.4	7.7	2044.5	2089.0	5.5	39.0	13.0
20	456.3	114.8	2036.0	10.1	2047.3	2089.0	5.5	36.2	13.0
21	462.6	114.8	2037.6	10.2	2039.5	2089.0	5.5	44.0	13.0
22	456.3	106.5	2036.5	10.3	2064.0	2089.0	5.5	19.5	15.0
23	462.6	106.5	2037.9	10.4	2033.5	2089.0	5.5	50.0	15.0
24	456.3	98.2	2037.0	10.5	2037.0	2089.0	5.5	46.5	15.0
25	462.6	98.2	2038.1	10.5	2043.8	2089.0	5.5	39.7	9.0
26	483.6	94.1	2041.8	9.6	2041.8	2089.0	5.5	41.7	9.0
27	493.0	94.1	2043.2	8.9	2040.2	2089.0	5.5	43.3	14.0
28	488.5	88.9	2042.1	9.2	2049.7	2089.0	5.5	33.8	14.0
29	483.6	84.3	2041.0	9.6	2029.5	2089.0	5.5	54.0	11.0
30	493.0	84.3	2042.1	8.7	2035.0	2089.0	5.5	48.5	11.0
64	367.7	14.5	2036.3	10.0	2033.5	2089.0	5.5	50.0	16.0
65	377.1	14.5	2034.3	9.3	2019.0	2089.0	5.5	64.5	16.0
66	372.2	9.7	2034.8	9.5	2032.8	2089.0	5.5	50.7	16.0
67	367.7	4.8	2035.6	9.8	2045.5	2089.0	5.5	38.0	13.0
68	377.1	4.8	2033.0	8.8	2034.7	2089.0	5.5	48.8	13.0

Figure O.1 Using Method 1 to randomly generate top of rock elevation at each Cement Treated Aggregate Column location at Pearson Hall. Method 1 assumes the Kriging-estimated mean and standard deviation of top of rock elevation at each Cement Treated Aggregate Column location define a normal distribution for top of rock elevation at that location.

The Monte Carlo worksheet re-ran the analysis on the key parameter worksheet in order to generate a new total length of CTA columns for each of the 1,000 lines of subsequent calculations that follow the SEEAM method for computing total embodied energy and CO_2 emissions. The worksheet then computed total quantities of materials based on the quantities per unit length determined from construction data, presented in Ch. 6 and Appendix L. The worksheet randomly generated values of the embodied energy and CO_2 emissions coefficients for each line of calculations in the analysis by randomly generating a number between 0 and 1 and using it in the inverse lognormal cumulative distribution function to generate a coefficient value. The coefficient lognormal parameters were at the top of the worksheet. Figure O.2 shows the upper left portion of the Monte Carlo worksheet for the analysis of Method 1.

Pearson Hall Rammed Aggregate Columns for Shallow Foundation Support

Material Unit Quantities		
Material	Qty	Unit
Cement (in CTA)	15.85	kg/LF
Aggregate (in CTA)	380.4	kg/LF
Aggregate (in non-CTA)	428.3	kg/LF
Materials per Truck	16,375	kg/truck
Diesel (All Columns)	0.86	L/LF
Drill Spoil	0.18	CY/LF
Drill Spoil per Truck	12	CY
Truck Fuel Economy	2.42	km/L

Embodied Energy Coefficient Properties (MJ/unit)			
Material	Mean	St. Dev	Distribution
Cement (MJ/kg)	4.800	0.980	Lognormal
Aggregate (MJ/kg)	0.083	0.12	Lognormal
Diesel (MJ/L)	43.000	1.43	Lognormal
Cement (MJ/kg)	1.548	0.202	Normal
Aggregate (MJ/kg)	-3.053	1.062	Normal
Diesel (MJ/L)	3.761	0.033	Normal

CO_2 Emissions Coefficient Properties (kg CO_2/unit)			
Material	Mean	St. Dev	Distribution
Cement (kg/kg)	0.927	0.1050	Lognormal
Aggregate (kg/kg)	0.0048	0.0069	Lognormal
Diesel (kg/L)	3.248	0.1100	Lognormal
Cement (kg/kg)	-0.082	0.1129	Normal
Aggregate (kg/kg)	-5.899	1.0585	Normal
Diesel (kg/L)	1.177	0.0339	Normal

Note: All calculations performed assuming the embodied energy and CO_2 emissions coefficients are lognormally distributed in order to avoid negative values. Random numbers generated from the coefficient distribution for each total CTA column length.

TOTAL Estimated CTA Length (ft)	TOTAL Design UTA Length (ft)	Material Quantities: Cement (kg)	Material Quantities: Aggregate (in CTA) (kg)	Material Quantities: Aggregate (UTA) (kg)	Fuel Qty: Diesel (L)	Waste Qty: Waste CY	Transportation Quantities: CTA # Truckloads	CTA Distance (km)	UTA # Truckloads	UTA Distance (km)	Waste # Truckloads	Waste Distance (km)	Materials: Cement EE (MJ)	Cement CO_2 (kg)	Aggregate EE (MJ)	Aggregate CO_2 (kg)
14,148	2,287	224,264	5,382,339	979,452	14,182	2,958	343	8	60	8	247	16	1,169,135	168,896	139,146	15,869
14,192	2,287	224,960	5,399,031	979,452	14,220	2,966	344	8	60	8	248	16	1,105,020	178,457	263,478	88,059
14,500	2,287	229,842	5,516,201	979,452	14,485	3,022	351	8	60	8	252	16	1,171,757	194,943	431,203	18,497
13,855	2,287	219,625	5,271,001	979,452	13,929	2,906	336	8	60	8	243	16	1,083,001	211,689	117,749	6,107
14,283	2,287	226,408	5,433,784	979,452	14,298	2,983	346	8	60	8	249	16	1,037,594	220,179	315,023	3,790
14,335	2,287	227,231	5,453,543	979,452	14,343	2,992	347	8	60	8	250	16	1,232,313	197,240	266,248	37,566
14,060	2,287	222,866	5,348,773	979,452	14,106	2,942	341	8	60	8	246	16	1,067,748	205,035	288,030	20,369
14,327	2,287	227,099	5,450,373	979,452	14,336	2,991	347	8	60	8	250	16	917,209	194,230	142,311	12,720
14,286	2,287	226,455	5,434,929	979,452	14,301	2,983	346	8	60	8	249	16	1,385,297	188,867	163,898	29,157
13,986	2,287	221,689	5,320,525	979,452	14,042	2,929	339	8	60	8	245	16	1,235,988	228,487	2,971,213	9,487
13,966	2,287	221,380	5,313,113	979,452	14,025	2,926	338	8	60	8	244	16	1,230,403	206,506	188,004	35,992
14,376	2,287	227,871	5,468,900	979,452	14,378	2,999	348	8	60	8	250	16	1,130,415	226,613	144,480	5,911
14,253	2,287	225,925	5,422,198	979,452	14,272	2,977	345	8	60	8	249	16	815,987	220,701	52,101	24,162
14,522	2,287	230,186	5,524,465	979,452	14,504	3,026	352	8	60	8	253	16	1,224,086	228,033	127,897	44,888
14,088	2,287	223,316	5,359,590	979,452	14,130	2,948	341	8	60	8	246	16	744,457	266,501	493,914	22,214
14,104	2,287	223,570	5,365,674	979,452	14,144	2,950	342	8	60	8	246	16	1,262,865	204,684	117,177	14,704
14,389	2,287	228,077	5,473,845	979,452	14,389	3,002	349	8	60	8	251	16	890,600	204,410	217,348	30,949
14,496	2,287	229,782	5,514,779	979,452	14,482	3,021	351	8	60	8	252	16	1,184,587	255,901	1,224,200	5,118
14,487	2,287	229,634	5,511,223	979,452	14,474	3,019	351	8	60	8	252	16	1,231,496	260,725	111,964	2,059
14,430	2,287	228,740	5,489,752	979,452	14,425	3,009	350	8	60	8	251	16	1,373,217	239,522	1,550,320	8,586
14,116	2,287	223,759	5,370,228	979,452	14,154	2,953	342	8	60	8	247	16	1,211,186	223,380	162,386	8,486
14,382	2,287	227,970	5,471,288	979,452	14,383	3,000	349	8	60	8	251	16	1,153,596	234,710	718,038	71,824
14,573	2,287	231,007	5,544,164	979,452	14,549	3,035	353	8	60	8	253	16	1,014,598	241,976	374,543	39,772
14,167	2,287	224,557	5,389,362	979,452	14,198	2,962	343	8	60	8	247	16	1,059,362	223,099	215,856	2,958
14,270	2,287	226,204	5,428,893	979,452	14,287	2,980	346	8	60	8	249	16	819,662	180,870	142,977	38,529
14,386	2,287	228,031	5,472,733	979,452	14,387	3,001	349	8	60	8	251	16	893,065	219,175	163,924	16,980
14,109	2,287	223,642	5,367,401	979,452	14,148	2,951	342	8	60	8	246	16	1,156,775	221,150	63,213	9,186
14,305	2,287	226,747	5,441,922	979,452	14,317	2,987	347	8	60	8	249	16	1,577,620	161,591	390,735	1,951
14,397	2,287	228,212	5,477,079	979,452	14,397	3,003	349	8	60	8	251	16	1,657,878	225,014	1,445,387	13,713
14,110	2,287	223,658	5,367,787	979,452	14,149	2,951	342	8	60	8	246	16	1,181,385	185,742	357,277	11,072
13,973	2,287	221,486	5,315,675	979,452	14,031	2,927	339	8	60	8	244	16	783,235	251,934	1,827,566	41,212
14,194	2,287	224,998	5,399,959	979,452	14,222	2,967	344	8	60	8	248	16	1,055,728	244,112	305,244	13,774
14,444	2,287	228,960	5,495,030	979,452	14,437	3,012	350	8	60	8	251	16	1,197,371	229,285	1,638,126	54,999
14,383	2,287	227,989	5,471,729	979,452	14,384	3,001	349	8	60	8	251	16	1,292,858	202,688	49,192	42,819
14,048	2,287	222,674	5,344,177	979,452	14,095	2,940	340	8	60	8	246	16	1,135,723	184,134	520,179	35,603
13,877	2,287	219,970	5,279,285	979,452	13,948	2,910	336	8	60	8	243	16	965,018	183,018	116,778	2,063
14,174	2,287	224,683	5,392,391	979,452	14,205	2,963	344	8	60	8	247	16	1,321,311	200,987	38,428	8,423
14,134	2,287	224,047	5,377,120	979,452	14,170	2,956	343	8	60	8	247	16	1,176,460	225,743	509,714	20,405
14,400	2,287	228,265	5,478,351	979,452	14,400	3,004	349	8	60	8	251	16	1,414,918	192,197	90,382	20,085
13,917	2,287	220,608	5,294,585	979,452	13,983	2,917	337	8	60	8	244	16	1,120,362	208,942	1,849,377	108,253
14,453	2,287	229,098	5,498,349	979,452	14,445	3,013	350	8	60	8	252	16	1,289,542	182,214	893,496	36,043
14,254	2,287	225,938	5,422,505	979,452	14,273	2,977	345	8	60	8	249	16	1,186,960	183,164	434,729	6,128

Figure O.2 Monte Carlo Simulation worksheet for Method 1. The worksheet generates 1,000 discrete values of total embodied energy and CO_2 emissions for the Rammed Aggregate Columns at Pearson Hall.

Complete results of the Monte Carlo simulation for Method 1 are summarized in Table O.1. The proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for rammed aggregate columns at Pearson Hall following Method 1 of accounting for subsurface variability are shown in Figures O.3 and O.4, respectively. The distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation are shown in Figures O.5 and O.6, respectively. Vertical lines in Figures O.5 and O.6 represent the mean and the lower and upper bounds of the 90% CI (denoted as Lower CL and Upper CL, respectively). All of these were generated from one realization of the Monte Carlo simulation in the *calculations workbook*, as copied into the *results workbook*.

Table O.1 Results from Monte Carlo simulation for total embodied energy and CO_2 emissions for Rammed Aggregate Columns at Pearson Hall using Method 1 to account for subsurface variability.

	Embodied Energy (GJ)					**CO_2 Emissions (tonnes)**				
	Mean	**St Dev**	**Max.**	**Min.**	**% of Total**	**Mean**	**St Dev**	**Max.**	**Min.**	**% of Total**
Materials	1,610	770	8,876	513	65%	240	45	535	156	78%
Materials Transportation	116	4	130	104	5%	9	0	10	8	3%
Site Operations	614	21	688	551	25%	46	2	52	41	15%
Waste Transportation	142	5	159	127	6%	11	0	12	10	4%
TOTAL	**2,481**	**772**	**9,736**	**1,380**	**100%**	**306**	**45**	**603**	**222**	**100%**
% Mean Error, 90% Confidence 1,000 points (+/-)	**1.62**					**0.77**				

90% Confidence Interval (CI)		
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**
Lower Confidence Limit (CL) (5% < Value)	**1,811**	**252**
Mean	2,481	306
Upper Confidence Limit (CL) (95% < Value)	**3,718**	**382**

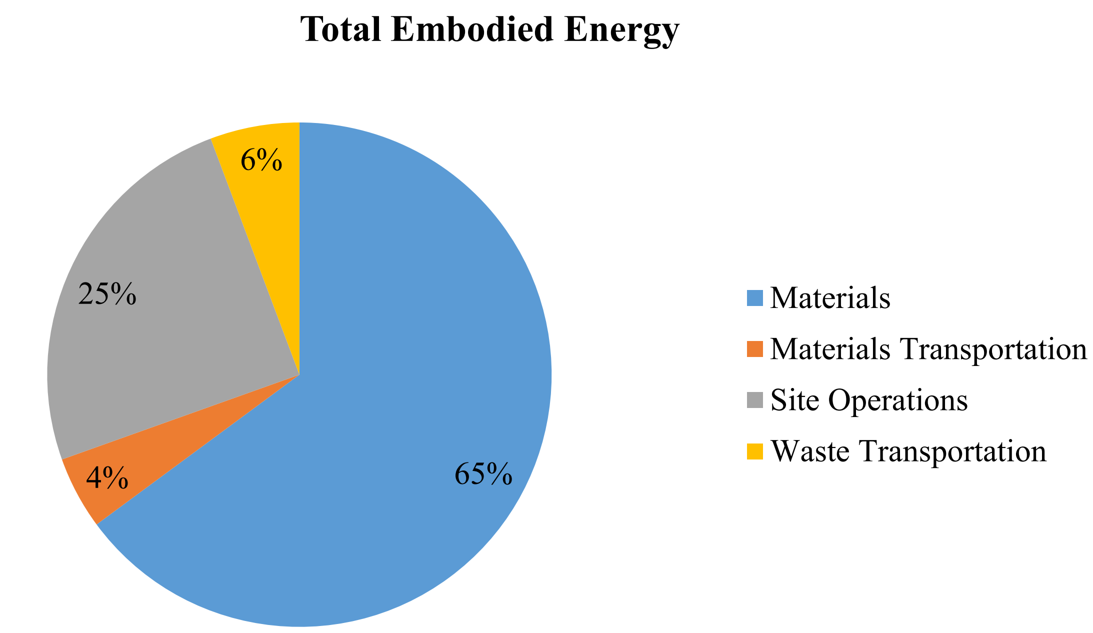


Figure O.3 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 1 of accounting for subsurface variability.

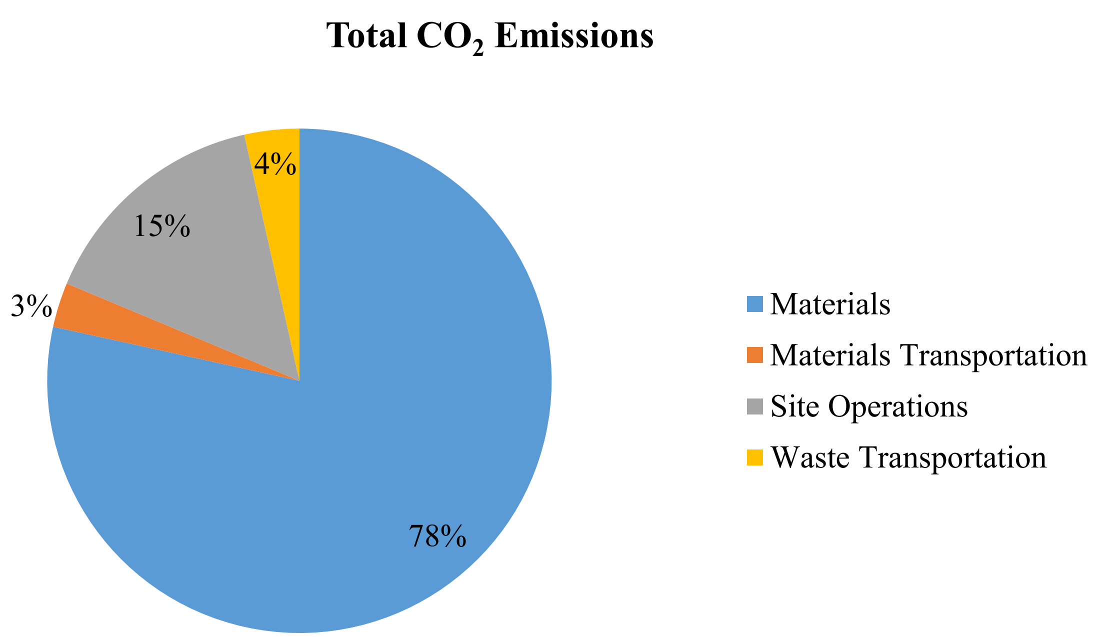


Figure O.4 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 1 of accounting for subsurface variability.

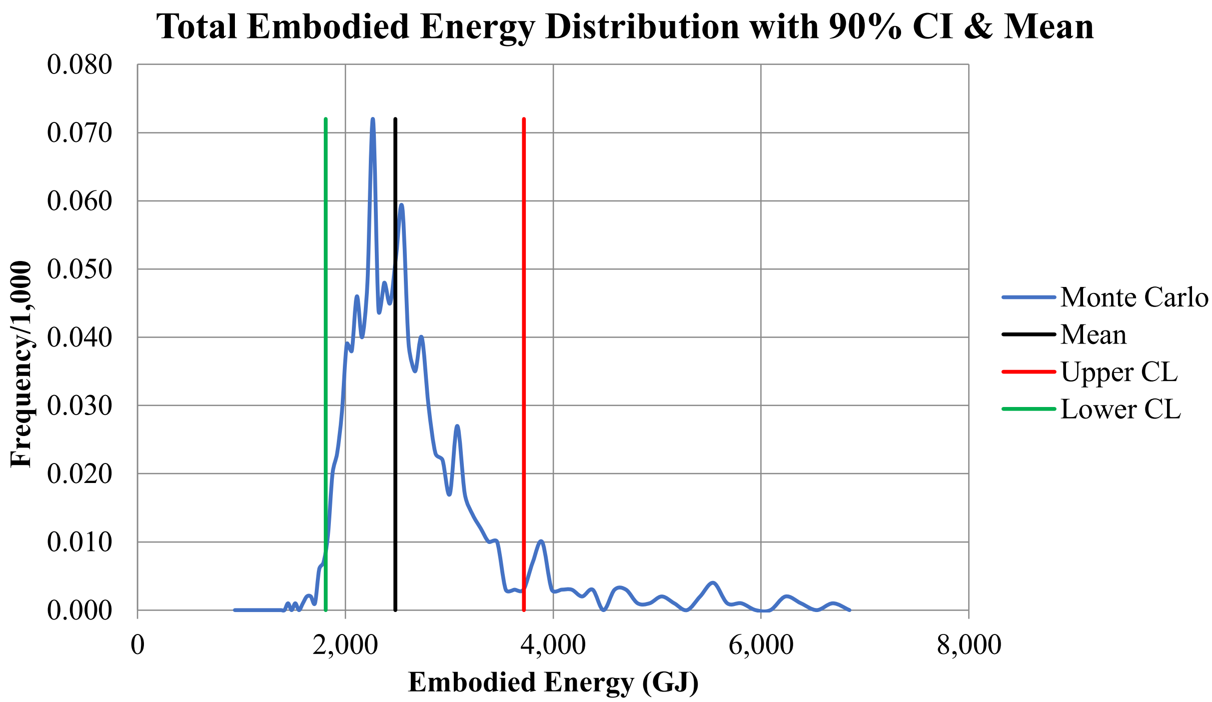


Figure O.5 Distribution of total embodied energy, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 1 of accounting for subsurface variability.

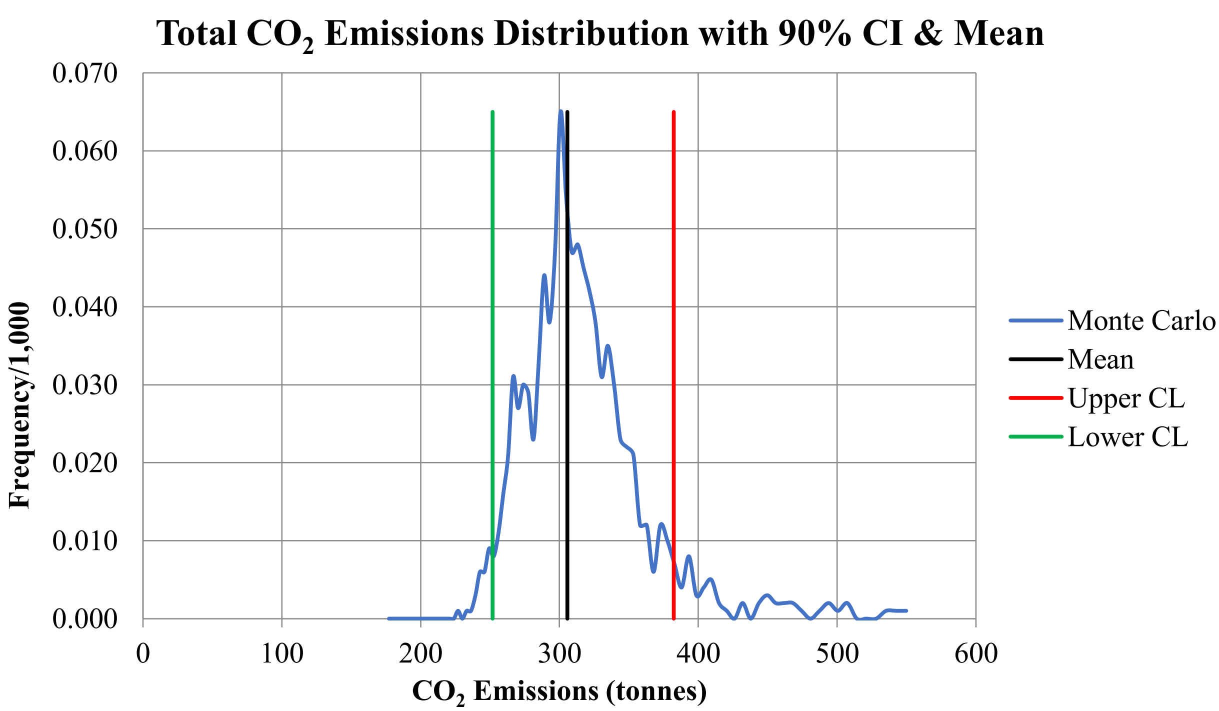


Figure O.6 Distribution of total CO_2 emissions, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 1 of accounting for subsurface variability.

O.3.2 Method 2

Method 2 involved performing Kriging with data from the geotechnical test program in order to estimate the TOR elevation at each CTA column location across the site. Kriging results are included in Appendix N. Figure O.7 shows the top section of the worksheet which generates values of TOR elevation (the key geotechnical parameter) at each CTA column location in the *calculations workbook*.

Unlike Method 1, which used the estimated mean and standard deviation from Kriging to define a normal distribution at each CTA column location, in this case, the mean and standard deviation of all the Kriging estimated TOR elevations (mean values) from all CTA column locations were determined and assumed to define a single normal distribution. Then, the TOR elevation at each column location was randomly generated from this normal distribution by randomly generating a number between 0 and 1, and using it in the inverse cumulative distribution function for the normal distribution to determine a value for TOR elevation. CTA column length was determined by subtracting the generated TOR elevation from the working pad elevation. The calculations were performed for all CTA column locations, and the total length of CTA columns was determined. This total length became the input for the Monte Carlo worksheet in the *calculations workbook*.

Pearson Hall - Rammed Aggregate Columns for Shallow Foundation Support									
Column Location Data			Kriging Results - TOR Elevation		Estimated (from Normal Dist)	Design			
Column No.	X coordinate (ft)	Y coordinate (ft)	Mean Estimate TOR Elevation (ft)	Standard Deviation (ft)	Top of Rock Elev. (ft)	Avg. Working Pad Elev. (ft)	Avg. Untreated Length CTA (ft)	CTA Length (ft)	UTA Length (ft)
1	462.4	235	2042.8	12.1	2040.1	2089.0	5.5	43.4	11.0
2	466.8	237.6	2043.2	11.9	2043.0	2089.0	5.5	40.5	13.0
3	471.2	235	2043.4	11.7	2041.0	2089.0	5.5	42.5	13.0
5	469.6	225	2043.4	12.1	2040.9	2089.0	5.5	42.6	8.0
6	462.6	218.9	2043.1	12.4	2037.0	2089.0	5.5	46.5	9.0
9	462.6	203.3	2042.2	12.6	2042.1	2089.0	5.5	41.4	8.0
12	490	171	2042.6	12.2	2034.8	2089.0	5.5	48.7	11.0
13	490	160.5	2042.4	11.7	2040.0	2089.0	5.5	43.5	11.0
14	511.6	136.5	2046.0	9.7	2043.5	2089.0	5.5	40.0	11.0
15	483.6	128.7	2042.5	9.7	2035.8	2089.0	5.5	47.7	11.0
16	493	128.7	2044.6	8.8	2039.1	2089.0	5.5	44.4	13.0
17	488.5	124.1	2044.0	8.9	2041.0	2089.0	5.5	42.5	13.0
18	483.6	119.5	2042.9	9.3	2040.0	2089.0	5.5	43.5	13.0
19	493	119.5	2045.4	7.7	2039.1	2089.0	5.5	44.4	13.0
20	456.3	114.8	2036.0	10.1	2045.8	2089.0	5.5	37.7	13.0
21	462.6	114.8	2037.6	10.2	2041.3	2089.0	5.5	42.2	13.0
22	456.3	106.5	2036.5	10.3	2032.0	2089.0	5.5	51.5	15.0
23	462.6	106.5	2037.9	10.4	2034.7	2089.0	5.5	48.8	15.0
24	456.3	98.2	2037.0	10.5	2034.4	2089.0	5.5	49.1	15.0
25	462.6	98.2	2038.1	10.5	2035.1	2089.0	5.5	48.4	9.0
26	483.6	94.1	2041.8	9.6	2041.1	2089.0	5.5	42.4	9.0
27	493	94.1	2043.2	8.9	2034.0	2089.0	5.5	49.5	14.0
28	488.5	88.9	2042.1	9.2	2040.8	2089.0	5.5	42.7	14.0
29	483.6	84.3	2041.0	9.6	2040.4	2089.0	5.5	43.1	11.0
30	493	84.3	2042.1	8.7	2030.2	2089.0	5.5	53.3	11.0
64	367.7	14.5	2036.3	10.0	2034.1	2089.0	5.5	49.4	16.0
65	377.1	14.5	2034.3	9.3	2030.8	2089.0	5.5	52.7	16.0
66	372.2	9.7	2034.8	9.5	2036.6	2089.0	5.5	46.9	16.0
67	367.7	4.84	2035.6	9.8	2041.2	2089.0	5.5	42.3	13.0
68	377.1	4.84	2033.0	8.8	2043.5	2089.0	5.5	40.0	13.0

Figure O.7 Using Method 2 to randomly generate top of rock elevation at each Cement Treated Aggregate Column location at Pearson Hall. Method 2 assumes top of rock elevation follows a normal distribution defined by the overall mean and standard deviation of top of rock elevations at Cement Treated Aggregate Column locations as estimated by Kriging.

The Monte Carlo worksheet re-ran the analysis on the key parameter worksheet in order to generate a new total length of CTA columns for each of the subsequent 1,000 lines of calculations that follow the SEEAM method for computing total embodied energy and CO_2 emissions. The worksheet then computed total quantities of materials based on the quantities per unit length determined from construction data, presented in Ch. 6 and Appendix L. The worksheet randomly generated values of the embodied energy and CO_2 emissions coefficients for each line of calculations in the analysis by randomly generating a number between 0 and 1 and using it in the inverse lognormal cumulative distribution function to generate a coefficient value. The coefficient lognormal parameters are at the top of the worksheet. Figure O.8 shows the upper left portion of the Monte Carlo worksheet for the analysis of Method 2.

Pearson Hall Rammed Aggregate Columns for Shallow Foundation Support

Material Unit Quantities

Material	Qty	Unit
Cement (in CTA)	15.85	kg/LF
Aggregate (in CTA)	380.4	kg/LF
Aggregate (in non-CTA)	428.3	kg/LF
Materials per Truck	16,375	kg/truck
Diesel (All Columns)	0.86	L/LF
Drill Spoil	0.18	CY/LF
Drill Spoil per Truck	12	CY
Truck Fuel Economy	2.42	km/L

Embodied Energy Coefficient Properties (MJ/unit)

Material	Mean	St. Dev	Distribution
Cement (MJ/kg)	4.800	0.980	Lognormal
Aggregate (MJ/kg)	0.083	0.12	Lognormal
Diesel (MJ/L)	43.000	1.43	Lognormal
Cement (MJ/kg)	1.548	0.202	Normal
Aggregate (MJ/kg)	-3.053	1.062	Normal
Diesel (MJ/L)	3.761	0.033	Normal

CO_2 Emissions Coefficient Properties (kg CO_2/unit)

Material	Mean	St. Dev	Distribution
Cement (kg/kg)	0.927	0.1050	Lognormal
Aggregate (kg/kg)	0.0048	0.0069	Lognormal
Diesel (kg/L)	3.248	0.1100	Lognormal
Cement (kg/kg)	-0.082	0.1129	Normal
Aggregate (kg/kg)	-5.899	1.0585	Normal
Diesel (kg/L)	1.177	0.0339	Normal

Note: All calculations performed assuming the embodied energy and CO_2 emissions coefficients are lognormally distributed in order to avoid negative values. Random numbers generated from the coefficient distribution for each total CTA column length.

TOTAL Estimated CTA Length (ft)	TOTAL Design UTA Length (ft)	Material Quantities: Cement (kg)	Material Quantities: Aggregate (in CTA) (kg)	Material Quantities: Aggregate (UTA) (kg)	Fuel Qty: Diesel (L)	Waste Qty: Waste CY	Transportation Quantities: CTA # Truckloads	CTA Distance (km)	UTA # Truckloads	UTA Distance (km)	Waste # Truckloads	Waste Distance (km)	Materials: Cement EE (MJ)	Cement CO_2 (kg)	Aggregate EE (MJ)	Aggregate CO_2 (kg)
14,327	2,287	227,094	5,450,245	979,452	14,336	2,990	347	8	60	8	250	16	1,520,564	194,584	6,755,065	9,446
14,176	2,287	224,715	5,393,156	979,452	14,206	2,963	344	8	60	8	247	16	907,210	200,754	971,676	7,443
14,290	2,287	226,510	5,436,232	979,452	14,304	2,984	346	8	60	8	249	16	1,241,866	179,423	4,408,277	5,548
14,202	2,287	225,112	5,402,685	979,452	14,228	2,968	344	8	60	8	248	16	775,667	235,002	15,039	6,910
14,295	2,287	226,594	5,438,247	979,452	14,309	2,985	346	8	60	8	249	16	1,525,455	205,246	192,133	20,940
14,294	2,287	226,579	5,437,888	979,452	14,308	2,985	346	8	60	8	249	16	923,236	218,235	2,642,904	71,897
14,352	2,287	227,501	5,460,013	979,452	14,358	2,995	348	8	60	8	250	16	1,299,362	208,549	527,216	57,598
14,171	2,287	224,624	5,390,970	979,452	14,201	2,962	343	8	60	8	247	16	1,192,272	234,071	232,893	32,097
14,178	2,287	224,733	5,393,581	979,452	14,207	2,964	344	8	60	8	247	16	1,084,317	169,942	118,472	62,181
14,271	2,287	226,214	5,429,134	979,452	14,288	2,980	346	8	60	8	249	16	1,359,366	219,120	508,849	7,466
14,270	2,287	226,190	5,428,555	979,452	14,287	2,980	346	8	60	8	249	16	1,383,681	199,118	1,226,282	30,833
14,293	2,287	226,567	5,437,603	979,452	14,307	2,984	346	8	60	8	249	16	845,984	212,874	657,524	62,591
14,309	2,287	226,823	5,443,747	979,452	14,321	2,987	347	8	60	8	249	16	1,169,842	229,329	495,781	10,761
14,345	2,287	227,385	5,457,245	979,452	14,352	2,994	348	8	60	8	250	16	809,498	232,138	113,337	15,035
14,201	2,287	225,108	5,402,591	979,452	14,228	2,968	344	8	60	8	248	16	1,019,213	188,721	280,164	42,692
14,167	2,287	224,565	5,389,563	979,452	14,198	2,962	343	8	60	8	247	16	1,352,442	238,005	85,860	32,930
14,364	2,287	227,690	5,464,557	979,452	14,368	2,997	348	8	60	8	250	16	1,289,994	215,244	164,234	10,481
14,272	2,287	226,232	5,429,578	979,452	14,289	2,981	346	8	60	8	249	16	759,603	223,719	950,991	3,252
14,297	2,287	226,624	5,438,972	979,452	14,310	2,985	346	8	60	8	249	16	1,037,091	213,675	599,761	7,995
14,197	2,287	225,033	5,400,783	979,452	14,224	2,967	344	8	60	8	248	16	1,181,129	210,744	65,608	39,682
14,235	2,287	225,642	5,415,419	979,452	14,257	2,974	345	8	60	8	248	16	1,592,266	196,705	2,121,381	10,352
14,277	2,287	226,308	5,431,398	979,452	14,293	2,982	346	8	60	8	249	16	1,080,951	207,997	518,901	23,133
14,275	2,287	226,280	5,430,709	979,452	14,291	2,981	346	8	60	8	249	16	1,015,154	214,577	1,410,762	107,878
14,130	2,287	223,983	5,375,601	979,452	14,166	2,955	342	8	60	8	247	16	788,511	202,042	61,723	32,260
14,220	2,287	225,404	5,409,704	979,452	14,244	2,971	345	8	60	8	248	16	1,309,921	202,337	421,268	123,114
14,244	2,287	225,786	5,418,857	979,452	14,265	2,976	345	8	60	8	248	16	1,223,927	211,681	132,776	14,083
14,300	2,287	226,666	5,439,978	979,452	14,312	2,986	347	8	60	8	249	16	847,910	204,856	175,708	2,116
14,206	2,287	225,190	5,404,568	979,452	14,232	2,969	344	8	60	8	248	16	1,039,620	194,648	145,162	49,975
14,233	2,287	225,604	5,414,506	979,452	14,255	2,974	345	8	60	8	248	16	945,871	254,394	264,706	2,455
14,270	2,287	226,191	5,428,578	979,452	14,287	2,980	346	8	60	8	249	16	1,182,189	234,613	299,616	19,814
14,159	2,287	224,436	5,386,471	979,452	14,191	2,960	343	8	60	8	247	16	1,130,897	230,241	134,059	19,532
14,280	2,287	226,357	5,432,573	979,452	14,296	2,982	346	8	60	8	249	16	1,183,288	248,681	309,523	8,861
14,179	2,287	224,753	5,394,072	979,452	14,208	2,964	344	8	60	8	247	16	919,711	169,991	407,567	2,425
14,212	2,287	225,284	5,406,818	979,452	14,237	2,970	344	8	60	8	248	16	1,137,936	207,931	371,762	9,411
14,239	2,287	225,709	5,417,015	979,452	14,260	2,975	345	8	60	8	248	16	996,941	221,168	537,212	10,134
14,262	2,287	226,068	5,425,627	979,452	14,280	2,979	346	8	60	8	249	16	1,279,124	157,141	333,023	83,464
14,281	2,287	226,371	5,432,906	979,452	14,296	2,982	346	8	60	8	249	16	814,003	230,920	708,914	5,099
14,241	2,287	225,737	5,417,695	979,452	14,262	2,975	345	8	60	8	248	16	966,398	229,299	1,799,284	9,670
14,160	2,287	224,459	5,387,028	979,452	14,192	2,961	343	8	60	8	247	16	755,973	212,469	138,715	6,135
14,267	2,287	226,147	5,427,538	979,452	14,284	2,980	346	8	60	8	249	16	1,466,667	215,736	558,782	41,065
14,321	2,287	227,007	5,448,168	979,452	14,331	2,989	347	8	60	8	250	16	1,492,801	231,312	122,482	9,358
14,350	2,287	227,467	5,459,210	979,452	14,356	2,995	348	8	60	8	250	16	747,508	234,176	151,774	16,338

Figure O.8 Monte Carlo Simulation worksheet for Method 2. The worksheet generates 1,000 discrete values of total embodied energy and CO_2 emissions for the Rammed Aggregate Columns at Pearson Hall.

Complete results of the Monte Carlo simulation for Method 2 are summarized in Table O.2. The proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for rammed aggregate columns at Pearson Hall following Method 2 of accounting for subsurface variability are shown in Figures O.9 and O.10, respectively. The distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation are shown in Figures O.11 and O.12, respectively. Vertical lines in Figures O.11 and O.12 represent the mean and the lower and upper bounds of the 90% CI (denoted as Lower CL and Upper CL, respectively). All of these were generated from one realization of the Monte Carlo simulation in the *calculations workbook*, as copied into the *results workbook*.

Table O.2 Results from Monte Carlo simulation for total embodied energy and CO_2 emissions for Rammed Aggregate Columns at Pearson Hall using Method 2 to account for subsurface variability.

	Embodied Energy (GJ)					**CO_2 Emissions (tonnes)**				
	Mean	**St Dev**	**Max.**	**Min.**	**% of Total**	**Mean**	**St Dev**	**Max.**	**Min.**	**% of Total**
Materials	1,625	700	10,062	718	65%	237	45	519	146	78%
Materials Transportation	116	4	129	104	5%	9	0	10	8	3%
Site Operations	613	21	685	554	25%	46	2	52	42	15%
Waste Transportation	142	5	159	128	6%	11	0	12	10	4%
TOTAL	**2,496**	**701**	**10,946**	**1,569**	**100%**	**303**	**46**	**581**	**214**	**100%**
% Mean Error, 90% Confidence, 1,000 points (+/-)	**1.46**					**0.78**				

90% Confidence Interval (CI)		
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**
Lower Confidence Limit (CL) (5% < Value)	**1,834**	**250**
Mean	2,496	303
Upper Confidence Limit (CL) (95% < Value)	**3,699**	**377**

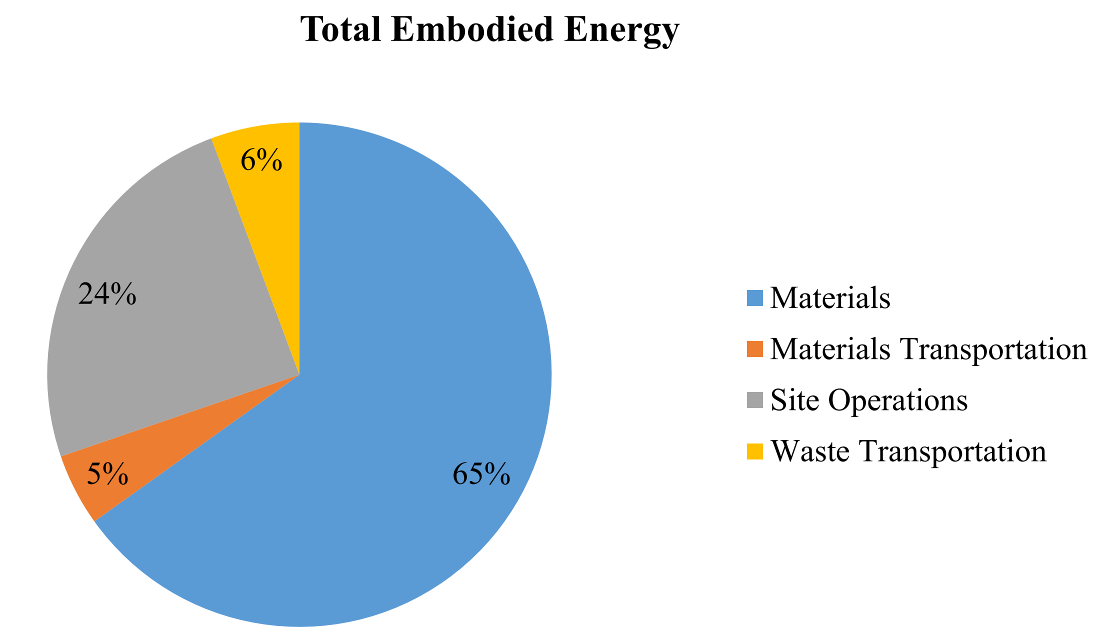


Figure O.9 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 2 of accounting for subsurface variability.

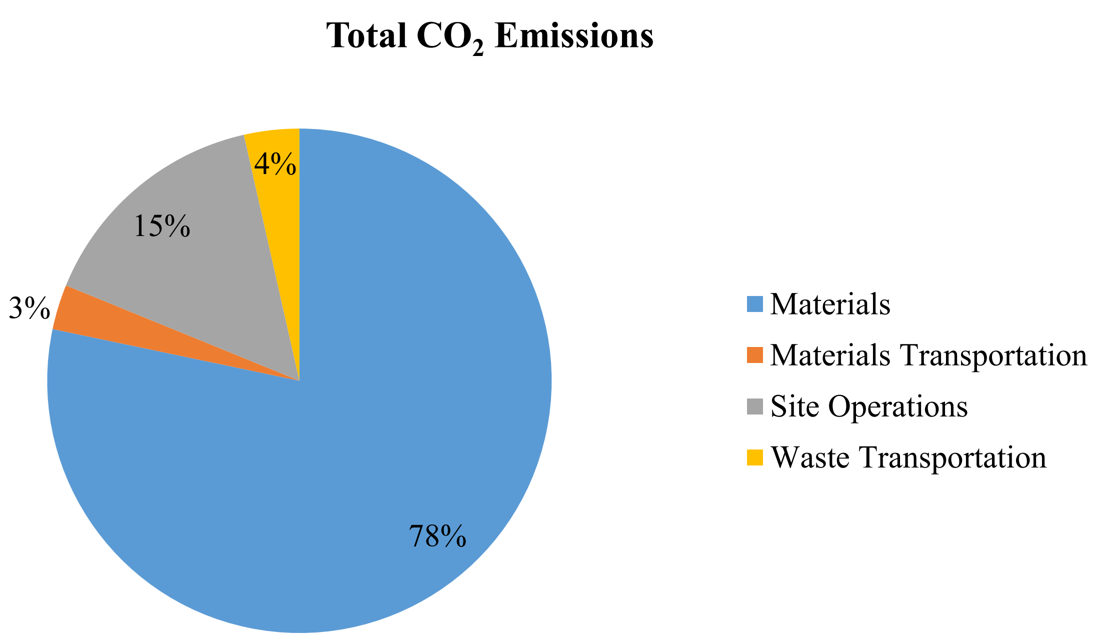


Figure O.10 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 2 of accounting for subsurface variability.

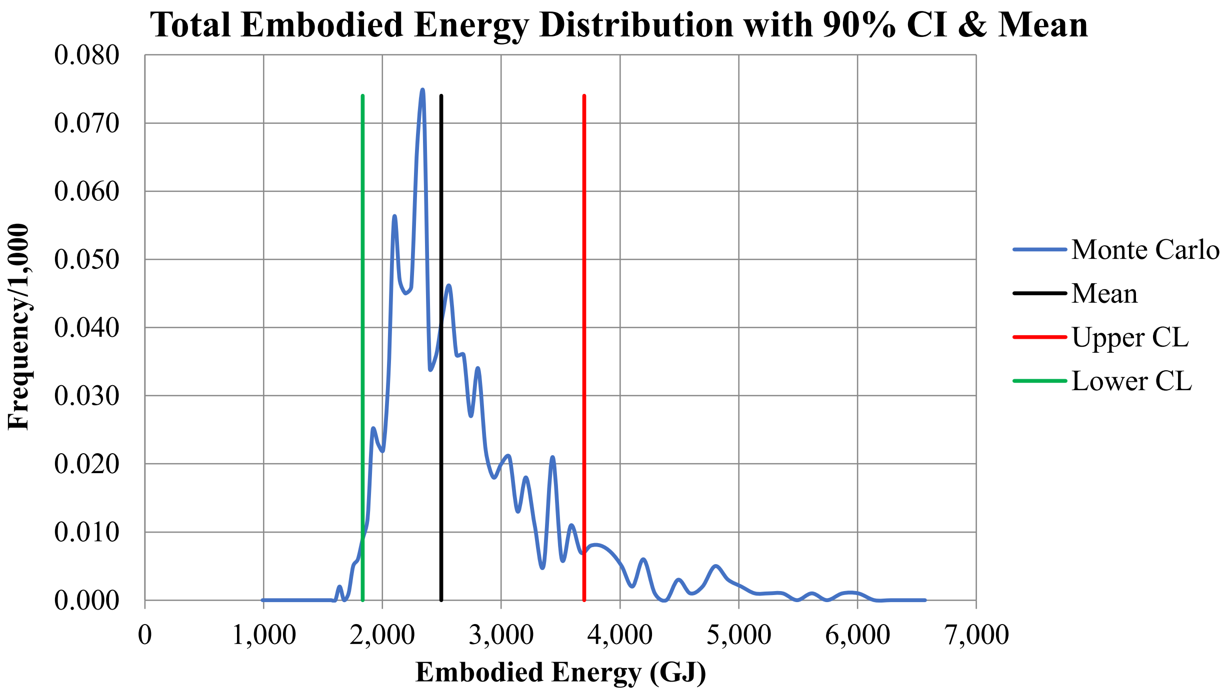


Figure O.11 Distribution of total embodied energy, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 2 of accounting for subsurface variability.

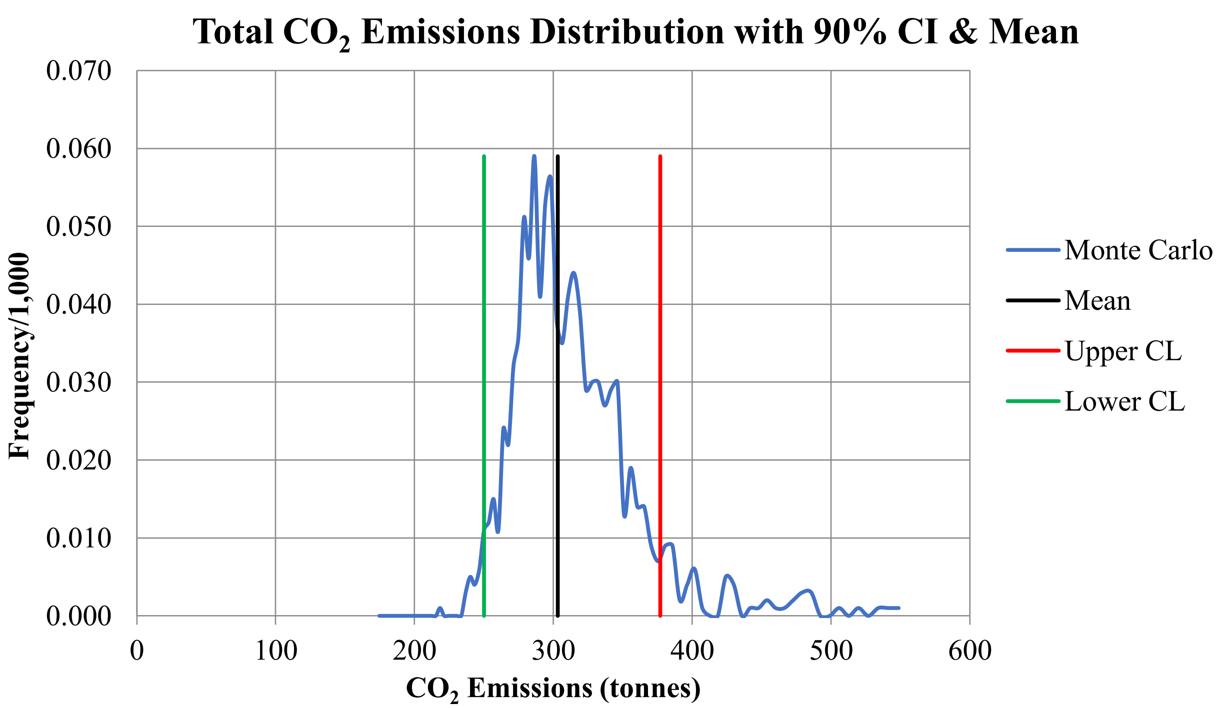


Figure O.12 Distribution of total CO_2 emissions, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 2 of accounting for subsurface variability.

O.3.3 Method 3

Method 3 involved determining the mean and standard deviation of TOR elevation as observed in the geotechnical test program. Unlike Methods 1 and 2, which used Kriging to estimate the TOR elevation across the site, this method simply relies on the assumption that the key parameter (TOR elevation) follows a normal distribution defined by the observed mean and standard deviation of the parameter values from the geotechnical investigation. The TOR elevation at each column location was randomly generated from this normal distribution by randomly generating a number between 0 and 1, and using it in the inverse cumulative distribution function for the normal distribution to determine a value for TOR elevation. CTA column length was determined by subtracting the generated TOR elevation from the working pad elevation. The calculations were performed for all CTA column locations, and the total length of CTA columns was determined. This total length became the input for the Monte Carlo worksheet in the *calculations workbook*. Figure O.13 shows the top section of the worksheet which generates values of TOR elevation (the key geotechnical parameter) at each CTA column location in the *calculations workbook*.

Pearson Hall - Rammed Aggregate Columns for Shallow Foundation Support

	Boring Data				Estimated (from Normal Dist)	Design			
	Boring No.	X coordinate (ft)	Y coordinate (ft)	TOR Elevation (ft)	Top of Rock Elev. (ft)	Avg. Working Pad Elev. (ft)	Avg. Untreated Length CTA (ft)	CTA Length (ft)	UTA Length (ft)
	B1	175.6	67.8	2053.5	2023.9	2089.0	5.5	59.6	11.0
	B2	98.1	77.2	2057.5	2035.3	2089.0	5.5	48.2	13.0
	B3	75.6	166.7	2073.0	2049.6	2089.0	5.5	33.9	13.0
	B4	95.9	245.9	2056.4	2044.2	2089.0	5.5	39.3	8.0
	B5	10.8	203.7	2048.0	2040.7	2089.0	5.5	42.8	9.0
	B6	21.4	84.9	2037.0	2030.0	2089.0	5.5	53.5	8.0
	B7	29.9	3.2	2059.0	2047.3	2089.0	5.5	36.2	11.0
	B8	127.4	3.2	2037.0	2043.0	2089.0	5.5	40.5	11.0
	B9	192.9	4.81	2027.0	2048.1	2089.0	5.5	35.4	11.0
	B10	501.1	263	2047.5	2038.5	2089.0	5.5	45.0	11.0
	B11	425.8	125.6	2026.4	2036.4	2089.0	5.5	47.1	13.0
	B12	388.2	70.8	2043.5	2059.4	2089.0	5.5	24.1	13.0
	B13	303	64.4	2035.0	2052.3	2089.0	5.5	31.2	13.0
	B14	312.4	1.44	2052.0	2055.1	2089.0	5.5	28.4	13.0
	B15	394.9	0.6	2027.0	2052.9	2089.0	5.5	30.6	13.0
	B16	505.5	2.2	2036.0	2050.9	2089.0	5.5	32.6	13.0
	B17	505.3	67.5	2041.0	2057.5	2089.0	5.5	26.0	15.0
	B18	505	116.2	2049.0	2059.3	2089.0	5.5	24.2	15.0
					2066.5	2089.0	5.5	17.0	15.0
Min				2026.4	2057.4	2089.0	5.5	26.1	9.0
Max				2073.0	2040.2	2089.0	5.5	43.3	9.0
Average				2044.8	2039.8	2089.0	5.5	43.7	14.0
Std Dev				12.693	2046.1	2089.0	5.5	37.4	14.0
					2044.2	2089.0	5.5	39.3	11.0

Figure O.13 Using Method 3 to randomly generate top of rock elevation at each Cement Treated Aggregate Column location at Pearson Hall. Method 3 assumes top of rock elevation follows a normal distribution defined by the mean and standard deviation of top of rock elevations observed in the geotechnical test borings.

The Monte Carlo worksheet re-ran the analysis on the key parameter worksheet in order to generate a new total length of CTA columns for each of the subsequent 1,000 lines of calculations that follow the SEEAM method for computing total embodied energy and CO_2 emissions. The worksheet then computed total quantities of materials based on the quantities per unit length determined from construction data, presented in Ch. 6 and Appendix L. The worksheet randomly generated values of the embodied energy and CO_2 emissions coefficients for each line of calculations in the analysis by randomly generating a number between 0 and 1 and using it in the inverse lognormal cumulative distribution function to generate a coefficient value. The coefficient lognormal parameters are at the top of the worksheet. Figure O.14 shows the upper left portion of the Monte Carlo worksheet for the analysis of Method 3.

Pearson Hall Rammed Aggregate Columns for Shallow Foundation Support

Material Unit Quantities

Material	Qty	Unit
Cement (in CTA)	15.85	kg/LF
Aggregate (in CTA)	380.4	kg/LF
Aggregate (in non-CTA)	428.3	kg/LF
Materials per Truck	16,375	kg/truck
Diesel (All Columns)	0.86	L/LF
Drill Spoil	0.18	CY/LF
Drill Spoil per Truck	12	CY
Truck Fuel Economy	2.42	km/L

Embodied Energy Coefficient Properties (MJ/unit)

Material	Mean	St. Dev	Distribution
Cement (MJ/kg)	4.800	0.980	Lognormal
Aggregate (MJ/kg)	0.083	0.12	Lognormal
Diesel (MJ/L)	43.000	1.43	Lognormal
Cement (MJ/kg)	1.548	0.202	Normal
Aggregate (MJ/kg)	-3.053	1.062	Normal
Diesel (MJ/L)	3.761	0.033	Normal

CO_2 Emissions Coefficient Properties (kg CO_2/unit)

Material	Mean	St. Dev	Distribution
Cement (kg/kg)	0.927	0.1050	Lognormal
Aggregate (kg/kg)	0.0048	0.0069	Lognormal
Diesel (kg/L)	3.248	0.1100	Lognormal
Cement (kg/kg)	-0.082	0.1129	Normal
Aggregate (kg/kg)	-5.899	1.0585	Normal
Diesel (kg/L)	1.177	0.0339	Normal

Note: All calculations performed assuming the embodied energy and CO_2 emissions coefficients are lognormally distributed in order to avoid negative values. Random numbers generated from the coefficient distribution for each total CTA column length.

TOTAL Estimated CTA Length (ft)	TOTAL Design UTA Length (ft)	Material Quantities: Cement (kg)	Material Quantities: Aggregate (in CTA) (kg)	Material Quantities: Aggregate (UTA) (kg)	Fuel Qty: Diesel (L)	Waste Qty: Waste CY	Transportation Quantities: CTA # Truckloads	CTA Distance (km)	UTA # Truckloads	UTA Distance (km)	Waste # Truckloads	Waste Distance (km)	Materials: Cement EE (MJ)	Cement CO_2 (kg)	Aggregate EE (MJ)	Aggregate CO_2 (kg)
12,070	2,287	191,317	4,591,609	979,452	12,388	2,584	293	8	60	8	216	16	988,867	180,070	288,850	22,103
12,646	2,287	200,457	4,810,967	979,452	12,886	2,688	307	8	60	8	224	16	688,902	183,486	436,446	23,191
12,598	2,287	199,695	4,792,679	979,452	12,844	2,679	305	8	60	8	224	16	963,712	214,878	457,267	20,701
12,653	2,287	200,573	4,813,751	979,452	12,892	2,689	307	8	60	8	225	16	937,389	195,184	113,035	754
12,198	2,287	193,359	4,640,608	979,452	12,499	2,607	296	8	60	8	218	16	1,391,024	184,447	140,934	1,652
12,504	2,287	198,199	4,756,776	979,452	12,763	2,662	303	8	60	8	222	16	1,051,025	231,632	1,082,222	5,563
12,564	2,287	199,149	4,779,583	979,452	12,815	2,673	305	8	60	8	223	16	1,147,237	145,740	236,144	38,131
12,747	2,287	202,053	4,849,271	979,452	12,973	2,706	309	8	60	8	226	16	778,941	173,761	557,210	5,570
12,299	2,287	194,952	4,678,845	979,452	12,586	2,625	298	8	60	8	219	16	1,134,354	198,761	1,040,457	10,601
12,651	2,287	200,540	4,812,966	979,452	12,890	2,689	307	8	60	8	225	16	1,412,350	178,383	4,177,938	14,655
12,148	2,287	192,554	4,621,304	979,452	12,456	2,598	294	8	60	8	217	16	862,938	187,693	679,934	2,723
12,165	2,287	192,826	4,627,822	979,452	12,470	2,601	295	8	60	8	217	16	985,951	190,159	118,523	14,372
12,718	2,287	201,589	4,838,137	979,452	12,947	2,701	308	8	60	8	226	16	901,941	168,728	255,045	21,723
12,606	2,287	199,819	4,795,661	979,452	12,851	2,681	306	8	60	8	224	16	851,391	202,237	236,094	32,750
12,383	2,287	196,290	4,710,958	979,452	12,659	2,641	300	8	60	8	221	16	996,820	195,616	994,213	5,813
12,330	2,287	195,444	4,690,665	979,452	12,613	2,631	299	8	60	8	220	16	797,154	219,899	222,402	3,753
12,352	2,287	195,793	4,699,025	979,452	12,632	2,635	299	8	60	8	220	16	966,497	197,938	319,295	7,328
12,385	2,287	196,311	4,711,475	979,452	12,660	2,641	300	8	60	8	221	16	1,154,259	155,106	1,783,981	2,624
12,499	2,287	198,119	4,754,857	979,452	12,758	2,661	303	8	60	8	222	16	1,037,756	190,037	80,482	22,859
12,405	2,287	196,632	4,719,175	979,452	12,678	2,645	301	8	60	8	221	16	1,156,862	213,754	569,280	11,066
12,118	2,287	192,080	4,609,927	979,452	12,430	2,593	294	8	60	8	217	16	610,480	205,822	1,692,857	7,790
12,495	2,287	198,066	4,753,594	979,452	12,756	2,661	303	8	60	8	222	16	1,230,117	198,797	637,342	14,942
12,559	2,287	199,080	4,777,919	979,452	12,811	2,672	304	8	60	8	223	16	753,674	174,436	366,126	3,319
12,431	2,287	197,039	4,728,931	979,452	12,700	2,649	301	8	60	8	221	16	890,083	179,295	150,282	9,835
12,658	2,287	200,637	4,815,287	979,452	12,896	2,690	307	8	60	8	225	16	1,005,304	160,483	1,461,462	17,660
12,345	2,287	195,685	4,696,447	979,452	12,626	2,634	299	8	60	8	220	16	1,041,322	199,651	320,019	11,806
12,249	2,287	194,163	4,659,910	979,452	12,543	2,616	297	8	60	8	219	16	775,098	148,543	108,974	14,566
12,757	2,287	202,210	4,853,051	979,452	12,981	2,708	309	8	60	8	226	16	966,387	173,662	235,877	49,146
12,592	2,287	199,596	4,790,299	979,452	12,839	2,678	305	8	60	8	224	16	910,666	198,287	456,310	19,844
12,342	2,287	195,640	4,695,370	979,452	12,624	2,633	299	8	60	8	220	16	1,032,598	162,428	70,696	33,412
12,101	2,287	191,815	4,603,564	979,452	12,415	2,590	293	8	60	8	216	16	800,366	155,160	167,714	37,494
12,494	2,287	198,046	4,753,093	979,452	12,754	2,661	303	8	60	8	222	16	792,710	182,339	299,820	2,060
12,671	2,287	200,845	4,820,280	979,452	12,907	2,692	307	8	60	8	225	16	1,096,000	162,305	315,094	5,202
12,188	2,287	193,191	4,636,575	979,452	12,490	2,605	295	8	60	8	218	16	711,387	177,409	323,780	9,363
12,284	2,287	194,720	4,673,292	979,452	12,573	2,623	298	8	60	8	219	16	867,099	189,510	227,613	2,210
12,402	2,287	196,581	4,717,953	979,452	12,675	2,644	301	8	60	8	221	16	1,034,960	161,859	293,494	10,057
12,825	2,287	203,292	4,879,003	979,452	13,040	2,720	311	8	60	8	227	16	983,597	173,201	212,133	40,524
12,478	2,287	197,792	4,747,019	979,452	12,741	2,658	302	8	60	8	222	16	960,689	175,259	352,982	41,435
12,421	2,287	196,891	4,725,382	979,452	12,692	2,647	301	8	60	8	221	16	781,003	155,738	1,366,455	11,321
12,813	2,287	203,103	4,874,462	979,452	13,030	2,718	311	8	60	8	227	16	815,580	203,737	857,759	27,513
12,806	2,287	202,989	4,871,729	979,452	13,024	2,717	310	8	60	8	227	16	1,058,723	144,037	373,979	53,060
12,357	2,287	195,866	4,700,777	979,452	12,636	2,636	300	8	60	8	220	16	1,152,473	179,382	40,526	8,205

Figure O.14 Monte Carlo Simulation worksheet for Method 3. The worksheet generates 1,000 discrete values of total embodied energy and CO_2 emissions for the Rammed Aggregate Columns at Pearson Hall.

Complete results of the Monte Carlo simulation for Method 3 are summarized in Table O.3. The proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for rammed aggregate columns at Pearson Hall following Method 3 of accounting for subsurface variability are shown in Figures O.15 and O.16, respectively. The distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation are shown in Figures O.17 and O.18, respectively. Vertical lines in Figures O.17 and O.18 represent the mean and the lower and upper bounds of the 90% CI (denoted as Lower CL and Upper CL, respectively). All of these were generated from one realization of the Monte Carlo simulation in the *calculations workbook*, as copied into the *results workbook*.

Table O.3 Results from Monte Carlo simulation for total embodied energy and CO_2 emissions for Rammed Aggregate Columns at Pearson Hall using Method 3 to account for subsurface variability.

	Embodied Energy (GJ)					**CO_2 Emissions (tonnes)**				
	Mean	**St Dev**	**Max.**	**Min.**	**% of Total**	**Mean**	**St Dev**	**Max.**	**Min.**	**% of Total**
Materials	1,428	688	8,183	577	65%	211	47	965	132	78%
Materials Transportation	103	4	116	90	5%	8	0	9	7	3%
Site Operations	548	20	615	477	25%	41	1	46	36	15%
Waste Transportation	127	5	142	110	6%	10	0	11	8	4%
TOTAL	**2,206**	**689**	**8,939**	**1,322**	**100%**	**270**	**47**	**1,024**	**189**	**100%**
% Mean Error, 90% Confidence, 1,000 points (+/-)	**1.63%**					**0.91%**				

90% Confidence Interval (CI)		
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**
Lower Confidence Limit (CL) (5% < Value)	**1,603**	**225**
Mean	2,206	270
Upper Confidence Limit (CL) (95% < Value)	**3,240**	**342**

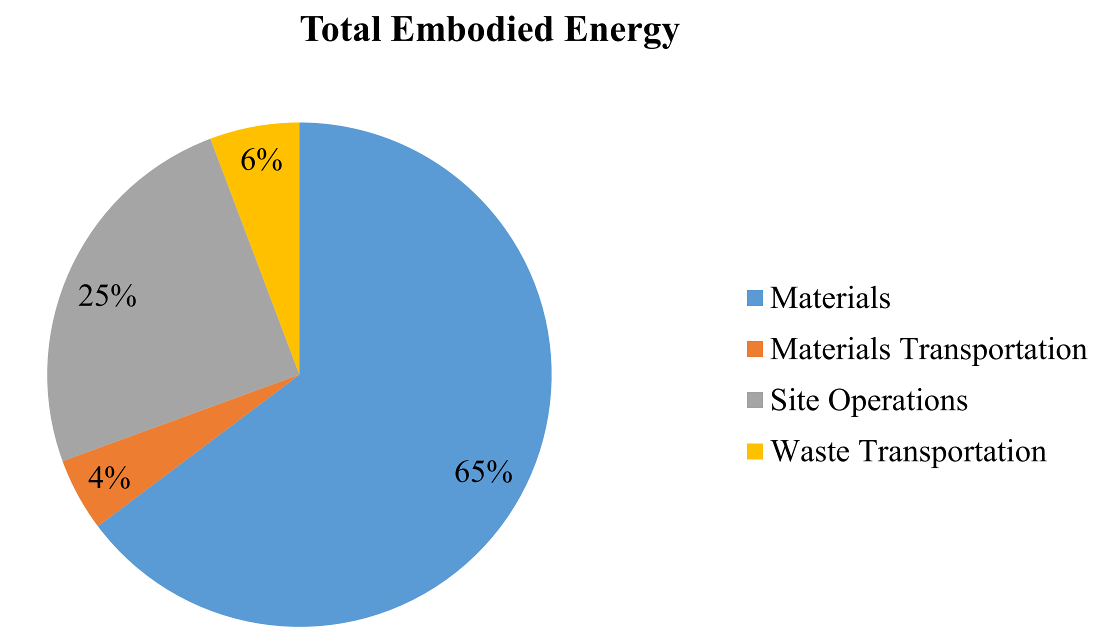


Figure O.15 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 3 of accounting for subsurface variability.

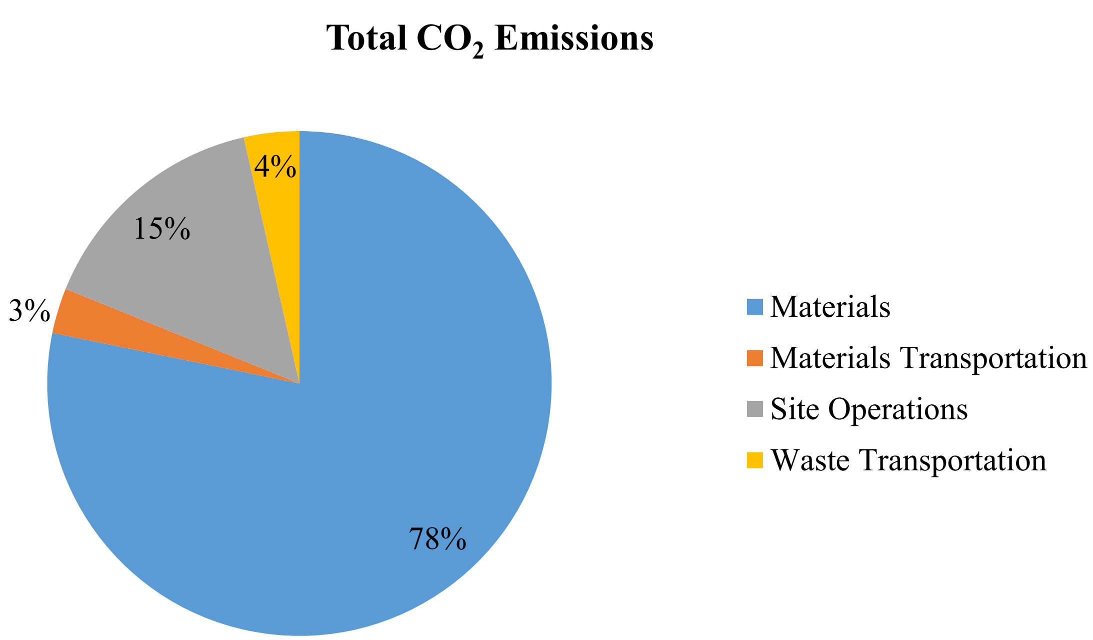


Figure O.16 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 3 of accounting for subsurface variability.

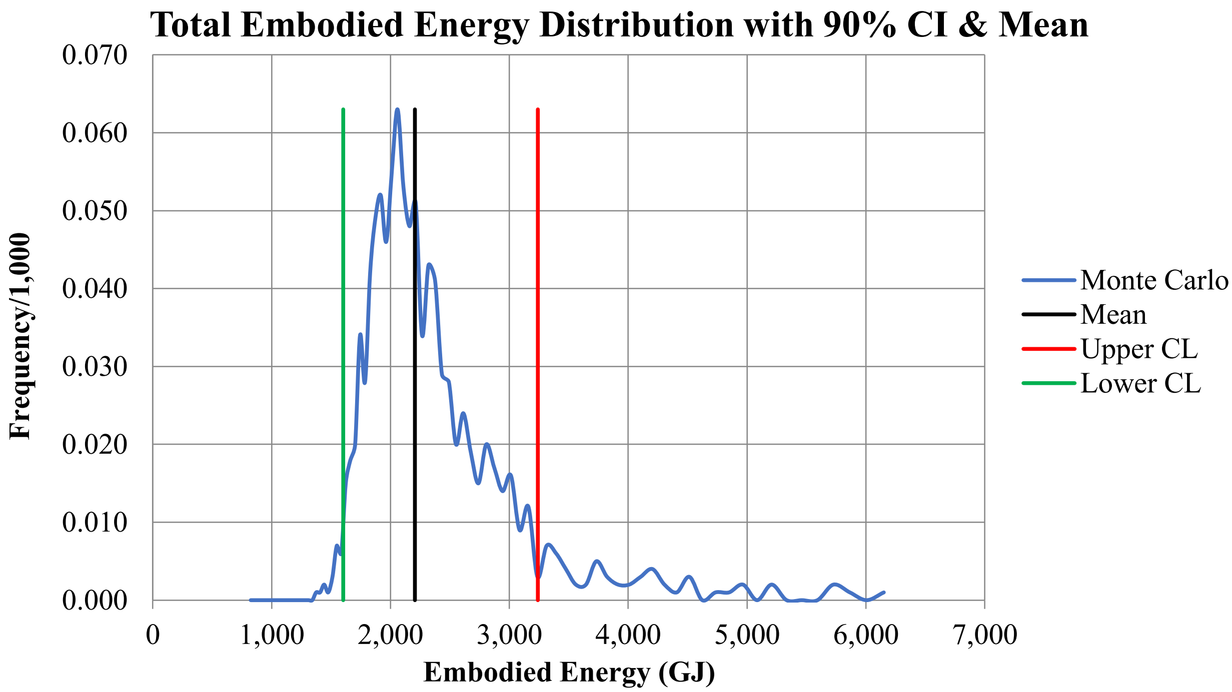


Figure O.17 Distribution of total embodied energy, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 3 of accounting for subsurface variability.

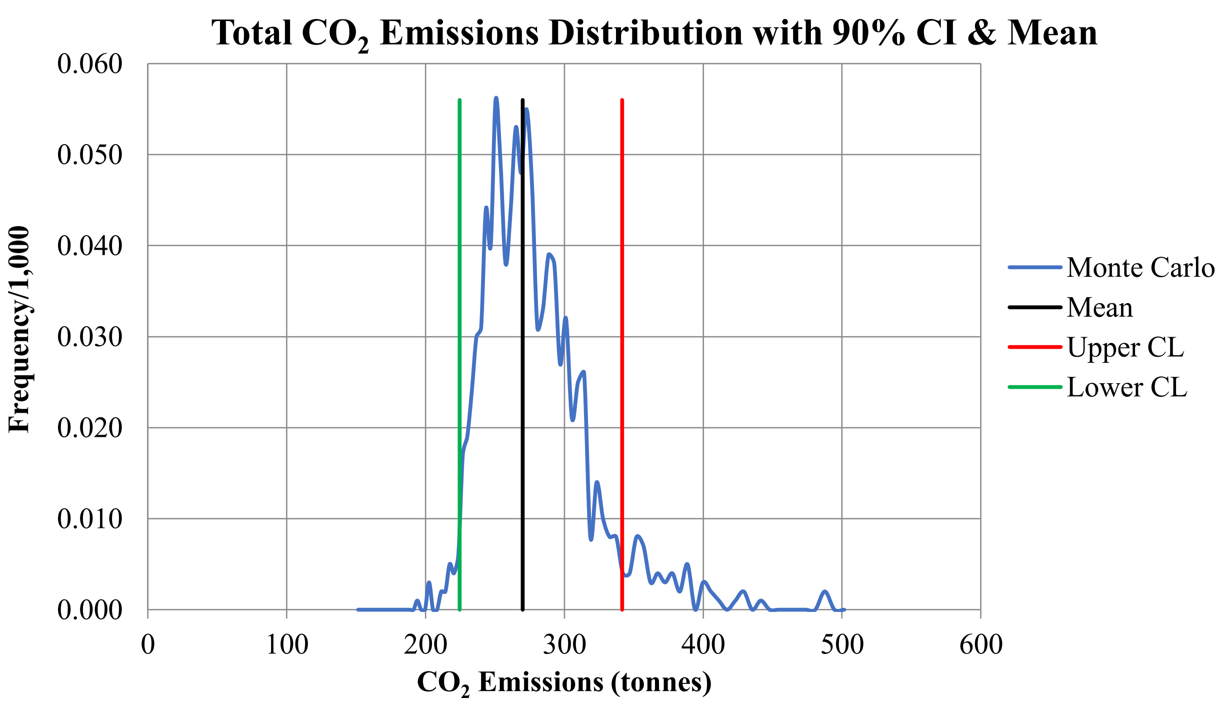


Figure O.18 Distribution of total CO_2 emissions, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 3 of accounting for subsurface variability.

O.3.4 Method 4

Method 4 involved plotting a histogram of values of the key parameter (TOR elevation) as observed in the geotechnical test program. Unlike Method 3, which assumes TOR elevation follows the normal distribution, this method involves fitting a theoretical distribution to the histogram of values of the key parameter as observed in the geotechnical investigation, and then determining the distribution parameters. For the Pearson Hall site, the histogram of TOR elevations from the geotechnical test borings is shown in Figure O.19. The best fit distribution to the histogram is the uniform distribution, bounded by the minimum (2026.4 ft) and maximum (2073.0 ft) TOR elevations observed.

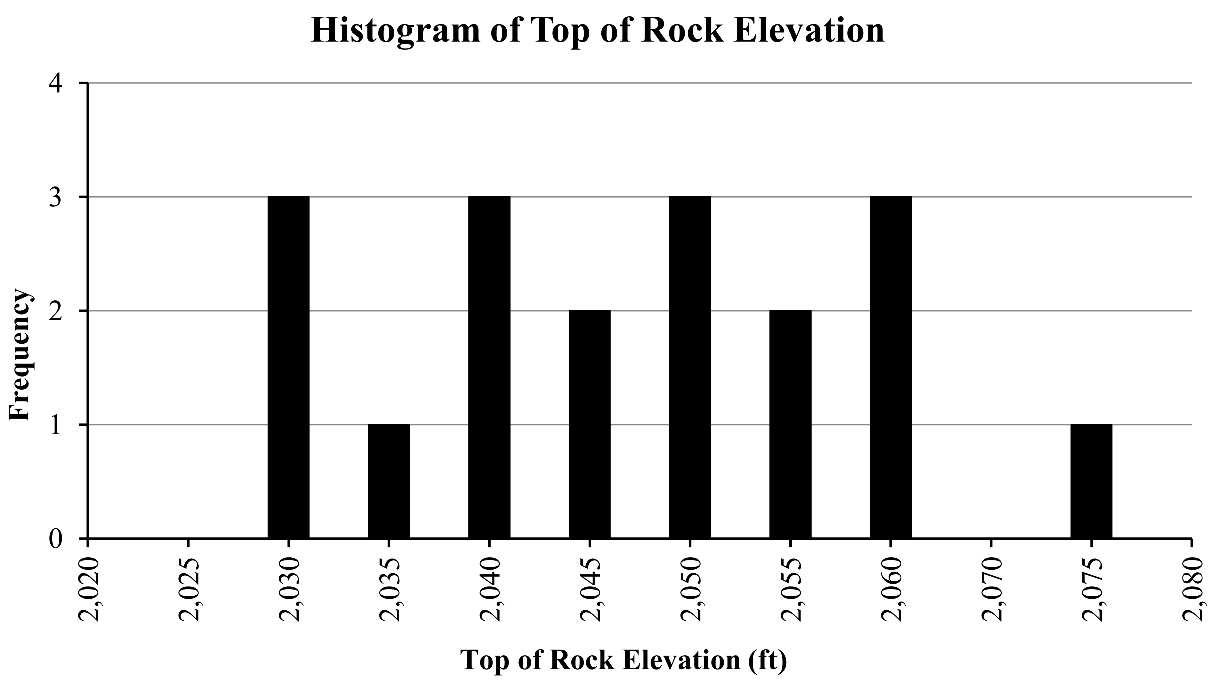


Figure O.19 Histogram of top of rock elevation as observed in 18 geotechnical borings around the Pearson Hall site.

The TOR elevation at each column location was randomly generated between the minimum and maximum values of TOR elevation observed in the test borings; these minimum and maximum observed TOR elevations define the uniform distribution. CTA column length was determined by subtracting the generated TOR elevation from the working pad elevation at each CTA column location. The calculations were performed for all CTA column locations, and the total length of CTA columns was determined. This total length became the input for the Monte Carlo worksheet in the *calculations workbook*. Figure O.20 shows the top section of the worksheet which generates values of TOR elevation (the key geotechnical parameter) at each CTA column location in the *calculations workbook*.

	Pearson Hall - Rammed Aggregate Columns for Shallow Foundation Support									
	Boring Data				Estimated (from Uniform Dist)	Design				
	Boring No.	X coordinate (ft)	Y coordinate (ft)	TOR Elevation (ft)	Top of Rock Elev. (ft)	Avg. Working Pad Elev. (ft)	Avg. Untreated Length CTA (ft)	CTA Length (ft)	UTA Length (ft)
	B1	175.6	67.8	2053.5	2046.0	2089.0	5.5	37.5	11.0
	B2	98.1	77.2	2057.5	2049.0	2089.0	5.5	34.5	13.0
	B3	75.6	166.7	2073.0	2042.0	2089.0	5.5	41.5	13.0
	B4	95.9	245.9	2056.4	2058.0	2089.0	5.5	25.5	8.0
	B5	10.8	203.7	2048.0	2060.0	2089.0	5.5	23.5	9.0
	B6	21.4	84.9	2037.0	2040.0	2089.0	5.5	43.5	8.0
	B7	29.9	3.2	2059.0	2041.0	2089.0	5.5	42.5	11.0
	B8	127.4	3.2	2037.0	2072.0	2089.0	5.5	11.5	11.0
	B9	192.9	4.81	2027.0	2068.0	2089.0	5.5	15.5	11.0
	B10	501.1	263	2047.5	2052.0	2089.0	5.5	31.5	11.0
	B11	425.8	125.6	2026.4	2040.0	2089.0	5.5	43.5	13.0
	B12	388.2	70.8	2043.5	2060.0	2089.0	5.5	23.5	13.0
	B13	303	64.4	2035.0	2050.0	2089.0	5.5	33.5	13.0
	B14	312.4	1.44	2052.0	2057.0	2089.0	5.5	26.5	13.0
	B15	394.9	0.6	2027.0	2032.0	2089.0	5.5	51.5	13.0
	B16	505.5	2.2	2036.0	2047.0	2089.0	5.5	36.5	13.0
	B17	505.3	67.5	2041.0	2054.0	2089.0	5.5	29.5	15.0
	B18	505	116.2	2049.0	2049.0	2089.0	5.5	34.5	15.0
					2034.0	2089.0	5.5	49.5	15.0
Min				2026.4	2050.0	2089.0	5.5	33.5	9.0
Max				2073.0	2069.0	2089.0	5.5	14.5	9.0
Average				2044.8	2041.0	2089.0	5.5	42.5	14.0
Std Dev				12.693	2042.0	2089.0	5.5	41.5	14.0
					2042.0	2089.0	5.5	41.5	11.0

Figure O.20 Using Method 4 to randomly generate top of rock elevation at each Cement Treated Aggregate Column location at Pearson Hall. Method 4 assumes top of rock elevation follows the best fit theoretical distribution to a histogram of top of rock elevations as observed in the geotechnical test borings.

The Monte Carlo worksheet re-ran the analysis on the key parameter worksheet in order to generate a new total length of CTA columns for each of the subsequent 1,000 lines of calculations that follow the SEEAM method for computing total embodied energy and CO_2 emissions. The worksheet then computed total quantities of materials based on the quantities per unit length determined from construction data, presented in Ch. 6 and Appendix L. The worksheet randomly generated values of the embodied energy and CO_2 emissions coefficients for each line of calculations in the analysis by randomly generating a number between 0 and 1 and using it in the inverse lognormal cumulative distribution function to generate a coefficient value. The coefficient lognormal parameters are at the top of the worksheet. Figure O.21 shows the upper left portion of the Monte Carlo worksheet for the analysis of Method 4.

Pearson Hall Rammed Aggregate Columns for Shallow Foundation Support

Material Unit Quantities

Material	Qty	Unit
Cement (in CTA)	15.85	kg/LF
Aggregate (in CTA)	380.4	kg/LF
Aggregate (in non-CTA)	428.3	kg/LF
Materials per Truck	16,375	kg/truck
Diesel (All Columns)	0.86	L/LF
Drill Spoil	0.18	CY/LF
Drill Spoil per Truck	12	CY
Truck Fuel Economy	2.42	km/L

Embodied Energy Coefficient Properties (MJ/unit)

Material	Mean	St. Dev	Distribution
Cement (MJ/kg)	4.800	0.980	Lognormal
Aggregate (MJ/kg)	0.083	0.12	Lognormal
Diesel (MJ/L)	43.000	1.43	Lognormal
Cement (MJ/kg)	1.548	0.202	Normal
Aggregate (MJ/kg)	-3.053	1.062	Normal
Diesel (MJ/L)	3.761	0.033	Normal

CO_2 Emissions Coefficient Properties (kg CO_2/unit)

Material	Mean	St. Dev	Distribution
Cement (kg/kg)	0.927	0.1050	Lognormal
Aggregate (kg/kg)	0.0048	0.0069	Lognormal
Diesel (kg/L)	3.248	0.1100	Lognormal
Cement (kg/kg)	-0.082	0.1129	Normal
Aggregate (kg/kg)	-5.899	1.0585	Normal
Diesel (kg/L)	1.177	0.0339	Normal

Note: All calculations performed assuming the embodied energy and CO_2 emissions coefficients are lognormally distributed in order to avoid negative values. Random numbers generated from the coefficient distribution for each total CTA column length.

TOTAL Estimated CTA Length (ft)	TOTAL Design UTA Length (ft)	Material Quantities: Cement (kg)	Aggregate (in CTA) (kg)	Aggregate (UTA) (kg)	Fuel Qty: Diesel (L)	Waste Qty: Waste CY	Transportation Quantities: CTA # Truckloads	CTA Distance (km)	UTA # Truckloads	UTA Distance (km)	Waste # Truckloads	Waste Distance (km)	Materials: Cement EE (MJ)	Cement CO_2 (kg)	Aggregate EE (MJ)	Aggregate CO_2 (kg)
10,117	2,287	160,367	3,848,805	979,452	10,703	2,233	245	8	60	8	187	16	839,657	160,526	429,324	51,892
10,550	2,287	167,230	4,013,531	979,452	11,077	2,311	256	8	60	8	193	16	693,387	170,752	25,143	215,409
10,786	2,287	170,971	4,103,312	979,452	11,281	2,353	262	8	60	8	197	16	1,361,569	180,193	56,006	3,889
11,010	2,287	174,522	4,188,528	979,452	11,474	2,393	267	8	60	8	200	16	791,878	153,963	276,391	4,591
10,687	2,287	169,402	4,065,650	979,452	11,195	2,335	259	8	60	8	195	16	849,683	137,236	240,981	9,644
11,092	2,287	175,822	4,219,724	979,452	11,545	2,408	269	8	60	8	201	16	637,067	172,123	812,914	5,998
10,647	2,287	168,768	4,050,432	979,452	11,161	2,328	258	8	60	8	195	16	786,346	179,666	1,243,479	9,154
10,727	2,287	170,036	4,080,867	979,452	11,230	2,343	260	8	60	8	196	16	939,589	180,088	216,518	12,886
11,026	2,287	174,776	4,194,615	979,452	11,488	2,396	267	8	60	8	200	16	783,018	137,597	709,257	19,392
10,905	2,287	172,858	4,148,583	979,452	11,383	2,375	264	8	60	8	198	16	966,105	170,363	375,079	91,863
10,641	2,287	168,673	4,048,150	979,452	11,156	2,327	258	8	60	8	194	16	782,838	130,346	40,531	5,445
10,486	2,287	166,216	3,989,183	979,452	11,022	2,299	254	8	60	8	192	16	429,618	152,917	121,673	10,992
10,957	2,287	173,682	4,168,366	979,452	11,428	2,384	266	8	60	8	199	16	1,352,704	132,589	138,883	26,139
10,758	2,287	170,528	4,092,660	979,452	11,256	2,348	261	8	60	8	196	16	714,512	133,832	5,825	10,652
10,905	2,287	172,858	4,148,583	979,452	11,383	2,375	264	8	60	8	198	16	831,305	168,496	1,047,245	17,642
10,805	2,287	171,273	4,110,540	979,452	11,297	2,357	262	8	60	8	197	16	685,655	152,170	49,531	4,372
10,713	2,287	169,814	4,075,541	979,452	11,218	2,340	260	8	60	8	195	16	788,783	143,650	207,161	18,524
10,628	2,287	168,467	4,043,204	979,452	11,144	2,325	258	8	60	8	194	16	782,364	144,495	236,683	6,952
10,858	2,287	172,113	4,130,703	979,452	11,343	2,366	263	8	60	8	198	16	741,792	175,280	304,637	130,112
11,067	2,287	175,426	4,210,213	979,452	11,523	2,404	268	8	60	8	201	16	798,789	181,536	733,910	23,086
10,927	2,287	173,206	4,156,953	979,452	11,402	2,379	265	8	60	8	199	16	740,911	186,077	294,982	31,437
10,669	2,287	169,117	4,058,802	979,452	11,180	2,332	259	8	60	8	195	16	1,159,450	178,750	223,242	29,782
10,746	2,287	170,337	4,088,095	979,452	11,246	2,346	261	8	60	8	196	16	817,121	179,869	1,123,910	9,148
11,019	2,287	174,665	4,191,952	979,452	11,482	2,395	267	8	60	8	200	16	650,144	175,677	190,547	9,972
10,710	2,287	169,767	4,074,400	979,452	11,215	2,339	260	8	60	8	195	16	711,146	176,595	265,404	8,167
10,778	2,287	170,845	4,100,269	979,452	11,274	2,352	261	8	60	8	196	16	767,063	161,386	44,049	19,263
11,317	2,287	179,388	4,305,320	979,452	11,739	2,449	274	8	60	8	205	16	829,618	130,617	241,144	10,432
10,636	2,287	168,594	4,046,248	979,452	11,151	2,326	258	8	60	8	194	16	823,580	151,447	378,056	7,250
10,901	2,287	172,794	4,147,062	979,452	11,380	2,374	264	8	60	8	198	16	631,314	184,253	1,057,869	13,255
10,849	2,287	171,970	4,127,279	979,452	11,335	2,364	263	8	60	8	198	16	767,951	159,546	981,451	26,355
10,971	2,287	173,904	4,173,692	979,452	11,440	2,386	266	8	60	8	199	16	827,705	161,488	325,220	83,538
10,749	2,287	170,385	4,089,236	979,452	11,249	2,346	261	8	60	8	196	16	919,582	146,013	616,167	18,584
10,352	2,287	164,092	3,938,206	979,452	10,906	2,275	251	8	60	8	190	16	1,316,537	129,226	919,411	15,815
11,042	2,287	175,029	4,200,702	979,452	11,502	2,399	268	8	60	8	200	16	942,932	151,040	216,582	50,677
10,550	2,287	167,230	4,013,531	979,452	11,077	2,311	256	8	60	8	193	16	902,340	138,619	180,433	6,148
10,884	2,287	172,525	4,140,594	979,452	11,365	2,371	264	8	60	8	198	16	763,775	201,819	82,557	2,928
11,087	2,287	175,743	4,217,821	979,452	11,540	2,407	269	8	60	8	201	16	1,082,828	166,157	529,553	25,432
10,636	2,287	168,594	4,046,248	979,452	11,151	2,326	258	8	60	8	194	16	697,410	134,689	190,505	27,042
10,998	2,287	174,332	4,183,963	979,452	11,464	2,391	267	8	60	8	200	16	775,819	147,776	335,382	23,145
11,172	2,287	177,090	4,250,158	979,452	11,614	2,423	271	8	60	8	202	16	889,364	137,520	143,852	12,325
10,621	2,287	168,356	4,040,541	979,452	11,138	2,323	258	8	60	8	194	16	932,091	160,562	62,736	14,597
10,782	2,287	170,908	4,101,790	979,452	11,277	2,352	261	8	60	8	197	16	1,021,821	167,994	65,716	1,530

Figure O.21 Monte Carlo Simulation worksheet for Method 4. The worksheet generates 1,000 discrete values of total embodied energy and CO_2 emissions for the Rammed Aggregate Columns at Pearson Hall.

Complete results of the Monte Carlo simulation for Method 4 are summarized in Table O.4. The proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for rammed aggregate columns at Pearson Hall following Method 4 of accounting for subsurface variability are shown in Figures O.22 and O.23, respectively. The distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation are shown in Figures O.24 and O.25, respectively. Vertical lines in Figures O.24 and O.25 represent the mean and the lower and upper bounds of the 90% CI (denoted as Lower CL and Upper CL, respectively). All of these were generated from one realization of the Monte Carlo simulation in the *calculations workbook*, as copied into the *results workbook*.

Table O.4 Results from Monte Carlo simulation for total embodied energy and CO_2 emissions for Rammed Aggregate Columns at Pearson Hall using Method 4 to account for subsurface variability.

	Embodied Energy (GJ)					**CO_2 Emissions (tonnes)**				
	Mean	**St Dev**	**Max.**	**Min.**	**% of Total**	**Mean**	**St Dev**	**Max.**	**Min.**	**% of Total**
Materials	1,240	622	9,452	489	64%	179	38	643	111	77%
Materials Transportation	92	3	103	83	5%	7	0	8	6	3%
Site Operations	485	18	545	435	25%	37	1	42	33	16%
Waste Transportation	112	4	126	101	6%	8	0	10	8	4%
TOTAL	**1,930**	**623**	**10,114**	**1,179**	**100%**	**232**	**38**	**695**	**164**	**100%**
% Mean Error, 90% Confidence, 1,000 points (+/-)	**1.68%**					**0.86%**				

90% Confidence Interval (CI)		
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**
Lower Confidence Limit (CL) (5% < Value)	**1,404**	**193**
Mean	1,930	232
Upper Confidence Limit (CL) (95% < Value)	**2,925**	**284**

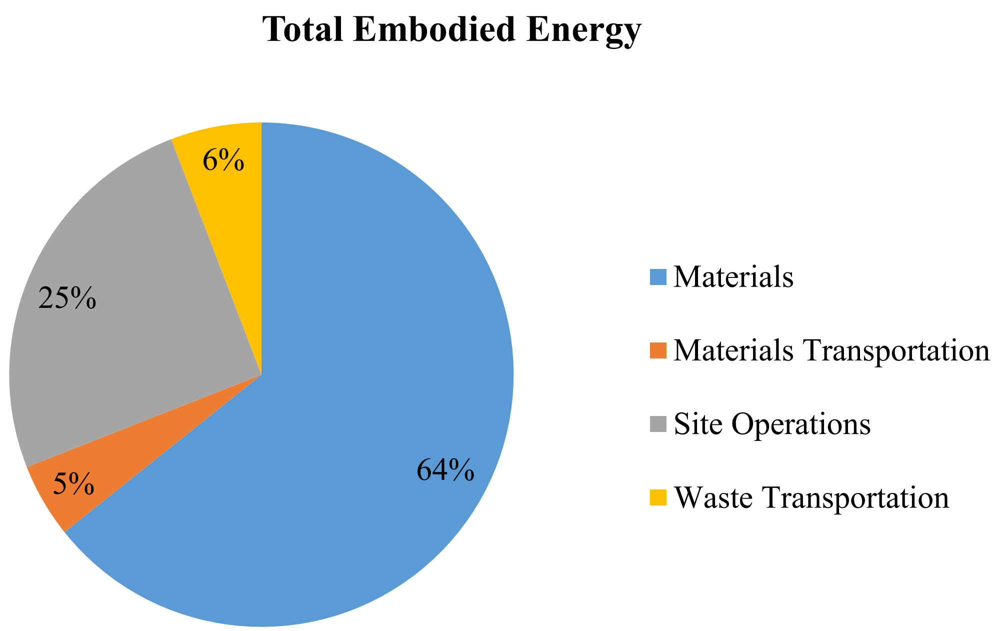


Figure O.22 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 4 of accounting for subsurface variability.

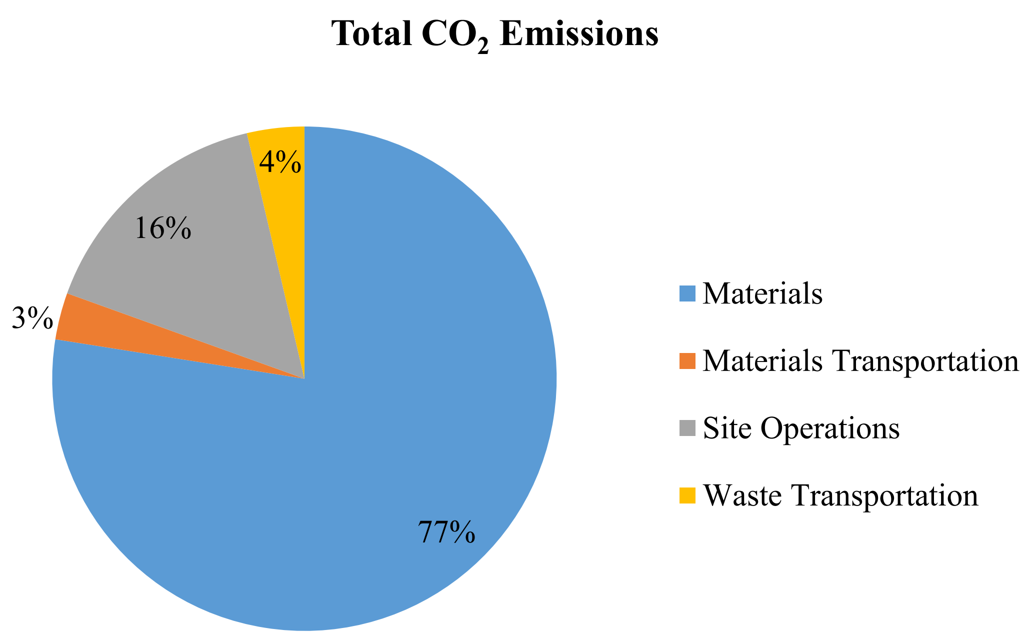


Figure O.23 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 4 of accounting for subsurface variability.

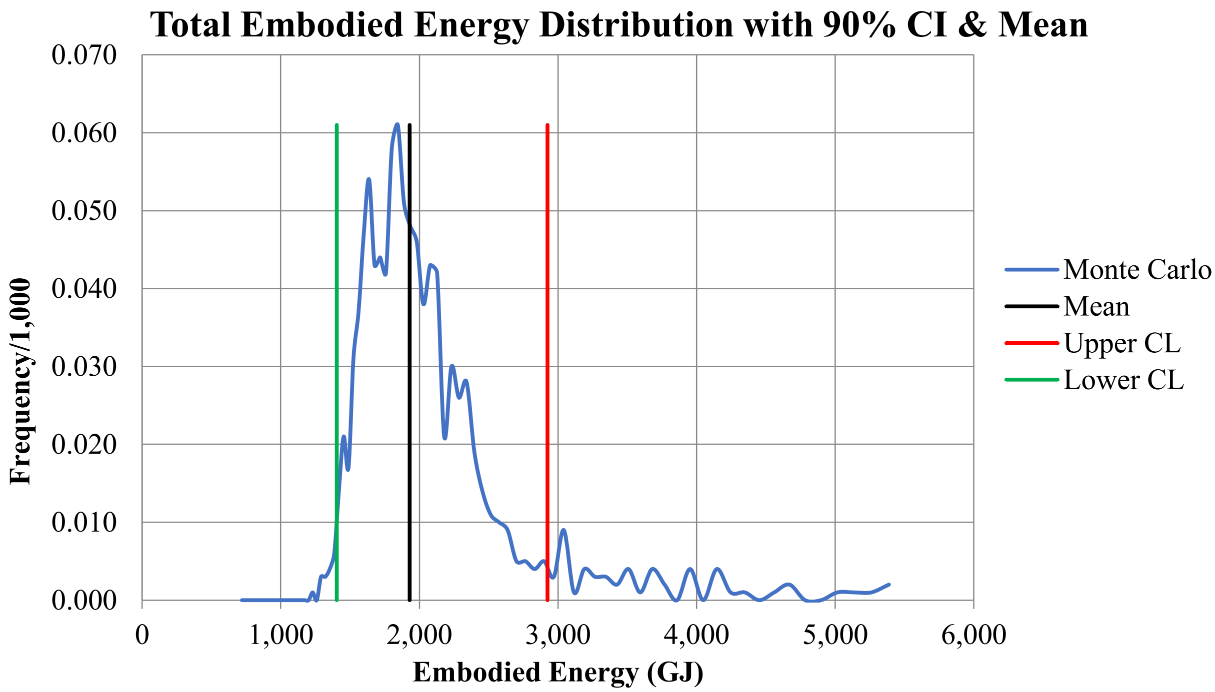


Figure O.24 Distribution of total embodied energy, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 4 of accounting for subsurface variability.

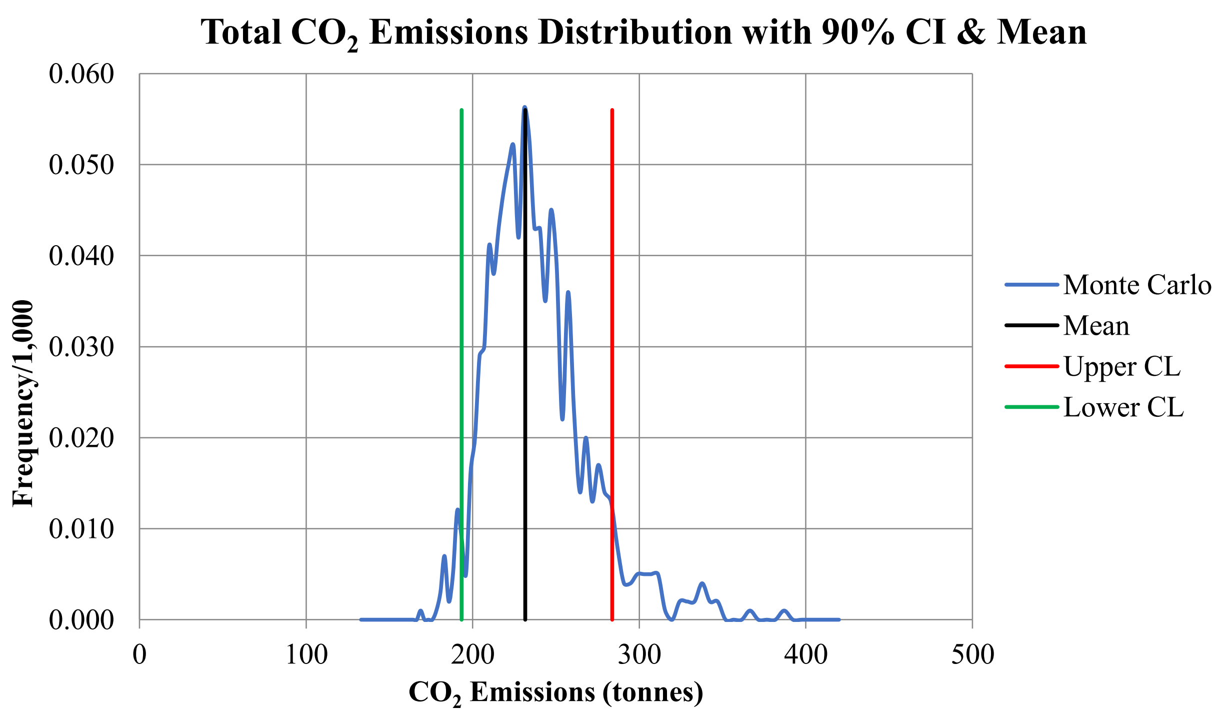


Figure O.25 Distribution of total CO_2 emissions, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 4 of accounting for subsurface variability.

O.3.5 Method 5

Method 5 involved determining the mean of TOR elevation as observed in the geotechnical test program. Unlike all other methods, which determine a unique estimated value of TOR elevation at each CTA column location across the site, this method relies on the assumption that on average, the key parameter (TOR elevation) across the site centers around the mean value of the parameter as determined from the geotechnical investigation. Therefore, the TOR elevation at each column location was assumed to be constant across the site at the mean value observed in the geotechnical investigation. The CTA column length was determined by subtracting the mean TOR elevation from the working pad elevation. The length of the column was multiplied by the number of columns to determine the total length of CTA columns. This total length became the input for the Monte Carlo worksheet in the *calculations workbook*. Figure O.26 shows the top section of the worksheet for TOR elevation at each CTA column location in the *calculations workbook*.

	Pearson Hall - Rammed Aggregate Columns for Shallow Foundation Support									
	Boring Data				Assumed at the Boring Mean	Design				
	Boring No.	X coordinate (ft)	Y coordinate (ft)	TOR Elevation (ft)	Top of Rock Elev. (ft)	Avg. Working Pad Elev. (ft)	Avg. Untreated Length CTA (ft)	CTA Length (ft)	UTA Length (ft)
	B1	175.6	67.8	2053.5	2044.8	2089.0	5.5	38.7	11.0
	B2	98.1	77.2	2057.5	2044.8	2089.0	5.5	38.7	13.0
	B3	75.6	166.7	2073.0	2044.8	2089.0	5.5	38.7	13.0
	B4	95.9	245.9	2056.4	2044.8	2089.0	5.5	38.7	8.0
	B5	10.8	203.7	2048.0	2044.8	2089.0	5.5	38.7	9.0
	B6	21.4	84.9	2037.0	2044.8	2089.0	5.5	38.7	8.0
	B7	29.9	3.2	2059.0	2044.8	2089.0	5.5	38.7	11.0
	B8	127.4	3.2	2037.0	2044.8	2089.0	5.5	38.7	11.0
	B9	192.9	4.81	2027.0	2044.8	2089.0	5.5	38.7	11.0
	B10	501.1	263	2047.5	2044.8	2089.0	5.5	38.7	11.0
	B11	425.8	125.6	2026.4	2044.8	2089.0	5.5	38.7	13.0
	B12	388.2	70.8	2043.5	2044.8	2089.0	5.5	38.7	13.0
	B13	303	64.4	2035.0	2044.8	2089.0	5.5	38.7	13.0
	B14	312.4	1.44	2052.0	2044.8	2089.0	5.5	38.7	13.0
	B15	394.9	0.6	2027.0	2044.8	2089.0	5.5	38.7	13.0
	B16	505.5	2.2	2036.0	2044.8	2089.0	5.5	38.7	13.0
	B17	505.3	67.5	2041.0	2044.8	2089.0	5.5	38.7	15.0
	B18	505	116.2	2049.0	2044.8	2089.0	5.5	38.7	15.0
					2044.8	2089.0	5.5	38.7	15.0
Min				2026.4	2044.8	2089.0	5.5	38.7	9.0
Max				2073.0	2044.8	2089.0	5.5	38.7	9.0
Average				2044.8	2044.8	2089.0	5.5	38.7	14.0
Std Dev				12.693	2044.8	2089.0	5.5	38.7	14.0
					2044.8	2089.0	5.5	38.7	11.0

Figure O.26 Using Method 5 to determine top of rock elevation at each Cement Treated Aggregate Column location at Pearson Hall. Method 5 assumes top of rock elevation at every Cement Treated Aggregate Column location is equal to the overall mean of top of rock elevation as observed in the geotechnical test borings.

Using the fixed total length of CTA columns, the Monte Carlo worksheet then computed total quantities of materials based on the quantities per unit length determined from construction data, presented in Ch. 6 and Appendix L. The Monte Carlo worksheet subsequently ran 1,000 lines of calculations following the SEEAM method for computing total embodied energy and CO_2 emissions. To account for coefficient uncertainty, the worksheet randomly generated values of the embodied energy and CO_2 emissions coefficients for each line of calculations in the analysis by randomly generating a number between 0 and 1 and using it in the inverse lognormal cumulative distribution function to generate a coefficient value. The coefficient lognormal parameters are at the top of the worksheet. Figure O.27 shows the upper left portion of the Monte Carlo worksheet for the analysis of Method 5.

Pearson Hall Rammed Aggregate Columns for Shallow Foundation Support

Material Unit Quantities

Material	Qty	Unit
Cement (in CTA)	15.85	kg/LF
Aggregate (in CTA)	380.4	kg/LF
Aggregate (in non-CTA)	428.3	kg/LF
Materials per Truck	16,375	kg/truck
Diesel (All Columns)	0.86	L/LF
Drill Spoil	0.18	CY/LF
Drill Spoil per Truck	12	CY
Truck Fuel Economy	2.42	km/L

Embodied Energy Coefficient Properties (MJ/unit)

Material	Mean	St. Dev	Distribution
Cement (MJ/kg)	4.800	0.980	Lognormal
Aggregate (MJ/kg)	0.083	0.12	Lognormal
Diesel (MJ/L)	43.000	1.43	Lognormal
Cement (MJ/kg)	1.548	0.202	Normal
Aggregate (MJ/kg)	-3.053	1.062	Normal
Diesel (MJ/L)	3.761	0.033	Normal

CO_2 Emissions Coefficient Properties (kg CO_2/unit)

Material	Mean	St. Dev	Distribution
Cement (kg/kg)	0.927	0.1050	Lognormal
Aggregate (kg/kg)	0.0048	0.0069	Lognormal
Diesel (kg/L)	3.248	0.1100	Lognormal
Cement (kg/kg)	-0.082	0.1129	Normal
Aggregate (kg/kg)	-5.899	1.0585	Normal
Diesel (kg/L)	1.177	0.0339	Normal

Note: All calculations performed assuming the embodied energy and CO_2 emissions coefficients are lognormally distributed in order to avoid negative values. Random numbers generated from the coefficient distribution for each total CTA column length.

TOTAL Estimated CTA Length (ft)	TOTAL Design UTA Length (ft)	Material Quantities: Cement (kg)	Material Quantities: Aggregate (in CTA) (kg)	Material Quantities: Aggregate (UTA) (kg)	Fuel Qty: Diesel (L)	Waste Qty: Waste CY	Transportation Quantities: CTA # Truckloads	CTA Distance (km)	UTA # Truckloads	UTA Distance (km)	Waste # Truckloads	Waste Distance (km)	Materials: Cement EE (MJ)	Cement CO_2 (kg)	Aggregate EE (MJ)	Aggregate CO_2 (kg)
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	738,149	179,740	568,534	11,034
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,185,479	155,550	35,729	50,154
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	870,953	184,276	317,664	21,677
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,100,410	206,111	270,052	2,575
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	890,365	145,381	147,378	66,463
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	978,471	161,780	82,481	56,941
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	889,818	162,019	70,370	1,881
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	973,949	164,950	97,679	966
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	812,862	166,712	65,388	23,039
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,001,085	172,732	373,212	20,914
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	913,830	196,401	371,484	87,852
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,065,876	162,430	145,340	97,678
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	955,067	158,838	115,493	41,076
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	727,209	171,103	65,405	11,806
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	870,770	196,063	672,088	4,262
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	994,949	239,257	231,730	4,649
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	745,522	210,550	94,142	55,722
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	846,995	201,992	274,155	17,593
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,478,084	163,884	131,586	24,256
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	827,995	182,034	312,690	1,820
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	800,788	199,081	97,188	14,618
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	872,542	196,469	82,864	8,603
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,088,169	179,561	82,510	41,496
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,018,381	161,338	398,421	7,455
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	749,126	161,473	207,559	17,067
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	819,250	202,909	57,949	122,480
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	821,340	170,406	93,105	54,141
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	729,001	214,467	1,283,653	26,249
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	602,730	158,967	222,131	2,775
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,545,997	164,176	444,906	7,882
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	609,620	223,496	648,170	27,195
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,267,810	152,273	45,233	102,398
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	810,432	188,081	275,369	6,294
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	807,271	194,934	975,264	6,219
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	721,588	185,110	61,034	50,589
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	844,453	173,213	557,712	32,765
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	790,700	153,664	1,025,458	5,751
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,032,569	191,574	2,022,776	28,066
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	711,115	183,505	390,969	8,030
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	1,278,559	192,611	64,343	4,352
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	790,851	170,285	64,002	5,290
12,472	2,287	197,699	4,744,767	979,452	12,736	2,657	302	8	60	8	222	16	2,164,762	195,554	5,901,765	15,569

Figure O.27 Monte Carlo Simulation worksheet for Method 5. The worksheet generates 1,000 discrete values of total embodied energy and CO_2 emissions for the Rammed Aggregate Columns at Pearson Hall.

Complete results of the Monte Carlo simulation for Method 5 are summarized in Table O.5. The proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for rammed aggregate columns at Pearson Hall following Method 5 of accounting for subsurface variability are shown in Figures O.28 and O.29, respectively. The distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation are shown in Figures O.30 and O.31, respectively. Vertical lines in Figures O.30 and O.31 represent the mean and the lower and upper bounds of the 90% CI (denoted as Lower CL and Upper CL, respectively). All of these were generated from one realization of the Monte Carlo simulation in the *calculations workbook*, as copied into the *results workbook*.

Table O.5 Results from Monte Carlo simulation for total embodied energy and CO_2 emissions for Rammed Aggregate Columns at Pearson Hall using Method 5 to account for subsurface variability.

	Embodied Energy (GJ)					**CO_2 Emissions (tonnes)**				
	Mean	**St Dev**	**Max.**	**Min.**	**% of Total**	**Mean**	**St Dev**	**Max.**	**Min.**	**% of Total**
Materials	1,397	594	7,334	586	64%	208	39	576	138	78%
Materials Transportation	103	3	113	93	5%	8	0	9	7	3%
Site Operations	548	18	601	493	25%	41	1	45	36	16%
Waste Transportation	127	4	139	114	6%	10	0	11	8	4%
TOTAL	**2,175**	**595**	**8,071**	**1,381**	**100%**	**267**	**39**	**634**	**194**	**100%**
% Mean Error, 90% Confidence, 1,000 points (+/-)	**1.42%**					**0.75%**				

90% Confidence Interval (CI)		
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**
Lower Confidence Limit (CL) (5% < Value)	**1,620**	**224**
Mean	2,175	267
Upper Confidence Limit (CL) (95% < Value)	**3,233**	**327**

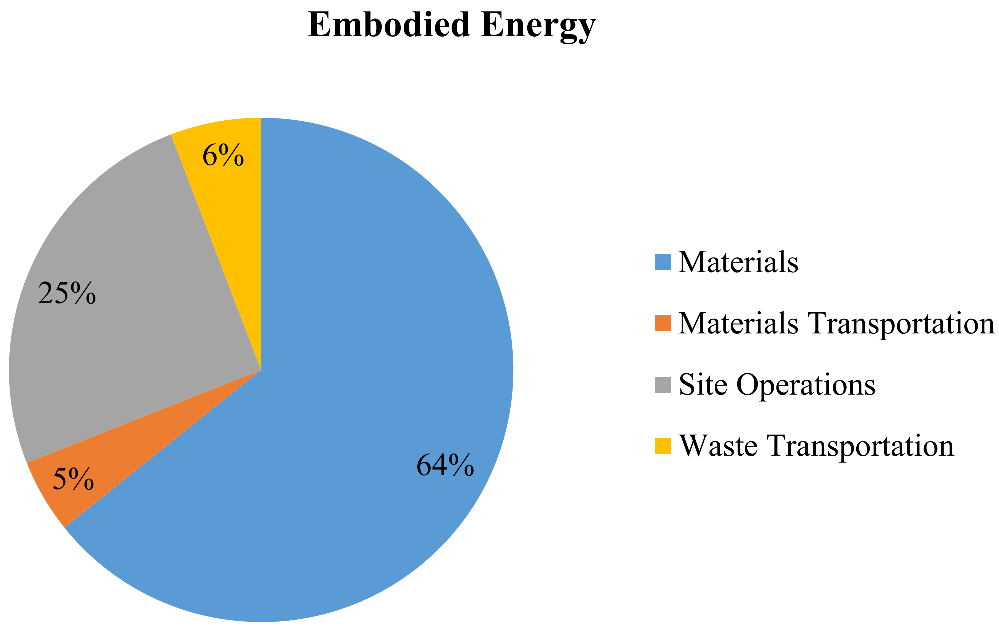


Figure O.28 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 5 of accounting for subsurface variability.

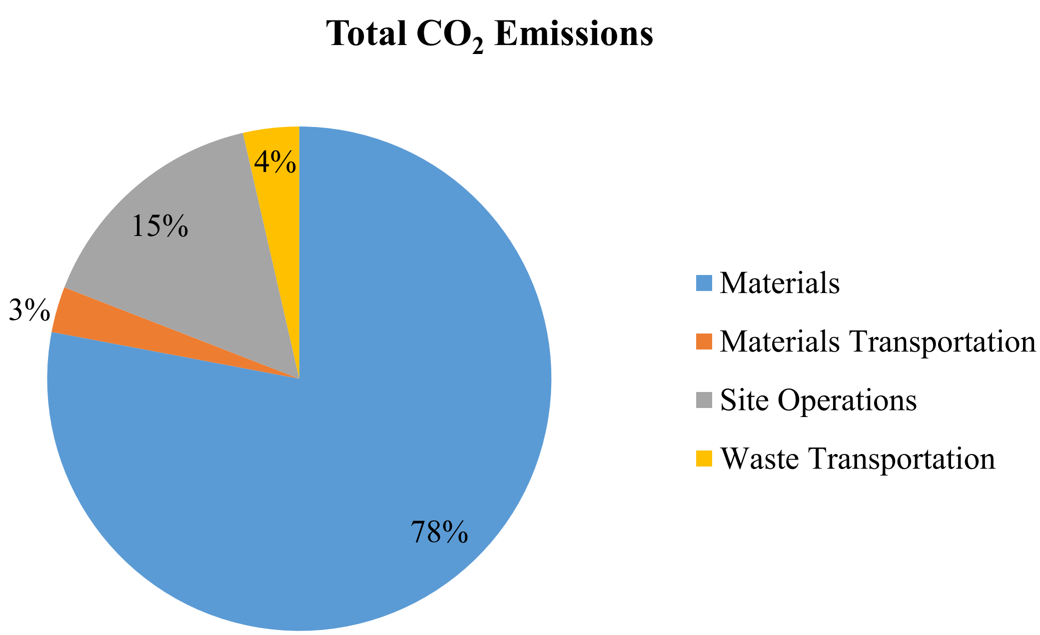


Figure O.29 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using Method 5 of accounting for subsurface variability.

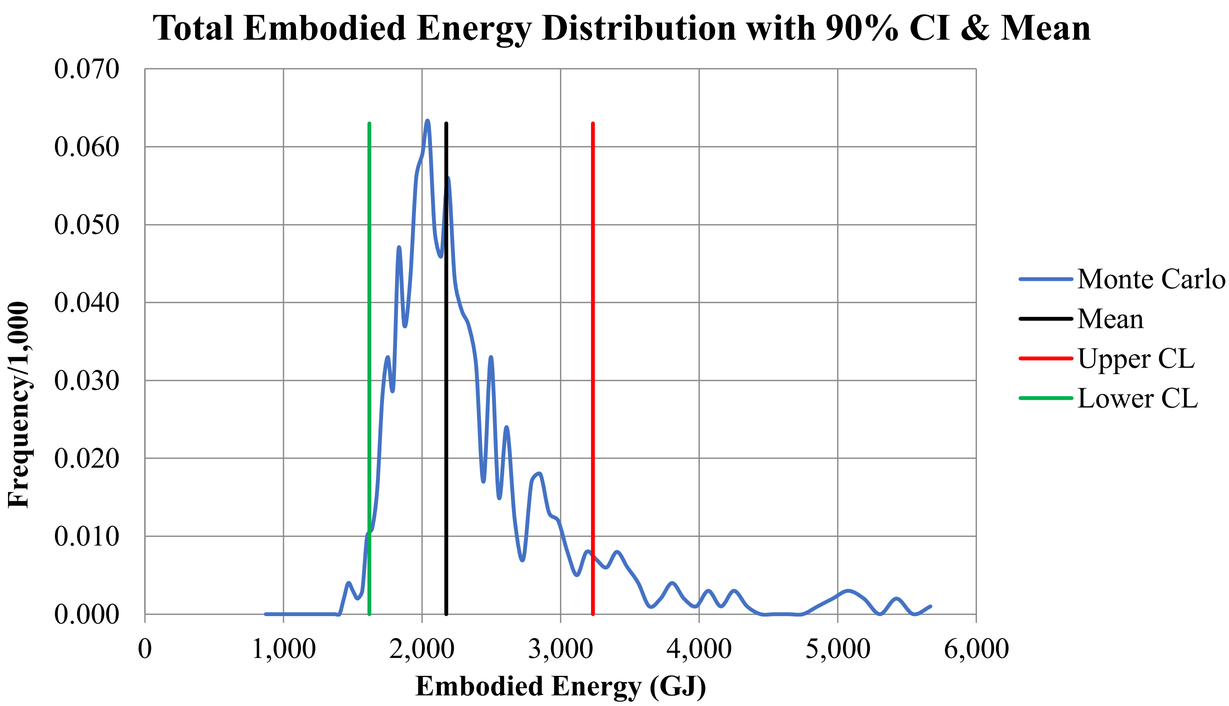


Figure O.30 Distribution of total embodied energy, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 5 of accounting for subsurface variability.

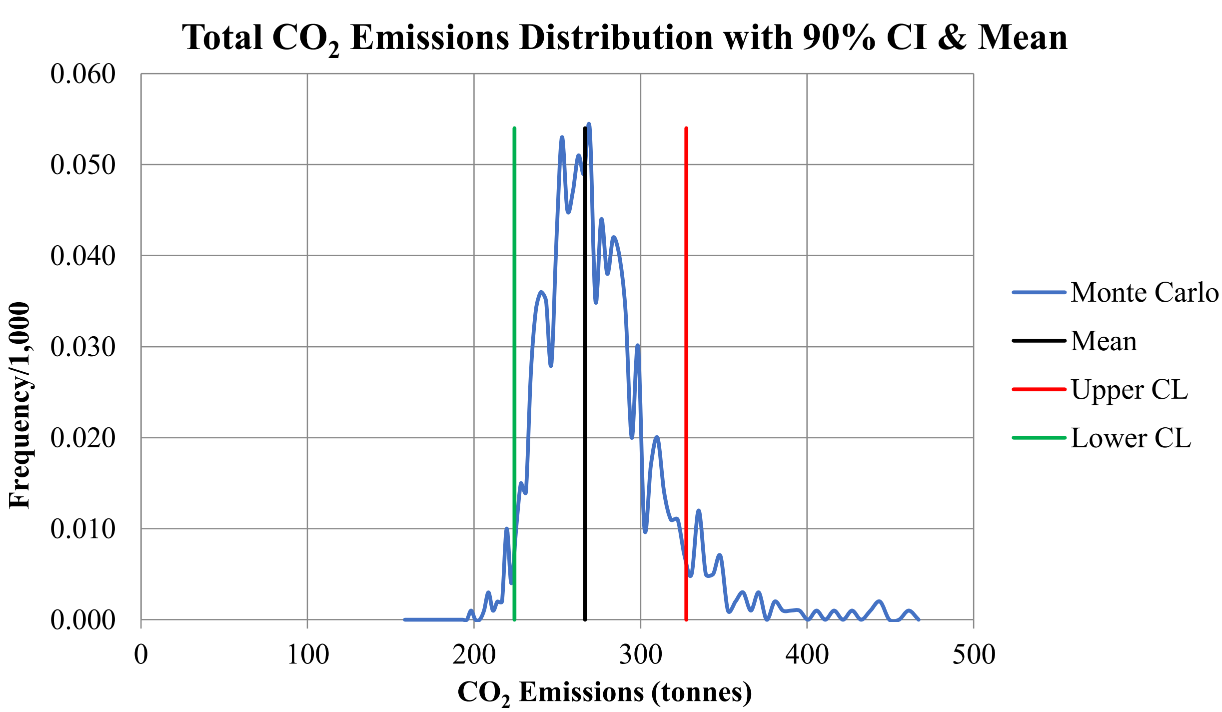


Figure O.31 Distribution of total CO_2 emissions, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using Method 5 of accounting for subsurface variability.

O.3.6 Results for As-Built Material Quantities

The analysis using the as-built construction quantities was conducted in a similar manner to the analyses that were performed using each of the methods of accounting for subsurface variability; both the *calculations workbook* and the *results workbook* were used. The difference in this case was there was no consideration for the subsurface conditions (i.e., the key geotechnical parameter, TOR elevation) for estimating material quantities. Instead, the actual quantities from construction (see Ch. 6 and Appendix L) were input directly into the Monte Carlo worksheet. The Monte Carlo worksheet then ran 1,000 lines of calculations following the SEEAM method for computing total embodied energy and CO_2 emissions. To account for coefficient uncertainty, the worksheet randomly generated values of the embodied energy and CO_2 emissions coefficients for each line of calculations in the analysis by randomly generating a number between 0 and 1 and using it in the inverse lognormal cumulative distribution function to generate a coefficient value. The coefficient lognormal parameters are at the top of the worksheet. Figure O.32 shows the upper left portion of the Monte Carlo worksheet for the analysis with the as-built quantities.

Pearson Hall Rammed Aggregate Columns for Shallow Foundation Support

Material Unit Quantities		
Material	Qty	Unit
Cement (in CTA)	15.85	kg/LF
Aggregate (in CTA)	380.4	kg/LF
Aggregate (in non-CTA)	428.3	kg/LF
Materials per Truck	16,375	kg/truck
Diesel (All Columns)	0.86	L/LF
Drill Spoil	0.18	CY/LF
Drill Spoil per Truck	12	CY
Truck Fuel Economy	2.42	km/L

Embodied Energy Coefficient Properties (MJ/unit)			
Material	Mean	St. Dev	Distribution
Cement (MJ/kg)	4.800	0.980	Lognormal
Aggregate (MJ/kg)	0.083	0.12	Lognormal
Diesel (MJ/L)	43.000	1.43	Lognormal
Cement (MJ/kg)	1.548	0.202	Normal
Aggregate (MJ/kg)	-3.053	1.062	Normal
Diesel (MJ/L)	3.761	0.033	Normal

CO_2 Emissions Coefficient Properties (kg CO_2/unit)			
Material	Mean	St. Dev	Distribution
Cement (kg/kg)	0.927	0.1050	Lognormal
Aggregate (kg/kg)	0.0048	0.0069	Lognormal
Diesel (kg/L)	3.248	0.1100	Lognormal
Cement (kg/kg)	-0.082	0.1129	Normal
Aggregate (kg/kg)	-5.899	1.0585	Normal
Diesel (kg/L)	1.177	0.0339	Normal

Note: All calculations performed assuming the embodied energy and CO_2 emissions coefficients are lognormally distributed in order to avoid negative values. Random numbers generated from the coefficient distribution for each total CTA column length.

TOTAL Estimated CTA Length (ft)	TOTAL Design UTA Length (ft)	Material Quantities			Fuel Qty	Waste Qty	Transportation Quantities						Materials			
													Cement		Aggregate	
		Cement (kg)	Aggregate (in CTA) (kg)	Aggregate (UTA) (kg)	Diesel (L)	Waste CY	CTA # Truckloads	CTA Distance (km)	UTA # Truckloads	UTA Distance (km)	Waste # Truckloads	Waste Distance (km)	EE (MJ)	CO_2 (kg)	EE (MJ)	CO_2 (kg)
		167,405	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	932,686	143,651	519,326	45,812
		167,406	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	986,605	149,327	186,102	45,370
		167,407	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	730,911	148,192	151,758	10,843
		167,408	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	609,777	149,910	148,754	28,640
		167,409	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	707,789	180,886	408,434	36,151
		167,410	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	773,485	160,701	463,734	15,148
		167,411	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	670,040	161,940	72,239	8,088
		167,412	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	734,792	173,499	170,886	69,707
		167,413	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	870,863	140,657	48,644	8,351
		167,414	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	574,408	154,419	778,493	38,903
		167,415	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	955,565	134,662	198,076	85,650
		167,416	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	621,375	149,668	167,390	18,408
		167,417	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	989,235	114,941	311,202	60,661
		167,418	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	898,666	148,980	488,580	15,974
		167,419	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	884,029	195,004	1,582,694	6,514
		167,420	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	1,006,031	171,695	315,334	4,671
		167,421	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	557,361	185,510	164,726	5,260
		167,422	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	1,053,256	111,678	146,899	38,411
		167,423	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	712,527	171,003	88,608	44,084
		167,424	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	892,068	146,532	553,442	2,732
		167,425	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	567,431	146,476	128,287	3,733
		167,426	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	905,270	180,417	119,417	20,728
		167,427	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	565,876	159,257	1,129,252	6,089
		167,428	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	817,173	165,552	66,402	65,420
		167,429	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	1,005,928	143,463	228,991	9,058
		167,430	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	942,154	164,737	1,577,406	28,346
		167,431	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	714,045	152,489	599,438	30,391
		167,432	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	1,243,193	146,322	427,790	11,779
		167,433	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	599,002	141,690	470,855	47,275
		167,434	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	762,261	154,318	96,110	58,393
		167,435	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	785,703	167,898	647,212	40,724
		167,436	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	687,969	131,599	797,401	77,617
		167,437	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	877,183	159,787	99,164	5,979
		167,438	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	767,237	149,107	945,257	10,474
		167,439	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	646,669	162,652	914,708	11,085
		167,440	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	604,795	134,626	180,952	57,709
		167,441	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	610,277	156,960	355,762	12,459
		167,442	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	657,896	149,600	49,713	13,458
		167,443	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	694,540	153,504	841,845	10,743
		167,444	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	603,287	166,428	581,223	25,366
		167,445	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	915,283	135,761	356,430	21,994
		167,446	4,017,716	1,192,949	11,250	2,345	256	8	73	8	196	16	985,711	138,575	49,806	8,333

Figure O.32 Monte Carlo Simulation worksheet for the as-built quantities at Pearson Hall. The worksheet generates 1,000 discrete values of total embodied energy and CO_2 emissions for the Rammed Aggregate Columns at Pearson Hall.

Complete results of the Monte Carlo simulation for the as-built condition are summarized in Table O.6. The proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for rammed aggregate columns at Pearson Hall for the as-built condition are shown in Figures O.33 and O.34, respectively. The distributions of total embodied energy and CO_2 emissions from the Monte Carlo simulation are shown in Figures O.35 and O.36, respectively. Vertical lines in Figures O.35 and O.36 represent the mean and the lower and upper bounds of the 90% CI (denoted as Lower CL and Upper CL, respectively). All of these were generated from one realization of the Monte Carlo simulation in the *calculations workbook*, as copied into the *results workbook*.

Table O.6 Results from Monte Carlo simulation for total embodied energy and CO_2 emissions for Rammed Aggregate Columns at Pearson Hall using as-built quantities.

	Embodied Energy (GJ)					CO_2 Emissions (tonnes)				
	Mean	**St Dev**	**Max.**	**Min.**	**% of Total**	**Mean**	**St Dev**	**Max.**	**Min.**	**% of Total**
Materials	1,242	645	7,194	503	64%	179	38	554	113	77%
Materials Transportation	94	3	105	84	5%	7	0	8	6	3%
Site Operations	484	16	541	431	25%	37	1	41	33	16%
Waste Transportation	112	4	125	100	6%	8	0	9	8	4%
TOTAL	**1,931**	**645**	**7,878**	**1,233**	**100%**	**232**	**39**	**607**	**165**	**100%**
% Mean Error, 90% Confidence, 1,000 points (+/-)	**1.74%**					**0.87%**				

90% Confidence Interval (CI)		
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**
Lower Confidence Limit (CL) (5% < Value)	**1,408**	**191**
Mean	1,931	232
Upper Confidence Limit (CL) (95% < Value)	**2,976**	**295**

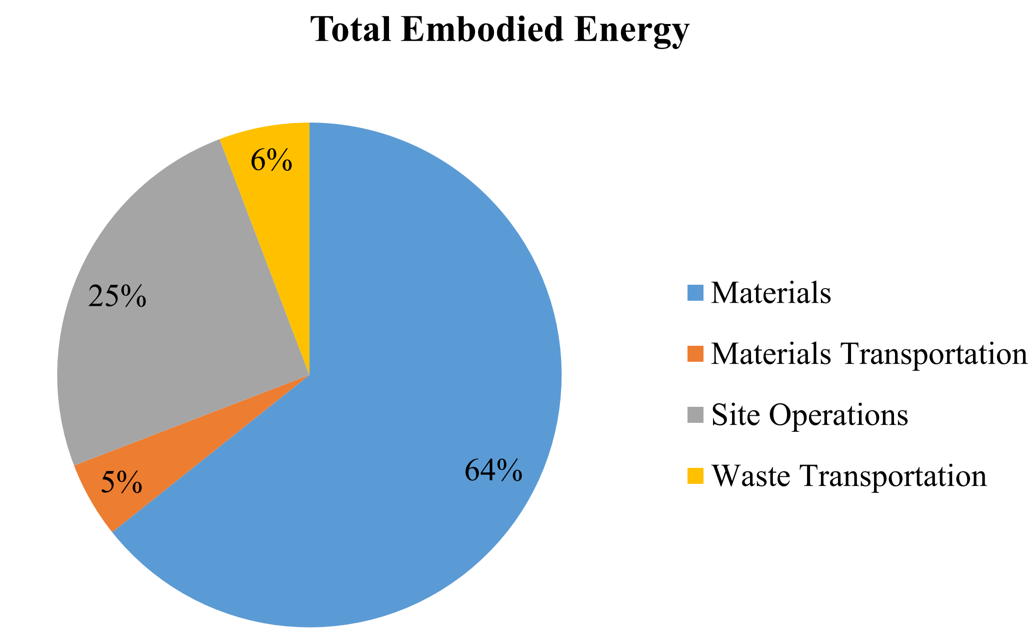


Figure O.33 Proportion of total embodied energy associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using as-built quantities.

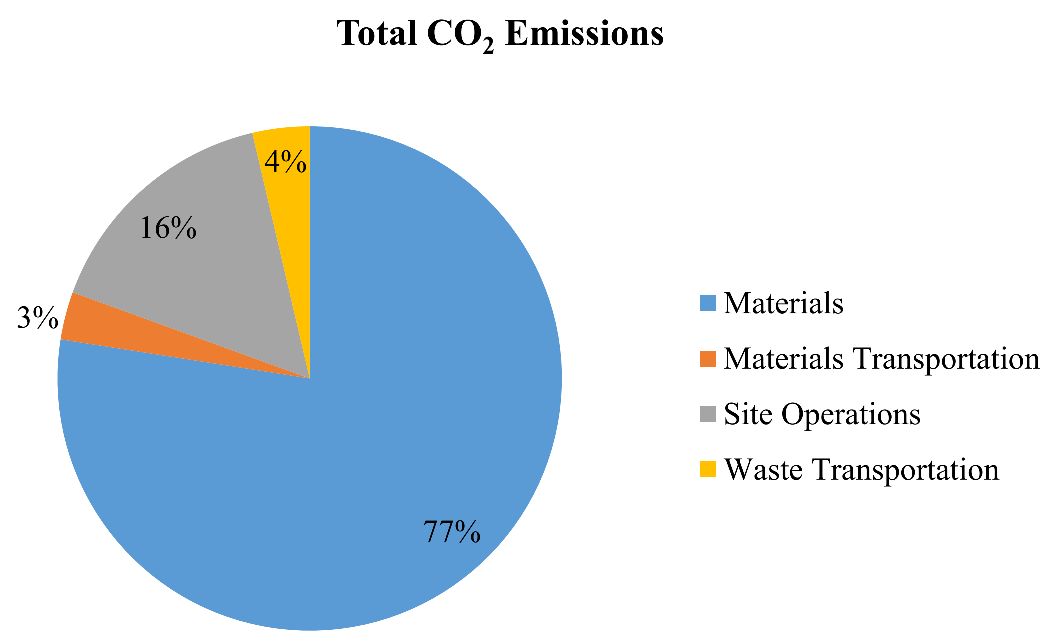


Figure O.34 Proportion of total CO_2 emissions associated with materials, materials transportation, site operations and waste transportation for Rammed Aggregate Columns at Pearson Hall, using as-built quantities.

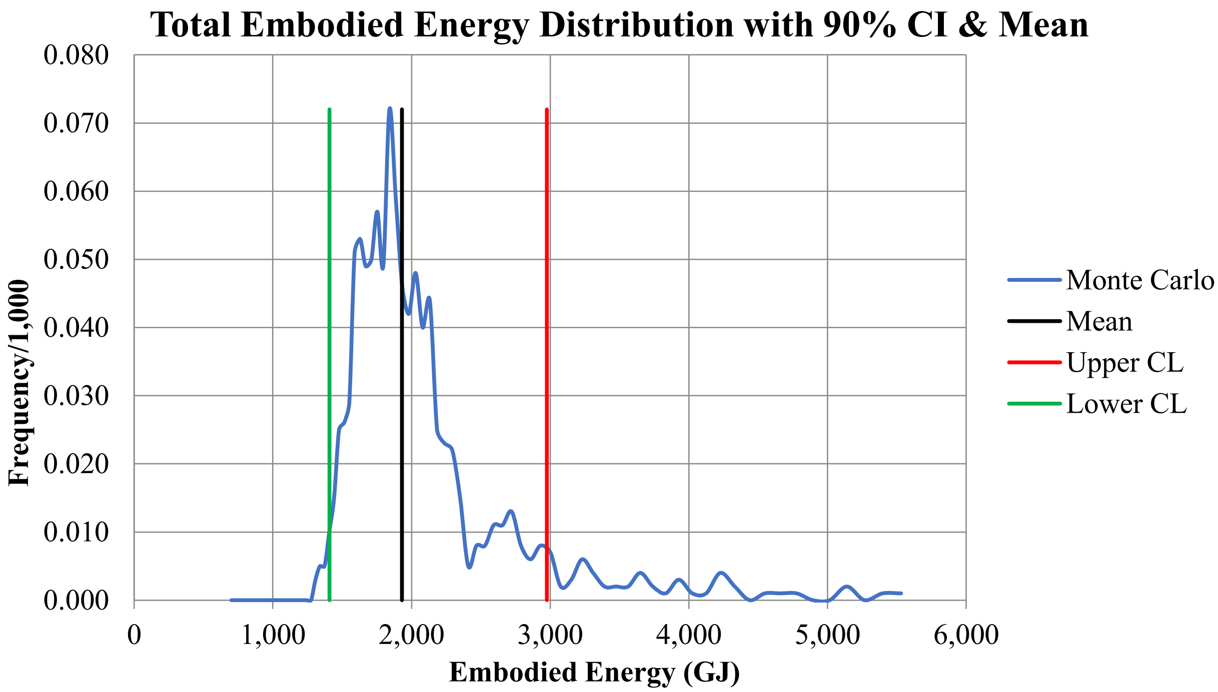


Figure O.35 Distribution of total embodied energy, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using as-built quantities.

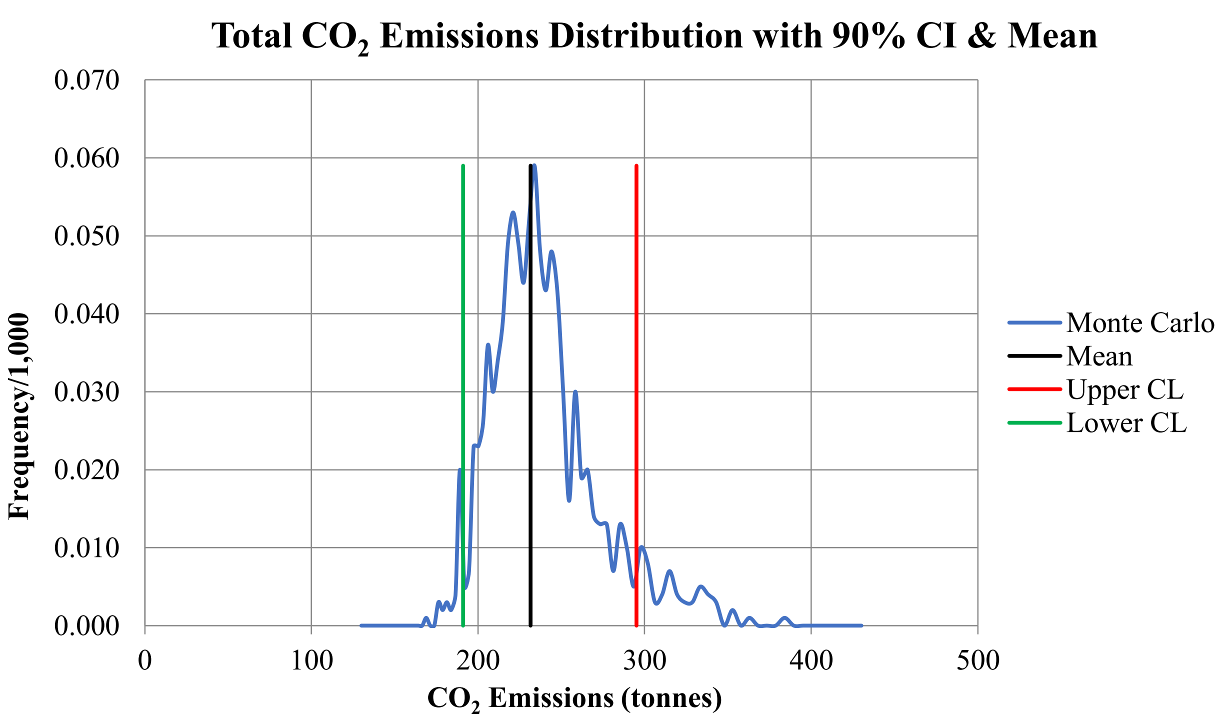


Figure O.36 Distribution of total CO_2 emissions, showing the 90% confidence interval and the mean for Rammed Aggregate Columns at Pearson Hall, using as-built quantities.

O.3.7 Total Embodied Energy and CO_2 Emissions Monte Carlo Simulation Data from All Analyses

Table O.7 (28 pages) contains the data sets for total embodied energy and CO_2 emissions from SEEAM method with Monte Carlo simulation for Methods 1 through 3 of accounting for subsurface variability. Table O.8 (28 pages) contains the data sets for total embodied energy and CO_2 emissions from the Monte Carlo simulations for Methods 4 and 5, plus the as-built condition.

Table O.7 Embodied energy and CO_2 emissions data sets for construction of Rammed Aggregate Columns at Pearson Hall, from Monte Carlo simulation following Methods 1 through 3 of accounting for subsurface variability.

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	2,494	255	1,798	299	1,714	373
2	2,136	290	2,574	309	1,678	250
3	1,852	300	2,381	322	1,970	273
4	2,377	260	2,246	292	2,055	317
5	2,401	365	2,179	299	2,042	241
6	1,779	406	3,252	508	2,032	298
7	2,427	396	1,972	320	2,134	229
8	1,791	315	2,382	243	2,874	288
9	1,651	294	1,964	352	1,965	259
10	2,547	316	1,950	291	2,742	318
11	1,863	335	2,707	306	1,589	242
12	2,170	244	2,428	365	1,988	248
13	3,055	551	2,466	301	2,285	224
14	1,940	256	2,547	298	2,284	239
15	2,308	361	2,198	246	2,423	211
16	2,222	254	3,358	291	1,832	256
17	2,155	269	2,562	291	2,179	294
18	1,827	290	2,184	303	2,713	232
19	2,924	316	2,002	283	2,279	289
20	2,782	356	1,985	287	2,647	266
21	5,215	283	2,176	315	3,792	245
22	2,081	301	2,175	351	2,098	286
23	2,134	289	2,123	287	2,321	221
24	1,961	326	2,085	271	2,413	276

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
25	2,163	257	2,061	297	2,351	293
26	2,297	309	2,469	320	1,781	315
27	1,461	603	1,909	245	1,842	305
28	1,854	237	2,021	312	1,663	235
29	1,840	290	2,162	258	1,819	240
30	2,946	328	2,218	304	1,821	238
31	2,682	331	2,174	419	4,055	273
32	2,240	438	1,939	287	2,005	275
33	2,090	341	2,209	274	1,868	291
34	1,944	296	4,638	290	2,357	258
35	2,681	353	2,282	265	1,925	228
36	2,167	312	2,352	242	1,924	270
37	2,375	260	2,323	290	2,369	472
38	2,255	282	7,078	262	2,891	293
39	2,183	256	2,411	364	3,981	265
40	2,222	335	3,693	265	2,083	243
41	2,349	284	3,695	280	1,625	242
42	1,718	290	2,592	248	1,532	249
43	2,090	321	3,622	316	1,860	237
44	2,617	307	1,881	344	2,121	223
45	3,033	315	2,177	326	2,397	239
46	2,836	260	4,930	352	2,406	227
47	2,216	440	2,138	275	2,614	270
48	2,424	243	2,089	352	2,200	233
49	1,871	338	2,081	256	2,094	288
50	2,118	298	3,748	296	1,562	261
51	2,438	261	3,480	273	1,893	279
52	2,078	333	1,985	292	2,361	245
53	3,684	324	3,273	264	2,300	292
54	2,797	296	2,035	334	1,861	283
55	2,525	279	2,165	276	2,473	318
56	2,079	278	3,286	303	2,056	267
57	2,608	330	2,240	336	2,388	314
58	2,471	304	3,730	308	2,609	287
59	4,512	353	2,542	304	1,681	245
60	1,997	581	2,259	348	2,708	241
61	2,236	270	2,450	280	1,932	244

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
62	1,935	363	3,454	273	2,720	260
63	2,812	260	1,915	269	1,860	251
64	1,888	304	2,593	336	2,985	282
65	2,288	267	3,842	262	2,022	228
66	3,133	303	3,373	319	2,151	230
67	2,428	324	2,878	284	2,351	250
68	1,870	364	2,154	272	4,285	279
69	1,970	370	2,016	275	1,581	248
70	2,399	244	2,017	468	1,723	303
71	1,777	293	2,261	271	1,840	260
72	2,250	323	2,671	292	2,223	215
73	2,977	349	1,955	291	1,817	278
74	3,000	269	2,238	263	1,986	224
75	2,118	301	2,109	248	2,186	362
76	2,661	242	2,235	313	2,030	254
77	2,474	263	2,511	361	2,210	219
78	2,426	281	2,758	368	1,464	315
79	2,710	247	1,874	275	1,780	232
80	3,201	270	1,864	256	2,004	272
81	2,034	301	2,518	258	1,703	299
82	2,882	270	2,143	301	1,645	264
83	1,940	268	3,155	276	2,121	268
84	2,166	270	2,754	327	1,862	257
85	2,354	267	2,347	310	1,825	276
86	1,744	448	2,190	330	2,240	249
87	2,055	279	3,064	295	1,734	245
88	2,723	366	2,847	283	1,865	345
89	2,378	327	2,403	309	2,080	288
90	2,014	298	2,047	331	1,657	272
91	1,875	304	2,514	214	1,677	232
92	2,154	293	3,242	299	1,982	248
93	2,012	331	2,017	361	2,008	244
94	1,887	336	1,813	266	3,958	229
95	2,148	252	1,823	262	2,358	270
96	2,815	321	3,502	246	2,081	243
97	1,995	287	2,502	269	2,207	280
98	2,808	280	2,635	311	1,727	219

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
99	2,946	347	1,795	291	2,467	369
100	2,824	280	3,142	270	1,593	220
101	1,971	399	3,112	314	1,968	275
102	2,555	308	2,785	271	1,680	244
103	3,735	234	2,431	289	2,327	372
104	1,515	310	1,953	310	2,419	242
105	2,430	305	2,091	298	1,785	265
106	1,989	314	2,120	373	1,718	303
107	2,928	286	1,994	280	2,008	250
108	2,291	306	1,698	357	1,873	266
109	2,550	309	2,469	295	2,231	260
110	2,429	361	2,144	355	2,022	223
111	1,972	311	1,902	546	1,657	277
112	3,139	295	3,376	279	2,518	276
113	2,493	297	3,445	238	2,331	377
114	4,880	260	1,909	256	2,151	251
115	1,921	330	2,304	283	2,248	288
116	2,682	341	1,710	284	1,731	258
117	1,979	258	2,400	332	3,941	247
118	2,489	328	2,770	279	1,842	232
119	1,685	294	1,773	302	1,766	239
120	2,302	291	2,395	308	1,926	359
121	2,022	296	2,036	285	2,315	263
122	1,925	325	2,234	336	2,007	265
123	2,125	328	4,726	268	2,655	277
124	2,563	267	1,897	287	1,751	248
125	2,020	306	3,233	298	1,946	281
126	2,156	283	2,005	295	1,377	255
127	2,323	302	3,255	246	1,708	307
128	2,408	571	3,074	277	2,145	358
129	1,892	334	1,795	308	1,576	252
130	1,904	314	1,973	354	1,995	272
131	2,258	273	2,479	267	2,020	244
132	2,354	339	2,335	287	2,591	295
133	3,063	300	1,718	324	1,958	284
134	2,307	287	3,865	286	3,650	278
135	2,105	317	2,021	450	1,628	252

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
136	1,635	283	1,652	327	2,040	246
137	2,174	294	2,436	290	2,775	228
138	5,261	258	1,947	300	2,374	334
139	2,719	329	2,229	315	1,930	236
140	2,510	258	2,797	340	2,048	240
141	1,902	292	2,169	377	1,562	310
142	2,426	297	2,645	292	2,000	258
143	2,918	291	1,987	277	2,650	247
144	2,777	303	1,941	296	2,187	394
145	2,749	232	1,821	337	2,547	265
146	2,468	277	2,787	366	2,797	252
147	1,818	281	3,644	258	2,190	305
148	2,042	311	2,605	270	1,608	247
149	1,825	286	3,063	306	1,977	281
150	2,898	276	2,184	237	2,540	279
151	2,542	285	2,538	306	1,935	308
152	2,306	288	2,840	396	1,835	265
153	2,380	278	2,230	291	2,486	272
154	2,610	266	2,236	232	1,823	291
155	2,532	250	1,927	303	1,629	255
156	2,200	269	2,156	287	1,833	253
157	2,386	293	2,701	256	2,270	234
158	2,330	304	1,743	295	1,835	283
159	2,375	314	1,576	278	2,835	269
160	3,156	278	2,767	299	2,205	260
161	1,810	295	2,949	412	2,258	321
162	2,115	275	2,586	274	1,973	224
163	2,622	258	1,790	230	2,272	287
164	2,548	299	1,904	260	1,883	286
165	2,447	278	1,871	331	1,872	235
166	2,948	322	2,517	318	2,134	244
167	2,027	361	2,239	272	1,889	377
168	2,781	342	2,527	359	2,518	345
169	2,302	377	3,012	282	3,581	249
170	2,896	290	2,156	331	1,864	241
171	2,596	325	2,214	285	2,143	261
172	1,874	287	4,740	273	2,200	269

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
173	2,191	310	2,118	318	2,150	282
174	4,025	276	2,288	289	2,095	360
175	2,872	321	1,904	276	2,436	259
176	2,001	334	2,003	277	1,846	292
177	2,305	405	3,707	306	1,859	256
178	3,046	271	1,976	386	2,267	284
179	2,204	310	2,117	268	1,486	236
180	2,230	294	2,099	321	2,755	272
181	2,997	308	3,282	322	1,723	431
182	2,558	293	2,062	339	1,788	241
183	2,693	311	2,284	264	2,087	287
184	2,341	270	2,539	329	1,966	274
185	3,857	244	3,317	301	1,760	259
186	5,594	322	2,015	336	2,655	300
187	2,403	384	1,994	360	2,767	306
188	2,116	304	1,863	308	2,182	263
189	3,655	337	1,943	262	2,225	279
190	8,303	323	2,869	377	2,622	254
191	2,075	329	2,526	311	2,390	246
192	1,705	420	2,615	332	1,570	271
193	2,401	322	2,159	235	2,542	233
194	2,362	315	1,814	311	1,812	236
195	2,171	332	3,982	314	2,122	386
196	2,067	329	4,540	286	2,806	259
197	2,165	289	2,175	333	2,726	274
198	1,876	341	1,899	245	1,665	263
199	1,945	297	2,621	328	2,956	275
200	3,619	328	2,405	273	2,071	228
201	1,785	265	2,209	302	3,046	313
202	2,486	314	1,842	250	2,761	391
203	2,495	354	2,656	231	2,277	226
204	2,962	319	2,512	300	1,959	261
205	2,237	299	2,108	298	1,893	259
206	2,448	255	2,177	269	1,884	248
207	2,374	345	2,993	256	1,634	254
208	1,905	299	2,198	285	1,976	269
209	2,101	249	2,640	318	2,130	225

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
210	2,826	317	2,944	291	2,079	236
211	2,014	282	1,671	475	1,867	242
212	2,410	282	2,013	308	2,249	274
213	2,135	322	2,188	337	2,451	376
214	2,108	279	2,581	302	2,531	271
215	3,053	306	2,229	301	2,485	254
216	2,689	308	2,064	347	1,794	299
217	2,035	285	3,417	313	1,755	257
218	2,017	423	3,142	289	2,008	266
219	2,476	310	2,819	307	1,965	263
220	2,456	293	2,057	278	1,755	245
221	2,511	310	2,741	271	2,074	303
222	3,198	293	2,869	294	1,916	284
223	2,112	369	2,404	280	1,662	218
224	2,537	326	2,717	280	1,950	302
225	2,241	280	2,093	330	2,721	275
226	2,912	330	2,226	333	1,897	256
227	2,451	346	2,306	415	2,158	292
228	9,736	280	1,823	282	2,251	269
229	2,006	310	3,165	249	2,226	295
230	3,029	295	2,268	344	3,086	248
231	2,909	286	2,377	250	4,158	243
232	2,436	317	10,946	359	2,036	264
233	2,231	272	2,997	256	2,039	265
234	2,946	263	2,380	295	2,402	269
235	1,987	336	1,798	273	2,002	230
236	2,192	240	1,997	304	2,816	253
237	2,874	275	3,724	312	1,665	270
238	2,332	271	2,940	349	1,795	220
239	2,230	358	2,189	520	2,338	248
240	2,584	253	2,818	292	2,096	269
241	2,158	305	2,013	305	1,911	301
242	2,036	277	2,060	310	2,798	253
243	2,168	335	2,918	286	1,683	251
244	2,218	311	2,475	244	1,961	245
245	2,230	271	2,725	352	1,988	275
246	2,056	371	2,573	283	4,750	291

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
247	3,757	322	3,582	250	2,389	283
248	2,488	310	3,248	257	2,228	240
249	2,102	304	2,492	268	1,899	276
250	2,507	298	3,454	249	1,718	196
251	2,079	285	2,575	310	1,628	219
252	2,006	295	1,844	290	2,048	370
253	2,023	366	2,796	257	2,604	286
254	2,270	348	2,672	331	2,176	228
255	2,428	256	1,966	272	1,948	263
256	2,313	296	2,235	276	2,120	256
257	1,941	282	1,818	308	3,207	261
258	2,241	307	2,394	293	2,110	296
259	2,436	277	1,901	302	5,473	278
260	4,176	316	3,008	349	2,251	249
261	2,702	255	2,247	274	2,316	254
262	2,302	275	2,083	263	1,640	237
263	2,289	253	3,532	278	1,690	246
264	2,377	289	3,243	307	1,952	329
265	1,768	318	1,818	260	2,099	282
266	2,410	268	1,975	274	2,115	281
267	1,772	274	1,909	277	1,916	244
268	3,037	300	5,412	282	2,373	262
269	2,511	236	3,015	257	2,651	313
270	2,003	292	2,034	467	2,470	298
271	1,918	248	2,156	343	1,600	260
272	1,943	311	2,036	307	1,904	261
273	2,755	340	2,554	322	1,883	263
274	1,911	292	2,431	255	2,053	217
275	2,757	367	2,647	303	1,569	245
276	1,973	332	1,992	296	1,985	255
277	2,118	289	2,246	333	2,368	256
278	2,347	267	2,688	297	1,549	224
279	2,233	260	4,568	271	1,663	225
280	1,880	335	1,926	256	2,617	257
281	1,912	299	4,481	333	1,908	389
282	2,144	338	2,378	285	2,189	238
283	1,947	275	2,494	262	1,839	251

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
284	3,424	283	2,314	315	2,250	290
285	1,875	306	2,604	242	2,031	340
286	2,604	285	2,066	372	2,225	255
287	2,712	305	1,956	270	2,014	233
288	2,239	273	2,441	378	2,727	276
289	2,029	315	3,320	351	2,002	225
290	2,347	346	2,243	493	1,942	230
291	2,163	317	1,862	276	1,742	284
292	4,051	329	2,875	314	2,437	251
293	2,319	488	1,925	312	3,414	280
294	2,215	340	2,148	337	2,219	286
295	2,014	305	3,248	357	2,322	270
296	2,155	324	1,871	284	1,768	278
297	1,693	319	2,260	301	2,029	260
298	1,992	335	2,746	258	1,639	261
299	2,337	253	1,934	285	1,788	250
300	3,711	291	2,199	355	1,601	242
301	2,619	338	2,401	265	3,819	260
302	2,375	261	2,170	308	1,748	236
303	2,637	267	2,176	328	2,256	301
304	2,400	316	2,077	347	2,117	208
305	2,718	314	6,870	284	1,816	268
306	2,033	456	2,353	326	1,824	265
307	2,340	274	1,889	281	2,203	298
308	2,475	289	2,421	301	4,129	312
309	2,072	296	2,707	275	1,784	268
310	2,246	312	2,020	323	1,411	247
311	2,459	283	2,083	358	2,275	254
312	2,714	271	1,988	324	1,822	239
313	2,192	282	3,065	278	1,754	266
314	2,788	293	2,183	305	2,282	272
315	2,150	319	1,874	313	1,823	365
316	1,904	275	2,340	269	2,001	256
317	2,256	305	2,333	274	2,934	285
318	2,468	302	2,572	284	1,983	238
319	3,518	272	2,042	282	2,056	304
320	2,576	259	3,399	283	2,257	262

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
321	2,280	286	2,193	267	1,611	297
322	2,441	351	2,698	264	1,739	285
323	1,929	330	2,347	298	1,778	223
324	2,459	252	2,067	281	1,597	235
325	2,324	321	2,116	285	2,018	245
326	2,919	250	2,487	281	2,969	282
327	2,327	431	2,225	306	1,906	262
328	2,265	262	2,292	286	2,103	350
329	2,169	322	2,046	316	1,792	240
330	2,038	305	3,655	280	2,805	322
331	2,574	385	2,094	285	1,846	244
332	1,963	391	2,194	336	2,085	243
333	1,995	292	2,816	298	1,964	240
334	2,184	431	2,342	281	1,925	241
335	2,351	316	2,272	346	2,461	278
336	2,094	264	1,858	246	1,850	250
337	2,164	291	2,376	338	1,734	273
338	1,853	298	1,878	283	1,947	245
339	2,395	337	3,263	272	1,802	242
340	2,142	327	2,161	343	1,864	230
341	1,987	262	2,266	433	2,186	340
342	3,281	306	2,622	299	8,416	232
343	2,781	278	2,335	274	2,776	283
344	3,180	352	2,044	285	1,777	228
345	2,967	288	2,748	413	2,242	278
346	2,662	305	2,346	290	2,286	236
347	1,799	240	1,753	260	2,387	231
348	3,028	311	2,467	270	2,563	473
349	1,878	262	2,687	325	1,653	232
350	2,588	266	4,339	289	2,015	254
351	2,119	307	1,787	264	3,526	277
352	3,211	278	2,027	373	3,301	257
353	2,271	269	2,011	276	6,742	220
354	3,223	298	2,640	270	2,006	245
355	2,597	294	2,265	250	2,851	328
356	2,098	357	1,929	273	1,512	264
357	2,659	302	2,087	276	1,853	273

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
358	2,519	267	3,110	291	1,990	238
359	2,879	307	1,774	285	2,136	294
360	2,176	298	2,617	314	2,888	270
361	2,117	295	3,072	312	2,000	243
362	1,806	265	1,990	335	2,203	252
363	5,228	384	2,256	347	1,795	229
364	1,988	312	2,134	294	2,318	245
365	2,349	337	1,886	300	2,002	333
366	3,359	282	2,292	328	2,250	298
367	6,062	332	2,263	364	2,402	259
368	2,136	325	2,750	339	1,997	294
369	2,884	262	2,003	287	2,585	338
370	2,585	319	1,777	311	2,137	237
371	2,167	308	1,820	339	3,021	284
372	2,934	314	2,156	288	2,019	267
373	2,084	300	2,569	317	1,554	322
374	2,395	322	2,449	330	1,517	249
375	2,651	300	1,840	286	1,727	220
376	2,485	396	2,479	262	1,755	238
377	2,161	280	3,550	337	2,101	276
378	1,969	326	2,096	338	1,530	327
379	2,415	314	2,500	279	2,212	211
380	2,235	327	2,611	278	3,000	264
381	1,868	238	2,407	322	2,074	288
382	3,965	386	2,656	272	2,391	250
383	2,153	315	2,861	282	1,856	241
384	2,696	263	1,925	253	2,198	216
385	2,443	343	4,003	314	1,645	253
386	2,522	342	1,963	262	1,753	239
387	1,380	286	2,228	325	1,950	246
388	2,393	344	2,201	257	2,330	273
389	1,748	290	2,058	276	1,713	239
390	2,326	276	2,221	550	1,979	285
391	2,057	251	2,402	307	7,007	237
392	3,082	343	3,049	323	1,760	235
393	3,318	263	2,263	298	1,601	281
394	2,260	336	2,466	278	1,946	252

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
395	2,256	323	2,225	336	1,980	292
396	2,220	252	2,299	307	2,721	302
397	3,452	297	2,087	319	1,645	269
398	4,438	279	1,843	348	2,329	261
399	2,133	288	2,897	326	2,207	341
400	2,385	280	2,045	275	2,106	221
401	2,466	372	2,282	302	1,753	252
402	2,208	291	2,359	261	1,997	279
403	8,345	325	2,228	282	1,942	291
404	1,787	266	2,393	246	2,724	278
405	3,739	299	3,181	370	2,114	265
406	2,593	282	2,399	299	1,894	289
407	2,796	294	1,979	387	3,068	294
408	3,731	240	2,542	281	4,009	209
409	2,397	344	2,164	335	1,936	233
410	1,977	355	2,622	255	1,792	242
411	2,169	334	2,592	267	1,947	261
412	2,429	283	2,025	258	1,770	257
413	2,433	315	2,201	297	1,836	244
414	2,159	439	1,853	285	3,570	229
415	2,834	284	1,958	283	3,149	274
416	1,555	311	2,087	332	4,922	246
417	2,261	276	2,462	288	1,811	258
418	2,049	293	2,321	309	1,825	413
419	1,782	293	2,828	346	2,191	251
420	2,383	308	2,224	419	1,966	304
421	2,105	269	2,528	339	2,013	241
422	2,099	333	2,375	284	2,430	216
423	3,221	248	2,595	282	2,913	284
424	2,278	350	2,953	277	2,279	230
425	2,750	343	2,964	345	2,472	254
426	2,797	497	2,281	338	1,700	270
427	2,367	294	2,707	305	2,346	249
428	2,930	298	3,525	257	2,213	312
429	2,585	292	2,471	284	1,825	304
430	2,154	326	3,297	296	2,910	327
431	3,331	332	1,685	320	3,220	235

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
432	1,911	277	2,401	285	2,323	246
433	3,046	289	2,687	369	2,019	227
434	1,802	287	2,727	308	3,973	398
435	2,141	293	2,308	344	1,748	267
436	3,371	267	2,377	242	2,406	251
437	2,139	560	3,606	270	2,592	281
438	6,875	279	2,388	290	1,839	243
439	1,880	326	2,209	315	2,153	255
440	2,462	299	2,036	274	1,925	266
441	2,278	252	2,404	272	3,223	265
442	2,372	294	2,518	289	2,108	235
443	2,670	339	2,221	322	2,308	243
444	2,166	256	2,139	309	1,886	229
445	2,365	280	2,164	355	2,030	232
446	1,983	303	2,152	272	2,077	257
447	3,060	364	5,774	267	1,757	257
448	2,426	373	2,066	327	2,661	300
449	2,431	288	2,513	321	1,836	266
450	2,877	271	3,320	232	1,831	284
451	2,453	267	1,940	279	1,662	226
452	2,774	288	2,190	288	1,806	273
453	2,212	281	3,059	286	2,219	291
454	2,047	311	3,301	273	1,823	219
455	3,598	366	2,474	280	1,853	229
456	2,200	302	2,543	296	2,079	292
457	2,759	332	1,997	324	2,007	258
458	1,808	345	2,986	321	3,024	262
459	2,073	325	2,473	279	1,944	212
460	2,070	310	2,428	278	2,274	261
461	2,189	301	1,981	310	2,054	242
462	2,386	281	2,110	296	1,906	231
463	2,414	311	2,695	273	1,800	245
464	1,857	290	2,120	308	1,953	269
465	2,113	300	2,741	356	2,646	299
466	2,056	318	2,438	334	1,772	245
467	3,119	320	2,002	313	2,134	282
468	2,262	261	2,073	329	1,876	341

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
469	4,625	303	2,739	380	2,235	260
470	2,291	321	2,075	313	1,547	276
471	3,024	452	2,130	271	4,916	247
472	2,211	275	1,948	375	3,701	1,024
473	2,478	287	2,431	305	2,199	237
474	2,592	286	3,394	275	2,789	222
475	2,198	334	2,260	263	1,974	240
476	3,173	328	2,241	296	1,925	271
477	2,086	278	1,827	286	2,140	235
478	2,765	282	1,736	325	1,748	251
479	2,207	300	2,325	288	2,146	198
480	2,572	326	2,907	267	2,135	226
481	2,382	314	2,215	299	1,920	297
482	2,454	265	2,186	291	1,960	254
483	2,145	296	2,699	345	1,841	257
484	2,450	308	2,035	259	2,146	288
485	2,251	313	2,494	354	1,639	291
486	2,491	294	1,855	326	1,874	247
487	3,289	323	2,616	312	1,888	285
488	2,478	267	1,952	319	1,972	267
489	3,076	313	2,239	312	2,121	285
490	2,160	283	1,669	315	2,493	213
491	1,986	276	1,984	311	2,061	322
492	2,033	260	3,298	296	2,363	264
493	2,999	350	2,561	281	2,278	269
494	2,038	339	5,005	462	2,662	305
495	2,381	319	3,609	288	1,956	227
496	2,620	266	2,807	303	2,576	252
497	2,161	262	2,118	335	1,957	290
498	2,580	315	2,445	308	2,162	257
499	2,297	286	2,840	272	1,897	355
500	2,993	307	2,337	266	2,147	230
501	2,134	294	1,959	276	1,908	361
502	1,662	275	2,548	367	1,738	307
503	2,439	280	2,439	275	1,973	279
504	2,472	256	2,182	290	2,625	263
505	2,280	292	4,732	288	1,633	238

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
506	2,253	289	2,848	269	1,976	256
507	1,803	270	3,100	273	1,924	287
508	2,519	251	3,040	293	1,767	317
509	2,546	273	2,100	315	3,140	241
510	2,959	261	2,626	278	1,995	268
511	1,831	268	2,326	326	2,143	294
512	2,803	479	2,080	276	2,424	224
513	2,100	265	2,641	333	2,271	295
514	1,885	532	3,827	308	1,735	229
515	2,983	320	2,224	274	3,165	256
516	4,331	292	2,159	332	2,160	234
517	2,172	362	1,823	279	1,992	346
518	1,883	261	2,226	317	1,821	243
519	2,448	305	2,092	254	2,421	269
520	2,052	258	2,236	280	1,905	329
521	2,342	292	2,893	318	1,825	270
522	2,040	280	2,764	277	1,801	248
523	1,945	300	2,542	296	2,176	278
524	1,876	266	1,970	279	1,663	248
525	2,096	308	2,748	257	2,683	244
526	1,558	299	2,244	294	1,817	256
527	2,657	354	1,675	282	1,672	274
528	1,842	349	3,976	332	2,888	255
529	1,923	327	2,440	258	1,787	279
530	2,306	330	2,031	270	1,959	302
531	2,002	296	2,431	530	1,796	355
532	3,842	285	2,172	301	2,707	317
533	2,645	302	2,417	294	1,976	248
534	2,618	291	2,247	269	1,783	229
535	3,276	312	1,916	299	2,753	290
536	2,604	313	2,058	289	2,334	236
537	2,803	278	2,158	307	1,780	257
538	2,420	310	3,422	266	1,842	268
539	2,221	293	1,852	289	2,218	271
540	2,270	321	2,164	344	2,581	330
541	2,470	242	1,891	248	2,061	265
542	1,744	396	3,256	285	2,317	237

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
543	3,219	287	2,583	317	1,768	253
544	5,963	280	3,071	262	3,293	311
545	2,575	298	2,983	267	2,355	278
546	1,923	276	2,176	262	1,948	233
547	2,263	352	2,304	317	1,979	231
548	2,170	345	2,234	326	1,799	303
549	2,076	303	1,968	305	1,928	320
550	2,328	280	1,987	388	1,973	292
551	2,319	288	2,708	339	2,152	286
552	2,149	294	2,243	273	1,718	228
553	1,844	313	2,158	319	1,707	240
554	2,011	344	2,479	261	1,930	307
555	2,138	285	2,848	279	3,442	267
556	1,993	340	2,913	269	2,618	236
557	1,982	312	2,663	255	1,906	268
558	2,270	320	2,642	298	1,610	235
559	3,354	320	3,013	299	1,925	236
560	2,056	347	3,405	242	1,973	261
561	2,262	314	2,486	318	2,859	281
562	2,504	287	2,383	290	1,923	245
563	1,831	316	2,828	336	1,527	273
564	7,047	308	2,223	270	2,260	260
565	2,184	228	2,101	243	2,546	259
566	2,265	357	3,468	369	3,544	285
567	2,278	298	3,157	466	1,678	290
568	2,586	258	2,851	271	1,517	244
569	2,047	290	2,466	267	1,775	250
570	3,255	384	1,771	266	1,738	282
571	2,177	300	2,021	304	2,304	288
572	2,064	442	2,302	296	2,564	259
573	2,128	295	4,602	314	1,879	246
574	1,762	297	1,746	279	2,014	262
575	1,669	262	3,094	324	2,434	348
576	2,940	476	3,534	278	1,692	267
577	3,706	304	2,268	310	1,706	227
578	2,373	280	2,916	293	2,543	239
579	2,099	342	4,312	284	1,923	249

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
580	2,110	355	2,967	378	1,672	227
581	2,160	268	2,578	376	1,782	227
582	1,886	298	2,712	295	1,746	302
583	2,436	287	1,888	254	1,917	248
584	3,174	290	2,101	328	1,927	242
585	2,023	277	1,990	288	1,604	318
586	2,361	293	2,019	291	1,613	234
587	3,196	247	2,352	271	1,782	235
588	1,789	303	2,303	290	1,925	294
589	2,968	319	2,512	285	2,045	340
590	2,988	260	1,847	289	3,266	254
591	2,212	378	2,407	352	1,990	227
592	2,610	314	2,264	307	1,667	213
593	2,634	304	2,073	261	2,845	260
594	2,957	288	2,411	233	3,643	237
595	2,414	334	2,332	319	1,997	253
596	2,424	287	2,518	280	1,754	233
597	2,393	298	1,829	305	1,965	282
598	2,630	252	2,041	310	1,896	240
599	2,087	299	2,298	237	2,130	317
600	3,325	325	2,233	288	2,404	264
601	2,706	270	2,601	304	1,618	226
602	3,905	256	2,005	336	2,104	257
603	3,160	267	2,749	288	2,821	325
604	2,601	279	2,399	306	2,386	254
605	2,009	347	2,203	297	2,049	269
606	2,245	348	2,272	272	1,721	257
607	2,158	317	1,986	278	1,996	233
608	2,511	310	2,938	332	2,706	288
609	2,243	264	2,663	266	2,037	257
610	2,238	307	3,944	250	2,071	234
611	1,755	276	1,739	271	1,676	292
612	1,925	338	2,878	350	2,571	343
613	4,028	455	1,792	330	1,554	264
614	2,992	295	2,294	279	1,956	221
615	2,417	257	1,723	303	2,268	251
616	1,968	300	1,830	363	2,030	240

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
617	2,152	257	2,153	431	2,511	279
618	2,414	282	2,813	327	2,042	310
619	2,349	329	2,113	290	2,016	236
620	2,306	337	3,068	340	2,095	253
621	1,966	303	2,549	331	2,320	264
622	2,531	327	2,407	300	2,442	290
623	2,219	260	2,324	347	1,672	253
624	2,440	296	2,209	329	2,021	344
625	1,789	316	3,073	335	1,954	266
626	2,168	306	2,289	283	1,587	282
627	2,016	237	2,066	574	2,072	295
628	3,930	305	2,399	246	2,209	311
629	2,518	291	2,312	559	1,837	299
630	2,258	338	1,983	310	1,762	238
631	2,185	316	2,772	298	1,666	241
632	3,293	274	2,671	271	2,055	243
633	1,844	301	2,310	310	2,761	322
634	3,773	283	2,493	347	1,670	261
635	2,506	285	3,276	391	2,121	256
636	2,277	303	2,212	277	1,727	246
637	2,490	270	2,334	293	1,734	234
638	2,005	267	2,755	322	1,843	314
639	4,191	329	2,240	243	1,996	262
640	2,117	236	2,241	269	2,231	306
641	2,208	292	2,711	261	2,407	306
642	2,297	332	2,535	439	1,851	293
643	3,590	290	2,582	321	1,811	263
644	2,543	264	2,149	284	1,524	266
645	2,900	302	2,664	315	2,559	241
646	1,723	302	2,045	294	2,536	305
647	2,325	257	2,351	316	1,891	270
648	1,745	283	2,030	353	2,146	265
649	2,092	287	2,050	413	2,100	270
650	1,981	288	2,213	247	1,681	419
651	2,095	325	1,990	278	1,999	272
652	2,406	257	2,200	279	1,771	285
653	2,025	302	2,324	299	1,688	378

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
654	2,587	260	3,139	333	2,354	350
655	2,198	271	2,465	326	1,943	284
656	2,656	271	3,769	263	2,800	266
657	3,660	347	3,159	304	1,949	248
658	2,465	266	2,623	271	1,859	274
659	2,819	282	2,449	412	1,558	241
660	4,395	294	2,231	280	2,062	241
661	3,722	304	2,181	269	1,697	231
662	2,646	295	1,569	232	1,943	259
663	2,320	263	1,686	320	2,863	224
664	2,533	318	3,305	337	2,469	297
665	1,920	288	2,194	266	1,813	239
666	2,180	326	2,501	278	2,155	292
667	2,183	314	2,057	280	2,307	235
668	2,317	345	2,305	302	1,795	292
669	2,529	293	2,021	321	7,858	305
670	2,424	369	5,615	291	2,279	263
671	3,580	295	1,822	326	1,644	284
672	2,994	316	2,265	276	2,627	253
673	2,397	307	3,037	291	3,158	301
674	2,814	295	2,369	322	1,773	242
675	2,101	308	2,779	300	1,600	342
676	2,158	346	3,054	348	1,807	280
677	1,961	316	2,069	347	1,537	262
678	2,623	273	2,373	262	2,199	277
679	2,436	342	1,964	266	2,033	255
680	2,655	247	2,606	286	1,900	234
681	2,628	337	3,346	306	3,585	245
682	2,040	310	1,978	346	1,781	266
683	2,246	270	3,122	289	1,870	236
684	3,260	309	2,383	271	2,079	235
685	2,229	233	2,090	265	2,425	254
686	2,031	275	1,972	272	2,476	266
687	3,035	329	2,447	249	1,932	239
688	2,361	247	3,745	313	2,530	285
689	2,929	339	2,949	264	2,219	228
690	1,910	305	2,912	356	1,487	189

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
691	2,331	292	3,076	372	1,914	262
692	2,309	261	2,236	300	2,043	260
693	2,041	309	2,184	259	2,066	306
694	2,139	302	1,964	267	1,564	251
695	1,932	319	2,178	274	2,511	225
696	2,026	275	2,105	290	1,724	300
697	2,628	275	2,857	268	1,912	232
698	1,856	303	2,572	250	2,085	266
699	2,648	373	4,554	416	2,680	299
700	2,253	276	2,596	286	2,985	296
701	2,442	249	2,224	329	1,607	222
702	2,154	309	1,896	333	2,104	245
703	2,521	531	2,330	317	1,593	261
704	2,580	309	2,184	265	1,716	246
705	2,146	281	2,594	262	1,886	293
706	2,367	335	2,166	264	2,544	238
707	2,560	287	2,503	334	2,038	285
708	2,113	281	2,075	265	1,322	245
709	2,094	327	2,458	275	1,650	238
710	2,345	316	2,215	275	2,877	337
711	2,701	344	2,193	304	1,891	267
712	2,387	318	2,122	338	1,959	219
713	5,430	244	2,309	301	2,130	261
714	2,598	254	2,470	239	2,688	223
715	1,773	314	2,153	321	2,423	229
716	2,146	259	4,824	329	1,644	269
717	2,563	292	1,988	302	1,958	258
718	2,425	282	2,217	289	2,472	278
719	2,568	360	2,212	304	2,689	257
720	2,349	311	2,089	276	2,051	276
721	2,784	258	2,594	279	1,927	281
722	2,057	314	3,569	322	2,162	283
723	1,996	255	2,175	291	2,051	267
724	2,126	301	2,540	293	4,603	265
725	2,138	292	2,141	266	1,335	225
726	6,404	268	2,259	259	3,024	255
727	2,123	324	3,509	259	2,075	270

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
728	2,105	292	2,156	288	2,290	246
729	2,348	301	2,297	284	3,166	279
730	2,367	352	2,785	463	1,891	315
731	1,967	244	2,654	331	1,463	366
732	3,715	299	2,218	305	2,843	266
733	1,929	269	3,701	357	2,475	376
734	4,348	324	2,621	471	1,792	275
735	2,261	481	4,753	271	1,645	417
736	2,161	282	2,070	290	2,380	265
737	1,979	298	2,258	307	2,484	231
738	2,937	287	1,954	280	1,861	251
739	2,177	294	2,891	306	2,711	284
740	2,883	331	2,248	322	2,328	219
741	1,826	291	4,471	280	3,106	556
742	2,607	306	1,852	278	2,198	254
743	2,695	303	2,951	303	2,149	272
744	1,674	298	3,687	288	1,729	259
745	2,928	283	3,837	271	1,986	233
746	2,179	317	2,390	254	2,236	246
747	2,022	299	2,534	289	2,153	267
748	2,734	355	2,154	370	2,755	247
749	1,699	300	3,829	359	3,937	257
750	2,069	340	2,395	257	2,343	268
751	2,618	283	2,083	319	1,772	295
752	1,927	285	3,781	308	3,498	269
753	3,674	312	1,729	351	1,884	297
754	2,722	327	2,002	444	2,233	265
755	2,595	386	2,163	581	3,306	223
756	2,570	265	2,814	251	2,197	308
757	1,984	264	2,334	346	2,145	227
758	2,621	291	2,511	267	1,742	256
759	2,079	284	2,902	335	2,231	242
760	2,186	288	1,831	271	2,395	329
761	2,175	288	2,010	305	2,087	270
762	1,907	295	2,551	344	2,268	395
763	2,199	314	2,163	280	3,227	217
764	2,215	266	2,214	281	2,052	224

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
765	2,087	281	2,191	242	1,833	271
766	3,046	262	2,826	324	2,149	312
767	2,262	299	2,574	392	2,090	280
768	2,312	314	1,907	303	2,538	264
769	1,978	263	2,427	276	1,845	242
770	3,040	273	1,945	289	2,283	284
771	2,392	364	2,008	289	1,954	291
772	2,459	261	2,038	266	2,135	268
773	2,320	272	2,356	267	1,954	256
774	2,484	294	2,523	317	1,866	271
775	2,441	264	2,059	336	1,756	278
776	2,262	282	2,438	325	1,818	316
777	1,813	318	2,046	262	1,794	249
778	1,988	241	2,532	309	2,224	205
779	1,900	272	2,618	275	2,471	318
780	3,249	238	2,950	265	2,487	259
781	2,450	301	2,027	283	2,159	268
782	5,925	443	8,222	274	2,253	346
783	2,218	381	1,947	327	1,683	245
784	2,119	246	2,387	322	1,901	294
785	4,765	310	2,211	336	2,930	270
786	1,975	257	2,340	360	1,440	257
787	2,305	304	2,673	391	2,672	510
788	1,953	310	2,216	243	1,574	224
789	2,323	303	1,993	302	2,584	251
790	2,510	365	1,754	279	1,536	244
791	1,882	306	1,964	309	2,622	232
792	2,516	331	2,456	384	1,757	230
793	2,299	327	1,994	285	2,105	266
794	2,315	394	3,969	393	2,254	269
795	1,852	392	2,018	308	2,486	291
796	2,107	320	2,371	269	1,789	261
797	1,842	260	2,431	532	2,114	241
798	2,247	248	2,388	326	1,910	272
799	4,674	325	2,354	288	2,987	213
800	2,091	377	2,684	290	1,780	275
801	1,893	346	2,169	269	2,341	244

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
802	2,168	364	2,763	331	2,083	300
803	2,444	364	2,155	261	2,852	322
804	2,903	276	2,632	296	1,762	239
805	2,400	293	2,175	259	2,390	318
806	2,316	283	2,706	267	1,720	229
807	2,056	297	2,345	254	2,309	352
808	2,588	301	2,866	314	3,759	206
809	2,305	294	4,399	323	2,916	248
810	3,050	311	2,009	270	1,588	287
811	3,291	294	2,366	284	2,647	311
812	3,026	302	2,167	325	2,113	259
813	3,171	284	2,205	269	1,898	300
814	2,162	261	2,913	261	1,861	290
815	2,059	304	2,002	271	2,112	291
816	2,622	303	2,000	262	2,260	247
817	2,301	250	1,904	275	3,014	246
818	2,412	251	2,008	297	5,441	229
819	2,248	336	2,265	293	2,098	248
820	2,813	319	2,815	243	2,324	286
821	2,667	283	2,464	346	1,979	254
822	3,064	301	2,243	270	1,882	277
823	2,050	250	2,705	294	2,473	285
824	4,215	297	2,947	310	2,830	218
825	3,121	300	2,414	279	2,278	282
826	3,835	288	2,132	289	2,396	271
827	2,687	288	1,823	325	2,376	244
828	2,414	299	2,190	310	2,120	235
829	2,244	237	2,129	362	2,460	236
830	1,848	251	2,307	295	2,271	256
831	1,999	278	1,789	300	1,558	315
832	1,940	319	2,083	286	2,276	258
833	4,438	344	3,248	309	1,899	196
834	2,713	298	2,465	289	3,002	257
835	2,696	254	1,859	236	2,405	253
836	2,011	287	2,028	278	2,267	307
837	2,672	264	2,261	265	4,290	252
838	2,527	330	2,188	268	2,105	261

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
839	2,580	306	2,283	276	3,233	282
840	2,175	294	2,004	345	1,493	257
841	2,021	316	1,757	325	1,970	226
842	2,948	262	2,292	299	1,908	244
843	2,533	321	2,048	286	2,106	222
844	1,922	263	2,220	262	4,462	242
845	2,919	292	2,865	310	4,064	280
846	3,118	409	3,693	307	2,550	245
847	2,482	292	2,038	334	1,678	315
848	2,471	255	3,028	318	2,673	235
849	2,560	356	3,033	304	1,981	257
850	1,820	374	2,685	274	2,867	242
851	1,984	383	2,396	352	1,871	307
852	2,186	292	2,245	306	2,318	220
853	2,043	295	2,008	374	2,196	243
854	2,139	283	1,819	285	1,905	236
855	2,106	327	2,228	298	4,292	256
856	1,796	460	2,138	311	2,320	250
857	2,728	304	2,662	296	2,425	306
858	1,875	313	3,012	277	1,934	565
859	2,182	285	2,100	314	2,530	236
860	3,506	330	3,428	270	2,306	235
861	1,928	276	2,070	265	1,485	260
862	2,597	281	3,275	284	1,775	235
863	1,995	260	4,280	247	2,000	295
864	2,006	297	2,195	327	2,196	248
865	2,358	267	2,742	283	1,820	249
866	2,841	242	1,997	256	2,031	283
867	1,986	258	2,487	267	2,898	292
868	1,594	323	2,356	278	2,102	232
869	3,310	290	2,387	279	3,367	295
870	2,230	289	3,249	328	1,706	286
871	2,262	267	1,861	355	1,519	241
872	1,901	322	1,863	277	1,824	256
873	2,141	299	2,089	343	1,930	246
874	1,909	259	1,917	292	3,308	271
875	2,715	374	1,890	292	2,795	331

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
876	1,934	326	2,470	288	1,686	349
877	2,022	259	1,924	312	2,009	305
878	2,951	340	2,475	389	1,886	301
879	2,689	326	2,357	312	1,928	254
880	2,216	306	2,212	355	1,860	285
881	2,043	297	1,942	336	2,602	277
882	2,167	278	2,246	289	2,668	267
883	2,037	365	2,897	308	2,165	282
884	1,711	295	2,069	253	2,061	250
885	2,413	377	2,096	265	1,762	296
886	2,046	286	1,998	476	1,639	284
887	2,653	266	2,656	271	1,797	286
888	2,420	340	2,038	291	1,752	305
889	3,047	271	2,791	267	1,445	235
890	2,465	346	2,813	285	2,088	242
891	2,763	308	2,038	254	2,652	287
892	3,426	291	2,171	273	1,957	285
893	3,653	309	2,206	278	2,474	270
894	2,240	266	2,435	452	2,997	329
895	1,814	292	2,323	341	1,818	308
896	9,672	338	3,561	296	2,247	246
897	2,576	276	1,865	344	8,939	263
898	5,332	306	2,154	312	2,609	289
899	3,602	284	2,049	287	2,238	301
900	2,233	320	2,245	321	1,695	245
901	2,326	311	2,510	279	2,114	268
902	2,376	301	2,544	338	2,167	229
903	1,752	336	2,383	320	1,696	247
904	1,987	307	2,102	276	1,771	338
905	4,834	351	2,299	282	1,790	246
906	1,893	236	2,461	287	2,464	322
907	2,125	310	2,249	297	2,029	296
908	2,747	300	2,261	307	2,073	270
909	2,000	250	3,885	261	1,894	281
910	5,238	292	1,991	340	1,710	334
911	1,952	284	2,239	295	5,881	261
912	2,753	325	2,549	293	1,690	251

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
913	2,571	313	3,721	312	1,842	232
914	4,054	355	2,315	289	1,927	237
915	1,912	400	2,255	359	2,776	246
916	2,330	362	2,006	250	2,083	242
917	2,422	272	2,261	308	1,955	284
918	2,857	294	2,663	298	1,904	234
919	1,750	275	2,668	317	1,567	236
920	2,983	230	2,912	291	1,908	269
921	2,058	308	3,446	300	2,221	270
922	1,905	254	2,524	285	1,551	304
923	3,128	309	2,461	289	1,659	244
924	2,399	248	1,730	349	1,748	301
925	1,728	294	2,574	318	1,615	301
926	2,287	323	1,869	285	2,547	308
927	2,009	295	2,461	293	3,127	294
928	2,202	297	2,008	277	2,067	238
929	2,761	296	2,265	302	5,548	253
930	1,811	287	2,348	284	2,662	258
931	2,584	288	2,959	293	1,759	298
932	2,474	291	1,920	332	2,298	262
933	1,841	264	4,064	294	1,962	302
934	2,444	332	2,073	303	1,578	336
935	1,878	287	2,155	316	1,989	314
936	1,837	295	3,184	309	3,042	235
937	2,517	385	2,771	275	1,808	277
938	1,895	278	2,031	309	1,781	274
939	1,903	521	2,574	267	1,542	264
940	2,104	387	1,839	284	2,019	238
941	2,824	261	2,236	242	2,868	289
942	3,086	303	3,305	292	2,946	258
943	1,991	291	2,182	245	2,361	244
944	1,885	301	3,292	266	1,854	305
945	1,818	257	2,171	251	1,721	242
946	1,670	309	2,047	281	1,777	227
947	2,218	338	3,041	263	2,074	231
948	2,622	289	3,593	279	2,726	289
949	2,366	339	2,702	285	2,152	230

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
950	1,976	321	3,068	240	2,063	258
951	2,218	247	1,830	245	1,454	245
952	2,848	311	2,170	324	2,478	263
953	1,938	370	2,305	302	2,079	280
954	2,823	285	2,519	234	2,066	233
955	2,126	323	2,492	288	2,120	292
956	2,068	382	2,482	299	1,940	260
957	2,428	306	2,200	420	2,118	265
958	1,771	312	3,544	249	2,247	241
959	2,300	272	2,728	263	1,621	219
960	1,937	496	2,193	276	2,325	274
961	1,842	274	4,028	306	1,761	282
962	2,854	329	3,155	266	1,461	263
963	2,348	281	2,228	330	1,820	255
964	2,529	222	2,107	252	1,830	301
965	2,167	316	2,317	320	3,636	228
966	2,690	315	2,510	280	2,206	234
967	2,870	311	2,315	251	2,474	254
968	5,135	270	2,100	381	1,899	271
969	2,545	368	2,071	310	1,736	255
970	2,408	267	5,149	278	1,867	228
971	1,801	326	2,449	323	1,923	265
972	1,951	330	2,646	278	2,252	277
973	2,302	268	2,690	370	1,702	281
974	2,159	328	2,057	373	1,606	546
975	2,656	312	2,115	303	2,093	223
976	1,944	253	2,158	279	1,615	265
977	2,649	316	2,115	347	2,064	276
978	2,058	294	2,278	315	3,137	236
979	1,749	311	2,377	301	2,094	249
980	2,223	246	2,937	275	1,388	306
981	1,903	299	3,302	241	1,942	235
982	2,018	396	3,990	284	2,128	263
983	2,012	328	2,106	271	2,902	281
984	1,933	280	1,813	313	1,740	265
985	1,874	261	2,702	278	4,694	306
986	2,578	303	2,348	294	1,904	217

	Method 1		Method 2		Method 3	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
987	1,699	289	2,208	302	1,855	257
988	2,963	334	2,640	264	2,862	243
989	2,677	289	2,505	375	1,811	280
990	2,858	272	2,906	294	1,780	267
991	2,473	291	2,231	327	1,962	533
992	2,675	290	2,146	287	1,817	259
993	1,605	344	2,267	255	1,650	251
994	1,790	291	2,232	335	1,803	287
995	2,434	307	2,249	270	2,912	240
996	2,402	300	2,482	270	2,025	255
997	2,228	259	2,546	393	1,825	248
998	2,157	292	2,975	333	1,818	261
999	3,272	256	3,025	355	2,133	348
1000	2,139	314	2,126	322	1,679	304

Table O.8 Embodied energy and CO_2 emissions data sets for construction of Rammed Aggregate Columns at Pearson Hall, from Monte Carlo simulation following Methods 4 and 5 of accounting for subsurface variability, and from the as-built condition.

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	2,233	272	1,937	265	1,906	174
2	3,150	258	2,700	231	1,390	213
3	2,084	205	3,115	265	2,032	210
4	1,908	275	1,667	233	1,754	205
5	1,561	217	2,626	271	1,772	218
6	1,377	226	3,041	234	1,875	202
7	2,114	200	1,731	305	1,704	220
8	1,872	197	2,297	245	1,890	221
9	1,978	220	2,161	250	2,002	172
10	1,576	198	1,930	254	2,152	193
11	2,041	252	2,189	233	1,540	295
12	1,964	239	1,997	278	1,765	212
13	1,888	198	1,871	241	1,691	215
14	1,698	254	1,953	256	1,848	230
15	2,030	249	2,234	308	1,496	240
16	1,740	219	1,893	258	1,539	223
17	1,897	219	2,102	304	1,768	276
18	1,477	220	2,175	247	1,657	215
19	1,326	218	1,699	256	1,665	257
20	1,964	225	1,887	266	1,367	189
21	1,615	229	1,992	262	5,250	235
22	5,287	259	2,222	240	1,609	244
23	1,740	225	1,639	227	1,718	193
24	1,963	250	1,574	369	1,537	256
25	1,470	255	1,938	452	1,551	201
26	1,881	206	1,871	273	1,779	243
27	3,426	214	1,769	255	1,692	196
28	1,606	239	2,888	230	2,069	211
29	1,384	224	2,089	257	1,452	263
30	1,904	196	1,991	290	1,624	214
31	1,815	199	2,643	247	2,021	224
32	1,229	243	2,544	251	1,505	211
33	1,783	185	1,825	260	2,052	223
34	1,602	212	2,386	319	1,868	240

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
35	2,458	213	1,805	271	1,562	242
36	1,534	224	2,189	276	1,424	224
37	4,912	225	2,308	281	2,759	207
38	1,577	211	2,302	243	1,653	224
39	1,564	222	1,854	240	1,512	284
40	3,322	203	2,222	255	2,971	243
41	2,068	217	1,549	256	1,439	208
42	1,877	219	1,493	312	2,374	198
43	1,643	235	2,021	248	1,755	227
44	1,835	222	2,001	276	1,630	214
45	1,984	246	1,683	271	1,557	241
46	2,024	177	1,771	270	2,552	278
47	1,848	204	2,229	246	1,739	217
48	1,815	191	1,982	278	1,715	227
49	3,730	212	2,000	242	1,303	259
50	1,677	204	1,837	253	2,106	226
51	4,388	243	1,890	233	1,557	194
52	1,687	201	3,109	249	2,032	306
53	2,100	219	2,077	316	2,578	216
54	2,178	255	1,849	227	1,971	191
55	2,563	215	2,773	244	2,010	230
56	1,497	243	1,755	237	1,692	230
57	1,713	222	2,392	328	1,402	219
58	1,765	221	1,695	211	1,554	185
59	1,546	218	2,275	316	1,753	217
60	1,597	192	1,896	288	1,832	194
61	1,636	222	1,891	286	4,909	229
62	2,149	228	2,131	236	1,406	211
63	1,582	216	1,955	254	1,422	286
64	1,381	215	2,204	263	2,220	266
65	1,860	214	1,974	236	1,748	222
66	1,518	233	2,109	255	1,670	207
67	1,628	290	2,117	270	2,210	206
68	1,593	219	2,264	359	2,686	212
69	2,240	236	2,056	206	2,268	218
70	1,933	195	1,941	308	1,418	223
71	1,682	223	2,847	258	1,828	241

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
72	1,553	253	2,225	249	1,862	232
73	2,114	236	1,892	264	2,875	229
74	2,032	250	2,428	237	2,825	259
75	1,487	218	2,479	244	1,765	211
76	1,898	210	1,763	242	1,860	242
77	1,798	259	1,897	279	1,635	203
78	1,615	216	1,867	302	1,816	255
79	3,339	228	1,808	245	1,282	210
80	1,910	218	1,961	280	1,511	236
81	3,986	213	2,441	280	1,524	207
82	1,427	227	2,292	211	2,506	200
83	1,785	237	2,099	303	1,982	196
84	1,586	273	1,580	249	1,853	241
85	1,791	233	1,707	261	1,750	243
86	1,555	250	2,235	221	1,465	213
87	1,394	293	1,634	250	3,027	300
88	1,440	217	2,304	289	1,695	232
89	1,631	216	2,049	246	1,761	230
90	2,225	224	2,749	290	1,500	217
91	1,794	226	1,875	215	1,629	222
92	1,516	213	2,002	263	3,322	236
93	1,606	237	2,522	292	2,460	200
94	1,509	272	4,884	241	1,608	210
95	1,670	216	2,227	314	1,481	205
96	3,520	229	2,168	253	1,523	217
97	1,462	232	2,050	304	1,857	212
98	1,807	199	2,014	302	3,567	234
99	1,560	210	1,888	303	1,519	197
100	2,919	219	1,679	263	1,477	226
101	1,415	198	2,152	291	2,108	215
102	2,165	253	2,107	222	2,553	233
103	1,475	244	1,404	262	1,649	213
104	2,051	242	2,339	262	1,613	215
105	1,339	215	2,747	281	2,488	202
106	2,346	214	3,070	308	1,526	253
107	1,767	273	1,766	285	2,056	202
108	3,918	236	4,966	227	1,971	195

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
109	2,678	226	2,583	232	3,546	246
110	2,189	208	3,054	293	1,426	213
111	1,468	418	1,923	242	1,991	265
112	2,033	220	1,887	261	1,553	195
113	2,204	217	1,739	247	1,493	215
114	2,640	242	2,963	220	1,562	238
115	1,719	246	1,665	231	2,217	215
116	1,775	208	2,181	374	1,923	200
117	2,165	265	1,530	246	1,751	209
118	1,793	257	1,959	244	2,085	194
119	1,869	214	2,282	245	1,458	232
120	1,688	251	3,091	273	1,651	237
121	1,460	194	1,450	246	1,806	194
122	1,357	209	3,648	267	1,508	201
123	1,399	217	1,832	245	2,037	212
124	2,047	205	1,881	237	1,549	211
125	1,926	315	1,821	302	2,499	228
126	1,754	204	1,899	231	1,324	205
127	1,976	246	2,079	255	1,531	206
128	1,559	203	2,213	303	2,857	237
129	1,272	230	1,989	249	1,904	247
130	1,970	248	2,246	267	1,514	243
131	1,540	229	3,139	261	1,685	247
132	1,650	300	2,134	278	1,552	217
133	1,723	234	3,043	256	3,143	180
134	1,638	223	2,078	269	1,498	191
135	1,650	222	2,143	235	1,820	194
136	1,567	323	2,451	246	1,753	238
137	1,966	210	2,219	214	1,726	197
138	1,784	186	4,666	289	1,928	214
139	1,910	242	2,258	276	1,830	240
140	1,569	205	2,083	268	1,653	228
141	1,753	210	1,647	264	1,643	278
142	1,412	213	1,884	247	2,605	263
143	1,433	239	1,850	257	1,579	231
144	2,032	206	1,936	289	1,447	218
145	2,588	257	2,795	272	1,791	209

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
146	1,491	229	2,481	228	1,793	217
147	1,887	245	2,037	271	2,038	237
148	1,919	231	2,754	290	1,417	236
149	1,490	250	2,174	257	1,953	225
150	1,837	269	2,346	297	2,112	203
151	1,764	178	1,985	308	1,917	183
152	2,788	186	4,764	282	1,614	185
153	2,885	218	2,798	250	1,990	210
154	2,458	206	1,605	252	1,892	242
155	2,909	219	1,972	238	1,710	228
156	1,724	204	2,304	258	1,922	235
157	3,573	201	2,222	279	1,855	245
158	1,839	211	1,801	307	1,910	219
159	1,855	194	2,504	282	2,257	270
160	1,714	232	2,373	252	1,337	234
161	2,081	225	3,278	253	1,751	227
162	3,301	223	1,993	502	2,000	222
163	1,623	196	1,865	214	1,489	230
164	5,254	252	1,827	292	2,063	244
165	1,579	216	2,685	285	2,061	224
166	1,669	264	1,848	250	1,862	271
167	1,809	227	2,140	263	1,933	295
168	3,489	230	2,038	272	1,900	207
169	1,841	241	2,092	257	2,039	311
170	1,598	237	1,633	256	2,318	213
171	2,068	237	2,040	242	1,785	214
172	2,215	267	2,118	253	2,460	259
173	1,587	164	2,067	232	1,771	231
174	2,006	193	2,665	254	1,826	230
175	1,844	242	2,035	240	1,610	326
176	1,550	264	2,873	253	1,551	222
177	2,228	197	2,041	253	1,967	191
178	1,795	229	1,706	235	1,816	209
179	1,701	234	2,562	261	2,025	214
180	1,516	216	2,890	235	1,442	234
181	2,221	232	2,803	264	1,332	215
182	1,465	216	1,624	248	1,752	217

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
183	1,665	249	3,110	229	2,101	215
184	1,719	229	2,180	244	1,705	193
185	1,669	294	1,905	204	1,607	297
186	2,143	240	2,287	319	1,251	235
187	1,719	185	2,212	209	1,694	252
188	1,662	214	2,245	281	1,746	209
189	1,896	225	2,217	278	1,668	231
190	2,132	201	1,699	258	1,658	224
191	1,290	209	2,128	213	2,100	222
192	1,964	253	1,641	352	1,756	341
193	2,049	201	4,068	278	2,668	244
194	1,508	233	2,830	290	1,741	215
195	2,147	262	2,137	274	1,683	284
196	1,846	264	1,618	246	2,554	209
197	7,066	208	1,781	255	1,529	251
198	2,036	244	3,363	314	1,838	216
199	2,312	227	1,694	242	1,834	236
200	1,732	227	1,863	216	1,788	488
201	1,732	193	2,724	272	1,519	196
202	1,303	198	1,798	272	1,813	241
203	1,267	206	1,990	244	1,353	217
204	1,568	260	2,489	263	2,479	258
205	1,579	232	1,717	260	7,315	199
206	2,042	232	2,869	290	2,526	235
207	1,847	212	1,959	241	1,923	233
208	1,432	237	1,896	279	1,743	222
209	1,776	236	2,999	228	1,836	250
210	1,627	203	2,284	273	3,391	200
211	1,866	225	2,376	230	1,428	222
212	2,000	249	1,759	234	1,651	194
213	1,807	244	1,833	235	1,972	219
214	1,431	226	1,782	277	1,938	243
215	1,998	227	1,476	296	1,695	219
216	1,648	252	1,772	274	1,907	245
217	2,331	227	1,779	274	1,832	232
218	1,497	243	1,933	249	1,494	287
219	1,885	174	1,895	245	1,939	220

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
220	1,826	206	1,931	309	2,046	278
221	1,674	178	2,379	257	3,752	223
222	4,475	204	1,551	263	2,423	215
223	1,806	187	2,252	237	1,971	223
224	2,228	240	1,778	246	2,116	220
225	1,854	215	2,110	208	1,785	198
226	1,602	278	2,773	334	1,565	222
227	1,499	234	2,044	271	2,125	229
228	1,295	201	1,862	239	1,763	254
229	3,778	229	2,924	249	2,200	236
230	2,683	201	1,750	270	2,639	223
231	2,433	237	1,984	282	1,528	210
232	2,792	216	6,235	239	2,724	228
233	1,400	234	1,525	227	1,794	209
234	1,864	268	2,084	218	2,343	290
235	1,481	198	2,081	341	1,661	267
236	2,008	251	2,825	242	1,531	201
237	1,585	237	1,745	243	1,963	230
238	1,608	234	1,667	315	1,874	225
239	1,667	240	1,840	268	1,615	231
240	2,171	223	2,327	220	1,459	257
241	1,814	219	1,599	278	1,569	204
242	1,978	213	1,922	261	1,942	229
243	1,964	208	1,741	238	1,872	212
244	1,574	231	2,397	255	1,465	241
245	3,470	206	1,727	285	1,500	221
246	2,481	251	1,710	275	2,186	211
247	2,131	234	1,895	498	1,559	210
248	1,880	212	1,918	230	1,802	227
249	1,965	225	2,305	236	2,539	196
250	1,467	218	2,148	312	1,465	215
251	3,046	217	2,744	268	2,062	224
252	1,531	206	1,579	288	1,283	237
253	2,053	241	2,386	230	1,642	205
254	2,871	187	1,928	236	1,591	291
255	3,059	204	2,277	264	1,792	246
256	1,945	198	1,836	290	1,692	265

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
257	1,572	225	2,060	251	1,442	327
258	1,782	209	2,483	223	2,312	174
259	1,705	247	2,125	271	1,677	262
260	1,697	216	1,939	232	2,233	250
261	1,348	256	2,753	246	1,763	317
262	1,547	265	1,995	234	2,232	326
263	3,956	318	1,645	241	2,189	267
264	1,945	220	2,211	252	1,563	262
265	1,727	194	1,741	247	2,118	253
266	1,902	242	2,188	338	1,986	203
267	1,533	427	2,558	236	1,645	264
268	1,932	202	1,557	282	1,441	205
269	1,548	299	2,516	321	1,616	185
270	1,742	210	1,680	340	1,607	221
271	1,791	226	2,064	259	1,452	208
272	2,306	263	2,114	279	1,558	242
273	1,942	214	1,858	252	1,655	223
274	2,179	224	2,263	363	1,942	305
275	1,972	260	2,770	315	1,803	288
276	1,618	271	2,097	260	1,511	254
277	1,285	229	2,198	279	1,695	231
278	1,772	231	2,932	237	1,967	213
279	2,527	193	1,457	265	1,663	230
280	2,032	229	1,708	270	1,758	202
281	1,707	243	1,881	227	2,008	192
282	1,585	201	1,947	288	1,569	228
283	2,101	209	2,032	277	2,139	208
284	1,465	272	2,093	233	2,460	228
285	1,462	261	2,703	314	1,504	215
286	1,541	206	1,653	264	2,262	222
287	1,639	216	2,098	246	2,163	206
288	1,979	239	1,881	285	1,560	276
289	1,663	242	1,965	244	3,008	255
290	1,820	267	2,106	264	1,545	243
291	1,662	193	2,017	311	1,550	199
292	1,724	301	1,863	279	1,734	234
293	4,816	221	1,796	248	1,395	220

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
294	2,212	269	3,929	239	1,447	251
295	1,662	210	1,730	289	1,589	223
296	1,648	214	3,323	256	1,914	226
297	1,740	217	1,668	275	1,876	278
298	1,972	219	2,883	260	2,011	272
299	1,831	192	1,565	274	1,595	222
300	1,650	233	1,772	271	1,780	221
301	1,882	226	1,957	218	1,818	216
302	1,518	214	1,700	271	2,508	194
303	10,114	234	1,690	271	1,992	198
304	1,635	247	2,386	236	2,000	198
305	2,135	229	2,325	254	1,916	292
306	1,504	199	1,785	271	1,832	232
307	1,716	201	2,117	229	1,405	291
308	2,275	221	2,083	280	1,853	203
309	2,500	234	1,828	304	1,801	193
310	1,443	230	1,938	282	1,885	212
311	2,357	239	2,094	297	2,146	237
312	3,330	249	1,837	266	1,637	203
313	2,107	267	2,163	241	1,561	236
314	1,821	224	2,839	248	1,713	225
315	1,403	238	1,865	282	1,784	229
316	1,941	273	2,028	247	2,214	204
317	4,084	248	2,569	299	1,362	194
318	1,836	237	1,980	233	1,367	199
319	1,729	234	1,786	253	1,691	238
320	1,860	196	2,500	251	1,950	283
321	1,731	206	2,740	267	1,724	205
322	1,521	245	1,817	268	2,013	223
323	1,533	200	1,719	248	1,755	268
324	1,585	229	1,816	242	1,667	225
325	1,557	219	1,649	301	1,849	266
326	2,604	177	2,811	325	2,077	209
327	1,940	204	1,945	279	1,667	324
328	1,562	242	1,608	275	2,593	225
329	2,013	303	1,944	214	1,639	269
330	1,789	221	1,745	254	2,243	223

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
331	1,489	214	2,799	244	1,619	312
332	2,168	241	1,717	225	3,049	210
333	1,876	205	2,188	290	1,866	195
334	1,699	259	1,608	309	2,123	218
335	1,637	257	1,775	281	1,741	228
336	1,533	327	2,397	299	1,524	261
337	1,681	222	1,999	253	1,539	230
338	1,461	207	1,773	291	2,738	334
339	1,986	264	1,787	242	2,590	247
340	1,789	213	1,927	224	2,391	211
341	1,402	238	1,742	236	1,572	332
342	2,192	204	2,072	281	1,511	244
343	2,139	260	1,740	255	2,368	190
344	3,301	302	2,330	261	2,122	199
345	1,465	238	2,181	227	1,503	238
346	2,405	217	3,615	265	1,525	227
347	1,506	275	1,955	268	1,937	243
348	1,971	211	2,066	231	1,445	191
349	1,473	206	2,014	257	1,474	219
350	1,508	212	1,909	270	1,404	199
351	2,667	241	2,448	241	1,757	222
352	1,893	212	2,345	272	1,439	213
353	1,373	254	2,099	276	2,365	183
354	1,633	251	1,980	249	2,438	217
355	1,779	202	2,089	290	1,453	210
356	1,961	254	1,774	320	1,472	208
357	1,314	231	1,907	232	1,605	210
358	2,617	220	1,844	249	2,174	282
359	2,104	293	2,088	257	1,537	238
360	1,527	236	1,821	219	1,643	207
361	1,626	256	1,896	276	2,051	213
362	2,263	210	2,503	271	2,560	217
363	2,883	246	1,612	276	2,044	229
364	2,050	218	1,688	240	1,302	210
365	1,636	197	1,644	239	2,339	214
366	1,494	222	3,272	255	1,506	197
367	1,485	259	1,857	235	2,158	607

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
368	1,678	293	1,895	336	1,726	203
369	2,375	252	1,568	246	1,998	200
370	1,948	212	1,761	306	2,155	306
371	2,230	275	1,880	306	1,756	249
372	1,761	221	1,960	252	1,764	249
373	1,728	208	1,951	232	1,817	232
374	1,892	325	2,710	236	2,187	254
375	1,353	251	1,978	224	1,891	219
376	1,558	216	1,570	283	1,792	294
377	2,002	205	1,875	249	1,607	214
378	1,550	205	1,745	289	3,477	239
379	1,651	216	2,185	301	1,735	191
380	1,704	208	2,295	280	1,315	215
381	1,944	247	1,690	250	3,294	252
382	2,466	212	2,265	235	1,548	251
383	2,338	211	2,145	273	1,786	323
384	1,538	209	1,911	266	1,553	199
385	2,276	283	1,724	255	1,555	263
386	3,728	275	1,808	291	2,447	253
387	2,290	201	1,911	252	1,754	208
388	1,393	220	1,863	263	1,948	214
389	1,509	194	1,761	248	1,721	305
390	1,616	243	1,789	301	1,587	183
391	1,705	243	2,396	245	1,824	207
392	2,418	214	2,389	282	1,894	199
393	2,433	233	2,697	255	1,565	228
394	2,161	249	1,888	243	2,778	241
395	1,625	219	1,973	276	2,032	239
396	1,533	249	2,245	219	1,630	259
397	1,411	262	1,662	224	1,746	224
398	2,144	223	1,693	221	1,308	213
399	2,266	268	5,166	262	1,721	266
400	2,211	231	1,958	241	2,209	196
401	1,710	237	1,673	290	2,026	262
402	1,771	269	1,928	247	1,583	202
403	1,799	286	2,581	248	3,969	183
404	1,793	275	1,762	263	1,994	276

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
405	1,553	358	2,115	221	2,132	273
406	2,054	177	8,071	271	1,562	220
407	1,687	227	2,157	266	1,924	233
408	1,700	262	2,498	348	1,354	239
409	1,728	225	2,078	323	1,665	242
410	2,068	270	2,531	280	2,571	223
411	1,641	215	1,934	306	1,468	225
412	1,783	226	2,927	227	1,489	201
413	2,297	242	2,166	258	1,628	213
414	1,616	197	2,073	282	1,687	209
415	2,035	211	2,695	252	2,377	230
416	3,093	202	2,173	270	1,632	195
417	1,367	185	2,135	265	1,929	230
418	1,738	255	2,133	244	3,066	249
419	3,055	244	2,194	307	1,587	275
420	1,610	227	2,079	303	2,092	258
421	1,703	198	2,109	303	1,452	209
422	1,311	210	1,743	258	2,392	237
423	1,710	214	1,623	297	1,955	228
424	1,368	179	1,738	273	1,483	224
425	2,185	186	1,899	283	2,046	215
426	1,612	243	1,802	226	2,013	287
427	1,493	256	1,629	234	2,040	207
428	1,727	224	1,822	329	1,412	203
429	2,929	211	1,854	261	1,515	296
430	1,774	203	2,188	284	1,719	201
431	1,801	261	2,372	256	1,428	243
432	1,785	255	2,119	299	1,711	187
433	2,293	207	1,897	350	1,420	227
434	2,052	220	1,932	230	1,972	231
435	2,169	210	1,768	288	2,121	183
436	2,948	217	1,717	250	1,538	234
437	1,771	204	2,415	236	1,753	202
438	1,447	228	1,641	246	3,091	226
439	1,878	211	1,914	228	2,027	205
440	2,029	197	2,234	237	1,595	201
441	1,592	208	1,851	303	1,634	211

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
442	1,455	212	2,700	243	2,201	253
443	2,238	187	2,142	256	1,984	179
444	1,768	219	2,142	263	1,539	327
445	1,616	276	1,985	232	1,591	206
446	1,978	233	1,670	291	2,068	203
447	1,937	205	1,702	251	1,832	205
448	2,017	187	1,624	330	1,719	274
449	1,449	229	4,191	285	1,422	199
450	1,895	306	1,627	360	1,722	218
451	1,540	221	1,757	282	1,396	226
452	2,226	337	1,781	228	1,586	236
453	1,390	206	2,224	243	2,102	226
454	1,791	234	2,558	214	1,698	213
455	1,419	225	1,728	266	2,107	209
456	1,650	251	1,988	261	1,830	226
457	1,628	220	1,782	384	1,786	242
458	2,242	222	2,062	298	2,162	251
459	1,856	223	1,874	337	1,602	211
460	3,376	212	1,848	472	1,993	251
461	1,921	219	2,681	282	1,576	221
462	1,394	271	1,974	293	2,149	260
463	1,945	202	1,565	229	1,970	310
464	1,419	231	1,842	302	1,551	211
465	1,823	232	2,140	232	1,702	219
466	1,755	227	2,145	266	1,764	218
467	1,575	254	2,371	231	1,639	210
468	1,368	251	1,938	234	1,790	225
469	1,647	242	2,028	310	1,683	233
470	1,942	251	3,860	276	3,976	176
471	1,566	200	2,331	253	1,507	217
472	1,666	218	1,940	264	2,753	207
473	2,490	196	1,906	272	1,797	211
474	1,915	194	1,990	277	1,563	242
475	2,395	232	1,758	233	1,589	305
476	2,033	240	3,230	267	1,779	188
477	1,752	201	2,128	326	1,807	198
478	1,614	227	1,981	270	1,615	232

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
479	1,667	178	2,121	256	4,036	292
480	2,226	199	2,266	317	2,096	215
481	1,630	231	1,501	272	1,485	267
482	2,356	198	1,739	251	2,390	228
483	1,552	198	2,051	243	1,609	239
484	2,377	205	1,599	244	1,775	235
485	1,785	203	1,701	276	2,009	231
486	1,964	192	1,932	434	2,548	308
487	1,942	243	2,070	258	1,831	241
488	1,807	241	1,922	241	1,511	220
489	2,062	255	1,940	244	1,505	216
490	1,494	195	1,844	257	1,889	234
491	2,274	231	2,075	306	1,821	194
492	1,503	223	1,691	309	1,756	261
493	1,753	206	1,540	247	1,893	233
494	2,516	229	1,987	251	1,783	187
495	1,876	194	4,720	238	1,772	225
496	3,154	225	1,974	278	1,567	213
497	1,836	265	2,071	260	2,259	218
498	1,912	193	3,175	254	1,698	271
499	1,624	206	2,187	271	1,992	283
500	2,443	250	2,300	249	1,826	197
501	2,401	249	3,413	276	1,535	213
502	2,187	204	1,994	267	6,084	201
503	1,802	223	1,870	334	1,558	426
504	2,081	185	2,507	247	1,436	214
505	2,087	201	2,092	232	1,813	249
506	1,572	187	2,041	295	1,500	191
507	2,328	241	2,393	242	2,359	215
508	1,961	231	1,876	224	1,977	228
509	1,696	223	2,049	297	6,699	266
510	1,666	282	1,681	287	1,681	216
511	1,550	181	1,639	250	1,845	202
512	2,261	236	1,825	248	1,618	223
513	1,897	210	2,887	259	1,616	234
514	1,516	199	1,386	234	1,576	209
515	2,047	217	2,244	260	1,610	261

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
516	2,143	225	1,851	288	1,759	238
517	1,721	224	1,830	323	1,908	535
518	2,797	228	2,319	234	3,153	220
519	2,048	240	1,940	277	1,675	212
520	1,765	231	1,886	238	1,489	199
521	1,734	274	1,742	247	1,579	263
522	1,941	228	1,403	227	1,509	351
523	1,943	199	2,049	259	1,770	223
524	1,935	260	1,799	269	1,748	227
525	1,830	250	1,898	406	1,959	217
526	1,858	236	2,575	264	2,172	230
527	1,778	226	1,589	254	1,945	242
528	2,144	229	2,404	261	2,314	236
529	1,743	215	2,726	218	1,485	171
530	1,468	214	2,342	294	1,846	195
531	1,540	208	2,266	292	1,405	224
532	1,702	262	1,980	268	1,777	233
533	1,864	215	1,858	245	1,440	184
534	1,809	204	2,530	246	2,094	244
535	1,623	202	3,321	312	3,420	227
536	1,705	250	2,377	251	1,437	270
537	2,003	229	2,130	251	2,475	229
538	1,649	213	2,756	280	1,652	213
539	1,819	251	2,007	244	1,988	217
540	1,973	222	2,051	288	1,635	237
541	1,616	272	2,108	284	1,842	215
542	1,729	227	1,821	234	1,584	193
543	4,126	209	2,882	271	1,726	227
544	1,647	229	1,748	250	4,024	239
545	1,802	270	2,179	239	1,575	217
546	1,373	241	1,873	275	1,626	215
547	1,463	673	3,283	227	2,711	228
548	2,211	231	2,003	234	1,881	202
549	2,040	216	2,668	225	1,670	233
550	2,183	268	2,068	264	2,029	207
551	2,046	206	1,945	240	1,659	236
552	1,864	214	2,551	252	1,921	222

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
553	2,700	216	1,642	255	2,215	253
554	2,149	231	1,588	276	1,652	273
555	1,805	202	2,098	255	1,523	193
556	1,444	230	1,857	280	1,588	256
557	1,360	221	1,702	268	2,038	237
558	1,390	225	2,441	219	1,640	217
559	2,091	224	3,555	289	2,931	240
560	1,617	189	2,432	251	1,478	252
561	1,879	268	2,164	250	1,608	183
562	1,674	254	2,079	273	1,592	201
563	1,401	200	2,013	249	1,386	212
564	1,328	233	1,665	288	1,476	210
565	2,047	219	2,135	325	1,496	215
566	1,812	227	2,228	238	1,760	221
567	1,609	266	1,532	282	1,972	226
568	2,188	242	2,468	260	2,596	232
569	1,398	198	2,162	276	1,856	228
570	1,595	245	1,764	245	1,327	239
571	1,946	183	2,494	252	1,578	375
572	1,917	206	2,487	294	2,581	250
573	1,698	202	1,964	263	2,041	224
574	1,702	291	2,019	254	1,824	212
575	1,672	208	2,416	263	1,953	220
576	1,373	187	2,013	271	2,669	216
577	2,110	223	4,840	273	1,557	232
578	1,670	200	1,663	283	1,574	232
579	1,837	250	2,093	244	1,362	241
580	1,781	217	1,879	233	1,776	205
581	2,083	210	1,903	325	2,078	242
582	1,699	234	2,023	253	1,934	242
583	1,899	238	1,694	269	1,504	229
584	1,975	205	1,736	263	1,444	226
585	1,767	218	2,033	269	1,672	215
586	1,601	214	2,434	287	1,539	193
587	2,231	211	2,052	233	2,504	246
588	1,570	274	1,505	265	1,505	208
589	1,982	175	1,840	272	1,929	241

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
590	1,885	254	1,743	272	1,662	217
591	1,986	193	2,214	218	1,620	219
592	2,173	246	2,390	255	1,773	223
593	1,780	247	2,325	312	2,161	250
594	1,536	216	2,420	244	1,819	217
595	2,672	188	1,758	277	1,601	248
596	1,547	240	1,628	309	1,887	256
597	2,315	228	2,021	426	1,289	195
598	1,842	206	1,871	220	1,636	230
599	1,817	254	2,089	297	3,112	212
600	2,422	227	2,019	260	1,446	243
601	2,115	427	1,670	257	1,530	249
602	1,661	249	1,899	247	1,550	234
603	1,664	266	1,702	258	1,670	213
604	1,493	222	1,897	305	1,913	200
605	1,918	261	5,754	297	1,809	212
606	1,342	280	3,428	328	2,047	255
607	1,244	224	2,078	250	1,606	248
608	1,567	234	1,779	263	2,002	233
609	1,664	429	1,667	264	1,815	229
610	1,703	196	1,947	285	1,779	239
611	1,903	213	1,729	244	1,654	289
612	1,706	206	1,884	231	1,793	226
613	1,721	261	3,649	316	1,664	245
614	1,798	204	3,321	258	2,133	193
615	1,805	251	2,036	298	1,677	194
616	1,653	201	2,076	415	2,588	217
617	2,061	245	1,649	289	4,598	227
618	2,909	205	2,907	283	1,583	228
619	2,201	219	2,629	264	1,585	191
620	1,958	327	2,041	230	1,940	192
621	1,610	220	2,252	252	1,724	224
622	1,500	253	1,645	326	4,844	247
623	1,500	199	2,083	259	1,814	221
624	2,034	242	3,692	245	2,086	184
625	1,942	227	2,399	240	1,779	220
626	2,103	197	3,902	256	1,574	225

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
627	1,589	220	1,922	265	1,850	222
628	1,765	228	1,941	278	1,397	331
629	1,612	214	1,587	238	1,451	206
630	2,583	333	3,238	321	2,236	235
631	2,488	261	1,645	293	1,596	200
632	2,014	249	1,685	301	1,817	185
633	1,540	228	2,167	235	2,014	318
634	1,719	202	1,691	276	1,461	189
635	1,638	240	1,776	278	1,781	277
636	1,882	181	3,260	279	1,813	212
637	1,727	217	2,793	238	1,750	232
638	1,772	211	2,114	262	1,278	253
639	1,764	259	1,918	251	1,656	196
640	1,738	214	3,155	232	2,389	236
641	2,123	239	2,373	250	1,638	268
642	1,504	251	3,488	246	1,658	276
643	1,927	232	1,869	245	1,657	198
644	1,941	190	1,827	287	1,804	204
645	1,607	185	2,051	224	1,983	195
646	1,455	222	1,885	277	1,923	295
647	1,843	249	2,690	229	1,508	243
648	1,724	240	2,778	270	2,178	209
649	1,560	237	2,192	257	4,047	200
650	1,453	218	2,386	235	1,385	218
651	1,959	210	1,583	323	1,837	211
652	1,519	216	1,880	501	2,039	250
653	2,101	199	2,293	251	1,900	198
654	1,741	256	3,229	284	1,562	214
655	2,026	219	2,335	273	2,872	228
656	1,691	241	1,811	283	2,051	212
657	2,025	237	2,754	297	1,791	229
658	1,360	212	2,611	340	1,837	212
659	2,014	270	1,593	267	1,412	252
660	1,391	208	1,940	292	1,414	233
661	2,061	228	1,960	264	1,915	290
662	1,541	213	2,704	223	1,567	176
663	1,918	209	1,948	230	1,677	215

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
664	1,910	242	1,772	347	1,621	243
665	1,952	211	1,536	231	1,617	228
666	2,369	331	2,671	246	1,686	236
667	1,572	229	1,824	240	1,795	225
668	1,537	186	2,490	279	1,999	232
669	1,734	216	2,851	252	2,041	217
670	2,781	244	1,762	261	2,168	238
671	2,212	206	2,224	258	1,687	182
672	1,537	230	3,044	253	2,257	320
673	1,334	251	1,959	214	2,079	216
674	1,764	178	1,803	247	1,758	233
675	1,587	264	2,085	296	1,959	189
676	1,462	196	2,686	263	1,393	252
677	1,470	218	1,784	258	1,747	247
678	1,874	217	1,743	257	1,761	262
679	1,681	234	2,239	241	2,106	207
680	1,973	232	2,275	335	2,024	218
681	2,617	211	2,874	240	2,568	212
682	1,460	230	2,583	249	1,641	223
683	1,834	196	3,387	234	1,550	205
684	1,920	277	3,270	279	1,786	181
685	1,930	208	1,798	396	1,809	223
686	1,523	203	1,875	299	1,927	203
687	2,182	189	2,197	289	2,713	201
688	1,705	230	2,723	319	1,884	268
689	1,518	232	1,955	245	1,596	240
690	5,107	216	2,190	251	1,988	241
691	1,708	202	1,963	265	3,508	216
692	1,638	227	2,031	280	1,938	238
693	2,063	228	2,300	258	1,814	200
694	1,769	236	2,437	282	1,529	203
695	1,981	211	2,766	277	1,495	300
696	1,383	228	1,941	266	2,644	181
697	1,485	226	2,154	277	1,685	239
698	2,366	239	3,061	228	1,966	217
699	2,271	201	3,148	299	2,186	241
700	1,450	244	1,679	278	1,957	214

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
701	1,946	221	2,255	263	2,206	225
702	2,311	220	3,057	257	1,679	216
703	1,545	297	1,920	255	2,811	204
704	1,870	245	1,842	255	2,581	229
705	1,753	233	1,837	237	1,344	258
706	1,774	236	1,942	294	3,194	278
707	2,061	201	2,249	233	1,771	248
708	1,882	211	2,088	251	1,750	235
709	1,995	233	3,036	229	1,717	201
710	1,703	214	1,405	332	1,962	202
711	1,739	227	2,164	326	1,692	231
712	1,566	217	1,711	259	1,995	235
713	2,158	285	2,686	248	2,082	203
714	1,634	234	2,394	277	1,548	184
715	1,852	209	1,692	226	2,777	241
716	1,690	214	1,954	202	2,706	219
717	2,405	216	2,383	233	1,861	257
718	1,492	223	2,240	288	1,875	197
719	1,350	198	2,264	248	1,619	220
720	2,168	252	2,481	434	1,744	207
721	1,558	262	3,005	233	3,126	239
722	1,369	492	2,686	264	1,610	222
723	1,673	261	2,091	253	1,526	242
724	1,535	182	1,943	271	1,785	229
725	2,080	214	1,936	258	1,548	214
726	1,603	264	2,593	247	2,043	236
727	1,752	221	1,898	274	1,848	266
728	2,918	214	2,200	279	2,100	224
729	1,780	206	2,486	330	1,395	205
730	1,587	189	2,494	236	1,764	208
731	1,765	251	2,095	339	1,768	235
732	1,375	267	2,520	277	1,415	262
733	2,081	225	2,098	222	1,723	205
734	2,360	213	1,761	244	1,465	281
735	1,823	230	2,003	233	1,715	564
736	1,519	224	1,642	338	1,636	239
737	2,229	279	1,978	252	1,789	206

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
738	1,551	198	2,093	268	1,388	236
739	2,506	287	2,810	259	1,718	280
740	1,905	213	2,223	260	2,231	246
741	1,748	215	1,992	268	1,758	204
742	1,406	218	1,820	252	2,558	244
743	1,741	230	1,865	263	2,761	246
744	2,222	207	1,962	264	1,698	270
745	1,929	228	2,028	371	1,941	199
746	1,687	196	1,397	261	1,533	209
747	1,987	213	1,926	222	1,479	201
748	1,689	186	2,478	268	1,739	228
749	1,735	210	1,896	284	1,773	251
750	2,034	228	1,761	257	1,914	252
751	1,816	276	1,845	245	1,941	254
752	2,022	268	1,846	269	1,938	260
753	2,037	256	1,777	290	2,030	220
754	1,599	204	1,893	249	2,461	277
755	1,599	211	1,814	299	1,823	215
756	2,019	255	2,089	264	1,591	252
757	1,761	227	2,292	219	2,043	245
758	2,107	217	1,950	213	1,770	317
759	1,726	199	3,168	258	1,754	241
760	1,774	235	2,412	229	1,558	220
761	2,017	195	1,681	259	1,484	221
762	1,320	237	1,833	245	1,872	224
763	1,938	210	2,139	285	2,045	259
764	1,700	245	2,700	231	1,721	294
765	1,993	214	1,613	194	1,523	190
766	1,627	223	2,226	294	2,133	219
767	1,562	247	1,720	315	1,806	251
768	1,661	231	2,174	269	1,546	178
769	2,226	326	1,949	281	1,884	257
770	1,646	204	1,973	256	1,664	244
771	1,797	225	1,768	284	2,809	227
772	1,813	242	4,971	249	1,614	191
773	1,837	203	1,932	251	7,878	224
774	1,528	237	1,917	265	1,850	188

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
775	1,572	230	1,955	214	3,452	185
776	2,249	247	1,952	249	2,175	270
777	5,179	239	1,979	290	1,936	229
778	1,505	238	2,094	230	2,566	194
779	1,582	179	1,854	261	1,372	314
780	1,981	237	1,963	237	1,924	225
781	1,642	215	1,763	227	2,673	241
782	1,701	239	2,654	275	1,682	219
783	1,587	249	1,891	269	1,759	254
784	1,463	206	1,757	236	1,793	240
785	1,693	224	2,130	270	1,733	184
786	1,698	238	3,171	259	1,719	244
787	1,824	227	1,912	257	1,573	216
788	1,773	202	2,177	238	1,780	242
789	2,207	213	2,040	274	2,025	266
790	1,847	262	2,229	264	2,008	281
791	2,593	230	2,350	259	1,744	201
792	1,727	239	2,077	254	1,236	210
793	1,715	218	1,767	234	1,831	227
794	2,327	266	2,011	292	1,683	236
795	3,945	219	1,862	249	1,612	221
796	2,417	239	2,189	200	1,515	206
797	1,817	221	5,389	327	1,891	213
798	1,411	209	1,976	257	1,995	185
799	1,445	278	2,692	330	1,822	233
800	1,508	214	1,891	262	2,130	229
801	1,684	218	1,930	225	1,736	260
802	2,007	197	1,699	261	1,905	236
803	1,596	224	2,145	227	1,387	211
804	1,516	290	2,252	234	1,284	165
805	2,783	184	2,249	285	3,048	236
806	1,600	327	2,511	237	2,611	199
807	5,617	226	2,255	263	1,678	226
808	1,752	241	1,922	263	1,233	232
809	2,269	230	2,040	342	1,516	237
810	2,137	241	2,257	267	3,736	214
811	1,489	257	3,363	252	1,582	251

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
812	1,661	215	2,079	245	1,872	192
813	1,494	695	1,756	233	1,596	236
814	1,553	239	2,282	269	1,796	265
815	1,922	264	2,091	257	1,747	276
816	1,771	239	3,004	263	1,643	200
817	2,352	274	1,430	260	1,625	217
818	2,826	242	2,102	266	1,695	269
819	1,643	232	1,853	245	1,948	237
820	1,894	240	2,567	258	2,245	218
821	1,482	196	2,287	278	3,230	199
822	2,251	209	1,744	255	2,773	281
823	3,154	302	2,645	229	1,618	254
824	1,666	209	2,424	291	1,523	235
825	1,481	218	1,814	328	1,703	264
826	1,420	246	2,151	225	1,720	221
827	2,845	208	2,744	253	2,099	233
828	1,523	245	2,017	261	1,723	273
829	1,405	223	2,493	257	1,426	198
830	2,436	234	3,708	259	1,727	235
831	1,472	304	2,025	261	2,061	199
832	1,878	215	2,355	252	1,718	203
833	1,556	263	2,315	240	1,672	269
834	1,955	249	2,043	227	1,729	224
835	2,623	217	1,679	273	1,677	215
836	1,811	227	2,041	264	1,509	204
837	2,022	272	2,047	272	1,757	238
838	1,769	208	2,528	230	2,066	216
839	2,217	281	1,921	252	1,905	254
840	1,534	224	1,963	270	1,926	342
841	1,993	184	1,902	243	7,319	286
842	4,957	218	2,382	263	1,607	236
843	1,852	222	2,037	279	1,845	216
844	1,747	223	1,708	262	1,347	239
845	1,755	294	1,710	235	1,877	217
846	2,326	231	3,215	339	1,451	231
847	1,970	187	2,445	262	1,905	303
848	1,506	226	2,191	254	1,881	209

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
849	2,231	203	1,799	280	1,516	234
850	1,965	275	2,122	293	1,517	252
851	1,635	218	1,814	277	1,705	223
852	1,550	197	2,274	279	1,387	191
853	1,512	226	2,031	312	1,482	228
854	1,552	320	1,625	222	1,736	238
855	1,671	245	3,098	304	1,602	210
856	2,168	338	4,040	245	1,641	300
857	2,493	239	2,173	494	1,870	219
858	2,052	211	1,867	232	1,506	228
859	2,147	223	1,706	356	1,949	216
860	1,820	245	2,049	236	4,469	233
861	1,685	230	1,918	301	1,411	205
862	2,202	211	1,839	277	2,003	311
863	2,208	216	1,995	232	1,624	229
864	1,877	208	1,857	243	2,000	191
865	2,855	252	1,979	248	1,821	217
866	1,466	222	2,152	249	2,309	323
867	1,756	240	1,625	230	2,024	210
868	1,179	202	1,381	291	1,560	227
869	1,714	283	1,762	262	3,837	289
870	1,456	277	1,912	379	1,794	227
871	1,754	207	2,451	244	1,941	242
872	1,683	298	2,143	353	1,741	184
873	1,566	222	1,609	267	1,358	239
874	1,553	236	2,478	222	1,664	228
875	1,832	251	1,811	282	1,750	274
876	2,046	250	1,882	240	1,506	195
877	1,777	202	1,726	203	1,765	197
878	1,904	206	2,374	267	2,471	572
879	1,823	225	3,200	246	1,844	213
880	1,573	226	1,971	247	1,775	291
881	1,528	300	1,448	256	2,583	234
882	1,454	251	1,774	281	1,441	210
883	1,841	466	2,201	224	1,928	206
884	1,872	200	1,922	232	1,603	224
885	3,037	225	1,796	219	1,888	260

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
886	1,447	206	2,596	299	3,710	234
887	2,484	244	2,477	232	2,095	229
888	1,533	210	1,569	271	1,682	184
889	2,106	233	2,057	261	3,487	229
890	3,814	194	1,602	300	2,869	209
891	1,848	224	2,170	246	1,476	172
892	3,470	234	1,598	227	1,785	186
893	1,524	194	1,677	325	2,029	250
894	1,858	242	1,720	245	2,167	233
895	1,820	219	1,787	271	1,766	235
896	2,355	204	1,594	229	2,897	254
897	1,510	244	1,872	303	6,437	217
898	1,820	213	2,143	242	1,666	220
899	1,739	196	1,906	269	1,844	223
900	1,842	235	1,948	234	1,666	227
901	1,639	234	1,985	289	1,607	213
902	2,310	208	1,540	237	1,962	238
903	1,739	199	3,657	268	5,117	235
904	1,656	258	1,734	263	1,517	229
905	1,549	217	1,873	264	1,609	190
906	2,427	239	1,829	258	1,615	200
907	1,767	238	3,779	284	2,128	257
908	1,936	230	3,369	273	1,746	260
909	1,832	227	2,067	259	1,942	220
910	1,783	203	2,036	240	2,116	196
911	3,147	253	1,790	285	1,555	204
912	1,519	203	2,406	283	2,064	215
913	1,883	226	1,545	280	2,184	229
914	1,870	206	2,525	235	1,675	291
915	1,473	219	2,182	290	2,381	231
916	1,533	227	2,421	246	1,918	245
917	1,274	233	2,168	242	1,828	229
918	1,731	283	1,915	268	1,511	251
919	2,176	213	2,141	279	1,915	186
920	1,911	234	1,993	284	1,743	318
921	1,750	216	4,021	260	2,834	203
922	1,654	253	2,190	284	1,668	247

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
923	2,293	289	2,105	248	2,020	281
924	1,589	213	2,850	238	1,876	197
925	4,413	205	1,949	247	2,792	247
926	1,419	244	1,946	252	4,359	233
927	1,830	237	2,264	310	1,719	232
928	2,034	222	2,064	265	2,013	240
929	2,258	213	2,929	272	2,075	233
930	2,920	243	2,383	270	1,553	220
931	1,457	211	2,271	245	1,866	275
932	1,892	253	1,900	261	2,846	244
933	3,588	209	1,984	268	1,586	228
934	1,427	225	2,143	274	1,539	255
935	1,648	241	3,540	282	1,350	206
936	1,567	244	1,754	247	1,389	204
937	1,499	221	1,673	279	3,074	200
938	1,784	377	1,832	277	2,397	229
939	1,861	281	2,129	258	1,787	229
940	2,515	191	1,892	261	1,616	201
941	1,839	267	2,209	236	1,758	223
942	1,577	255	1,793	285	1,880	229
943	2,431	246	2,787	281	1,742	201
944	1,522	269	1,794	242	2,671	230
945	1,741	184	2,299	292	1,800	210
946	2,250	233	2,322	272	1,634	227
947	2,159	231	1,750	275	1,368	212
948	2,169	246	1,999	238	3,649	223
949	2,259	215	1,897	237	4,152	230
950	1,504	281	2,309	275	3,161	218
951	2,272	233	2,648	272	1,742	238
952	2,128	223	1,988	311	1,884	242
953	2,116	198	3,949	250	1,485	226
954	1,572	243	1,949	287	1,323	243
955	2,118	236	1,580	295	1,414	250
956	1,594	203	1,940	268	2,476	203
957	1,721	219	2,368	229	1,486	256
958	2,262	192	1,690	239	1,843	240
959	1,775	233	1,911	250	2,038	228

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
960	1,825	315	1,939	253	2,181	184
961	2,332	242	2,304	260	1,913	194
962	2,161	205	2,374	289	1,396	184
963	1,493	216	1,539	253	1,655	230
964	1,740	225	2,033	238	1,367	226
965	1,529	232	1,683	251	1,364	308
966	1,638	271	1,649	634	1,600	197
967	1,497	204	2,078	259	1,460	260
968	1,236	240	2,393	296	1,980	259
969	1,840	223	2,018	260	2,362	295
970	1,546	272	2,131	222	1,809	226
971	1,806	205	2,161	261	1,884	207
972	1,931	232	2,245	240	1,710	281
973	1,977	234	5,240	258	1,612	324
974	3,154	224	2,835	264	2,243	252
975	1,503	293	2,423	232	2,179	229
976	2,150	244	3,010	273	4,156	215
977	2,129	274	1,838	231	1,877	242
978	2,133	225	1,737	253	1,875	212
979	1,677	231	1,965	234	1,880	331
980	1,888	224	3,362	265	1,955	282
981	2,421	226	2,326	243	1,990	296
982	1,359	209	1,908	310	1,605	197
983	1,838	291	1,628	226	1,576	270
984	1,705	197	1,861	252	1,625	243
985	1,550	238	4,902	222	1,406	205
986	1,809	256	2,259	222	1,654	216
987	1,850	228	2,020	284	2,680	258
988	1,962	225	2,180	247	1,460	193
989	1,385	235	1,831	308	1,721	237
990	1,556	229	2,327	225	1,527	225
991	1,390	211	2,043	215	1,296	210
992	1,774	248	2,401	304	1,541	241
993	1,520	242	1,914	240	1,681	221
994	1,899	229	2,674	224	2,143	176
995	1,889	254	1,654	228	1,719	236
996	1,352	222	1,636	325	2,029	207

	Method 4		Method 5		As-Built	
Monte Carlo Calc No.	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
997	2,148	257	1,982	319	1,743	191
998	1,404	220	2,021	529	2,014	213
999	2,141	234	2,141	270	1,781	254
1000	1,959	204	2,045	276	1,667	199

O.4 RESULTS OF STATISTICAL ANALYSIS COMPARING THE FIVE METHODS AND THE AS-BUILT CONDITION

O.4.1 Embodied Energy

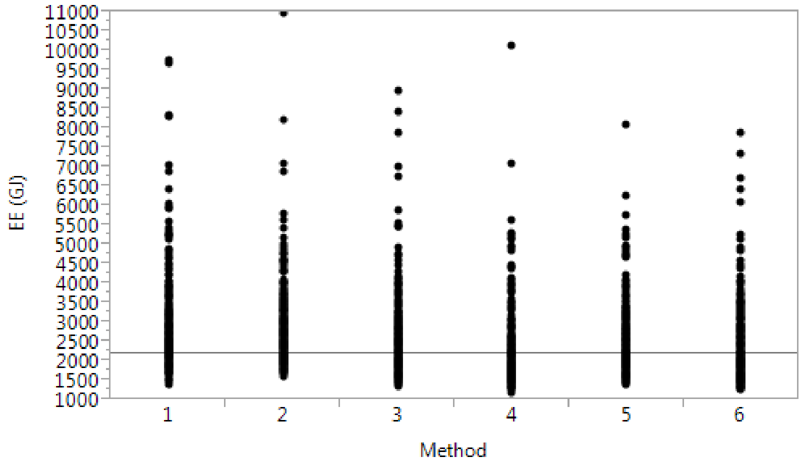
Results from the statistical analysis comparing the five different methods of accounting for subsurface variability in JMP Pro (SAS Institute 2013) for embodied energy are shown in Figure O.37. As described in section O.1.2, a significance level $\alpha = 0.1$ was used for the statistical analyses performed with JMP. In the JMP analysis, Levels 1 through 5 correspond to the five methods of accounting for subsurface variability; level 6 corresponds to the as-built material quantities. In this case, the null hypothesis for the nonparametric Kruskal-Wallis test was that all methods estimate the same total embodied energy. The alternative hypothesis was that at least one method estimates different total embodied energy. The Kruskal-Wallis test resulted in $p < 0.0001$, as shown in the upper portion of Figure O.37. Based on this p-value, there is sufficient evidence to conclude the null hypothesis is not true; therefore, at least one of the methods estimates different total embodied energy from the others.

All pairwise comparisons were made using the nonparametric Steel-Dwass method in JMP Pro (SAS Institute 2013), as shown in the lower portion of Figure O.37. Based on the Steel-Dwass pairwise comparisons, the estimated embodied energy for Methods 1 and 2 ($p = 0.8164$), and Methods 3 and 5 ($p = 0.9890$) are not significantly different (i.e., they estimate statistically equivalent total embodied energy). In addition, the estimation of total embodied energy from Method 4 is not significantly different from the total embodied energy resulting from the as-built materials quantities ($p = 0.9817$). Comparisons of all other pairs of methods result in $p < 0.0001$, indicating the methods estimate significantly different total embodied energy. Of the methods of accounting for subsurface variability, Methods 1 and 2 result in the highest estimated total embodied energy, while Method 4 results in the least. The results of the Steel Dwass comparisons for total embodied energy by method of accounting for subsurface variability may be summarized as follows:

$$(As\ Built = Method\ 4) < (Method\ 3 = Method\ 5) < (Method\ 1 = Method\ 2).$$

Fit Group

Oneway Analysis of EE (GJ) By Method



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
1	1000	3993420	3000500	3993.42	19.857
2	1000	4079606	3000500	4079.61	21.580
3	1000	3041930	3000500	3041.93	0.829
4	1000	1969058	3000500	1969.06	-20.627
5	1000	2994942	3000500	2994.94	-0.111
6	1000	1924045	3000500	1924.05	-21.527

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1458.0033	5	<.0001*

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*	Alpha
2.58852	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	4	379.080	25.82632	14.6780	<.0001*	239.000	199.000	279.000
2	1	32.062	25.82632	1.2414	0.8164	23.000	-26.000	73.000
5	3	-16.214	25.82632	-0.6278	0.9890	-10.000	-53.000	33.000
6	4	-18.139	25.82631	-0.7023	0.9817	-10.000	-48.000	27.000
3	1	-345.721	25.82632	-13.3864	<.0001*	-255.000	-302.000	-208.000
5	1	-371.050	25.82632	-14.3671	<.0001*	-266.000	-312.000	-220.000
3	2	-376.022	25.82632	-14.5596	<.0001*	-277.000	-324.000	-231.000
4	3	-384.830	25.82632	-14.9007	<.0001*	-250.000	-292.000	-209.000
6	5	-399.740	25.82632	-15.4780	<.0001*	-248.000	-288.000	-209.000
5	2	-402.671	25.82632	-15.5915	<.0001*	-287.000	-332.000	-242.000
6	3	-403.558	25.82632	-15.6258	<.0001*	-259.000	-300.000	-218.000
4	1	-647.104	25.82633	-25.0560	<.0001*	-506.000	-551.000	-462.000
6	1	-654.023	25.82633	-25.3239	<.0001*	-515.000	-559.000	-471.000
4	2	-670.007	25.82633	-25.9428	<.0001*	-526.000	-571.000	-483.000
6	2	-677.445	25.82633	-26.2308	<.0001*	-535.000	-579.000	-491.000

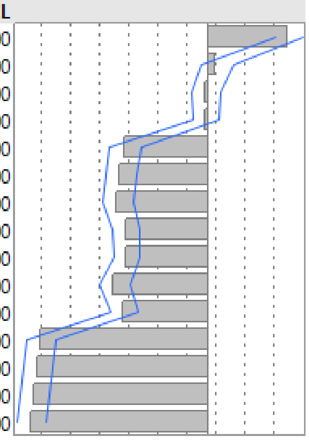


Figure O.37 Nonparametric statistical test results which compare methods of estimating total embodied energy for Rammed Aggregate Columns at Pearson Hall. Results obtained from JMP Pro.

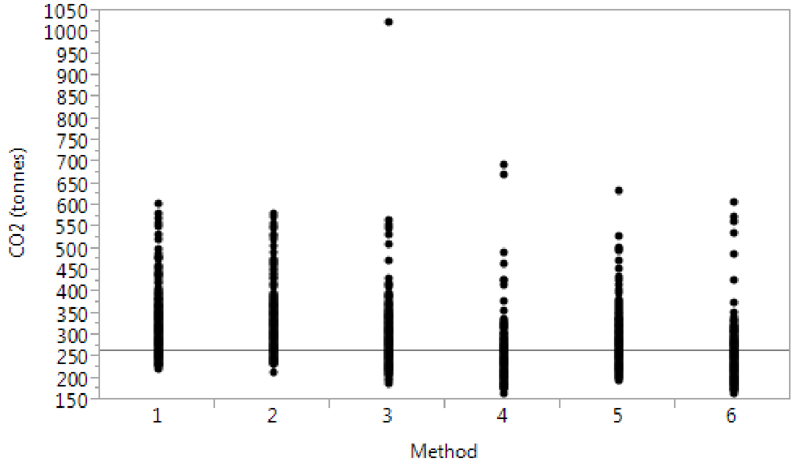
O.4.2 CO_2 Emissions

Results from the statistical analysis comparing the five different methods of accounting for subsurface variability in JMP Pro (SAS Institute 2013) for CO_2 emissions are shown in Figure O.38. As described in section O.1.2, a significance level $\alpha = 0.1$ was used for the statistical analyses performed with JMP. As stated in section O.4.1, Levels 1 through 5 in the JMP analysis correspond to the five methods of accounting for subsurface variability; level 6 corresponds to the as-built material quantities. In this case, the null hypothesis for the nonparametric Kruskal-Wallis test was that all methods estimate the same total CO_2 emissions. The alternative hypothesis was that at least one method estimates different total CO_2 emissions. The Kruskal-Wallis test resulted in $p < 0.0001$, as shown in the upper portion of Figure O.38. Based on this *p*-value, there is sufficient evidence to conclude the null hypothesis is not true; therefore, at least one of the methods estimates different total CO_2 emissions from the others.

All pairwise comparisons were made using the nonparametric Steel-Dwass method in JMP Pro (SAS Institute 2013), as shown in the lower portion of Figure O.38. Based on the Steel-Dwass pairwise comparisons, the estimated CO_2 emissions for Methods 1 and 2 ($p = 0.3241$), and Methods 3 and 5 ($p = 0.8069$) are not significantly different (i.e., they estimate statistically equivalent total CO_2 emissions). Similar to the analysis for embodied energy, the estimation of total CO_2 emissions from Method 4 is not significantly different from the total CO_2 emissions resulting from the as-built material quantities ($p = 0.9975$). Comparisons of all other pairs of methods result in $p < 0.0001$, indicating the methods estimate significantly different total CO_2 emissions. Similar to the analysis for total embodied energy, Methods 1 and 2 result in the highest estimated total CO_2 emissions, while Method 4 results in the least. The results of the Steel Dwass comparisons for total CO_2 emissions by method of accounting for subsurface variability may be summarized as follows:

$$(As\ Built = Method\ 4) < (Method\ 3 = Method\ 5) < (Method\ 1 = Method\ 2).$$

Oneway Analysis of CO2 (tonnes) By Method



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
1	1000	4486985	3000500	4486.98	29.728
2	1000	4394252	3000500	4394.25	27.873
3	1000	3118065	3000500	3118.06	2.351
4	1000	1478513	3000500	1478.51	-30.438
5	1000	3029621	3000500	3029.62	0.582
6	1000	1495566	3000500	1495.57	-30.097

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
2915.7036	5	<.0001*

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*	Alpha
2.58852	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	4	636.608	25.82504	24.6508	<.0001*	34.0000	31.0000	38.0000
6	4	-11.792	25.82421	-0.4566	0.9975	-1.0000	-4.0000	2.0000
5	3	-32.535	25.82470	-1.2598	0.8069	-2.0000	-5.0000	2.0000
2	1	-52.470	25.82515	-2.0317	0.3241	-3.0000	-7.0000	1.0000
3	2	-521.600	25.82530	-20.1973	<.0001*	-33.0000	-36.0000	-29.0000
3	1	-554.291	25.82539	-21.4630	<.0001*	-36.0000	-40.0000	-32.0000
5	2	-569.468	25.82522	-22.0508	<.0001*	-34.0000	-38.0000	-31.0000
5	1	-601.051	25.82534	-23.2737	<.0001*	-38.0000	-41.0000	-34.0000
6	5	-624.689	25.82516	-24.1892	<.0001*	-35.0000	-38.0000	-32.0000
6	3	-633.703	25.82515	-24.5382	<.0001*	-37.0000	-40.0000	-33.0000
4	3	-644.781	25.82514	-24.9672	<.0001*	-36.0000	-39.0000	-33.0000
6	2	-865.384	25.82572	-33.5086	<.0001*	-69.0000	-73.0000	-66.0000
6	1	-874.296	25.82574	-33.8537	<.0001*	-73.0000	-76.0000	-69.0000
4	2	-883.518	25.82570	-34.2108	<.0001*	-69.0000	-72.0000	-65.0000
4	1	-890.856	25.82573	-34.4949	<.0001*	-72.0000	-76.0000	-69.0000

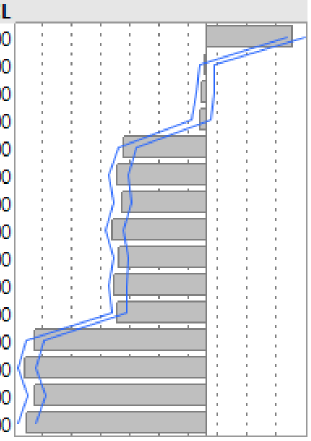


Figure O.38 Nonparametric statistical test results which compare methods of estimating total CO_2 emissions for Rammed Aggregate Columns at Pearson Hall. Results obtained from JMP Pro.

O.5 CONCLUSIONS

In conclusion, this comparison of five methods of accounting for subsurface variability reveals that Method 4 is the only method that estimates total embodied energy and CO_2 emissions that are not significantly different from the total embodied energy and CO_2 emissions associated with the as-built material quantities for the Pearson Hall case history project. Method 4 involves plotting a histogram of values of the key geotechnical parameter(s) (TOR elevation in this case) as observed in the geotechnical investigation program. A theoretical probability distribution is then fit to the histogram and its parameters are determined. The theoretical probability distribution is then used to randomly generate values of the key parameter at appropriate locations across the site for determining required construction quantities for the SEEAM analysis. Of note, when the normal distribution is the best fit to the histogram of the key parameter(s), Method 4 converges to Method 3. Since Method 3 was not significantly different from Method 5 for the Pearson Hall case history project, it may be justified in such instances to simply use Method 5 for the analysis.

The methods involving Kriging (Methods 1 and 2) generate the highest overall estimates of total embodied energy and CO_2 emissions. The estimates made using Methods 1 and 2 also have the greatest difference between the estimated values and the actual embodied energy and CO_2 emissions resulting from the as-built quantities. This is likely because the actual TOR elevation is both more irregular, and generally higher than the TOR elevation as estimated by Kriging using data from the geotechnical borings (see Figures 6.2 and N.3). The irregularity in TOR elevation is not unexpected given the limestone/dolomite bedrock underlying the site is known to be highly variable in other locations. Overall, Kriging may not be the best method for interpolating TOR elevation in this situation because the site is small, there are relatively few input data values, there is no input data within the building footprint, and the input data does not provide much information for small separation distances over which significant spatial correlation likely occurs.

Analyses of additional case history projects could confirm these conclusions; however, based on the analyses with these different methods of accounting for subsurface variability for the Pearson Hall project, Method 4 is a good starting point for accounting for subsurface variability in SEEAM analyses for embodied energy and CO_2 emissions. Kriging may be beneficial for making embodied energy and CO_2 emissions estimates for larger projects with more input data and a key parameter that does not exhibit significant variability over short distances.

O.6 REFERENCES

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Appendix P: Comparing the Total Embodied Energy and CO_2 Emissions of Project Alternatives

This Appendix describes two approaches for how total embodied energy and CO_2 emissions for different project alternatives may be compared when Monte Carlo simulation has been conducted following the SEEAM method to account for uncertainty (see Ch. 6 and Appendix K). Such comparisons are useful when seeking to make project decisions based on environmental impact information in addition to performance and cost criteria. The first method uses established statistical hypothesis test methods to compare two or more project alternatives at once. The second method involves taking the difference between alternatives and may only be used to compare two project alternatives at once. The descriptions of each method as presented in this Appendix are similar to the details presented in Appendix B, which is the complete instruction manual for the SEEAM Spreadsheet Calculator. The approaches described here are not implemented within the SEEAM Spreadsheet Calculator; however, they may be easily implemented with results from the SEEAM Spreadsheet Calculator.

The two approaches are both demonstrated by making comparisons of the total embodied energy and CO_2 emissions associated with the Deep Soil Mixing (DSM) and Prefabricated Vertical Drains (PVDs) design alternatives for the LPV 111 levee upgrade in New Orleans, LA (see Chs. 4-5 and Appendices E-F for details about LPV 111).

P.1 COMPARISON BY NONPARAMETRIC STATISTICAL HYPOTHESIS TESTS

P.1.1 Method and Applicable Statistical Hypothesis Tests

Nonparametric statistical hypothesis testing is applicable when the data does not follow the normal distribution, or the distribution is unknown. These tests do not rely on a theoretical distribution to draw conclusions. Nonparametric statistical hypothesis testing can be performed using data sets of total embodied energy and CO_2 emissions generated from Monte Carlo simulations that follow the SEEAM method (see Ch. 6 and Appendix K) for each alternative. The statistical hypothesis tests indicate whether different project alternatives result in significantly different total embodied energy and/or CO_2 emissions.

The nonparametric statistical hypothesis tests are conducted using the null hypothesis that the project alternatives have the same total embodied energy and CO_2 emissions. The alternative hypothesis may either be that the alternatives do not have the same total embodied energy and CO_2 emissions, or that one alternative is greater than or less than another. The statistical hypothesis tests are conducted by comparing the *p*-value generated by the test method with the desired significance level, α (such as 0.05 or 0.1). When the *p*-value is less than α, the statistical hypothesis test indicates there is significant evidence to suggest the null hypothesis is false. A definition for the *p*-value is presented in Ch. 6.

The most appropriate nonparametric statistical hypothesis tests to use in this application include the Wilcoxon Rank Sum test (Wilcoxon 1945; Mann and Whitney 1947) for comparing two alternatives, and the Kruskal-Wallis test (Kruskal and Wallis 1952) for comparing more than two alternatives. The Wilcoxon Rank Sum test is analogous to the parametric *t*-test, while the Kruskal-Wallis test is analogous to the parametric ANOVA test. If the Kruskal-Wallis test rejects the null hypothesis, it indicates that at least one of the alternatives is significantly different, but does not indicate which one. In such instances, the Steel-Dwass method of multiple comparisons may be used to explore the differences between all possible pairs of alternatives. The Steel-Dwass method was originally proposed independently by Steel (1960) and Dwass (1960), and was further elaborated on by Critchlow and Fligner (1991).

The best method for conducting statistical hypothesis tests is to use a statistical software package such as JMP (SAS Institute), SPSS (IBM), SAS (SAS Institute) or R (The R Foundation). However, the tests could also be programmed into Microsoft Excel by advanced users.

For the comparison of LPV 111 alternatives presented here, the values (and only the values) from rows 62-1061 of columns CJ and CK of the Monte Carlo worksheet in the SEEAM Spreadsheet Calculator (See Appendices A and B) were copied and pasted into a separate Microsoft Excel workbook. In the SEEAM Spreadsheet Calculator, these values consist of the n = 1,000 Monte Carlo simulated data sets for total embodied energy and CO_2 emissions. Values were copied from analyses of both the DSM and PVD design alternatives at LPV 111 into the same Microsoft Excel workbook and grouped by design alternative. The grouped data (by design alternative) was then imported into JMP Pro (SAS Institute 2013) for performing the statistical testing to compare alternatives; DSM = Level 1 in JMP, PVDs = Level 2 in JMP.

P.1.2 Results

Descriptive statistics from the Monte Carlo simulation for total embodied energy and CO_2 emissions for each LPV 111 design alternative (DSM, PVDs) are shown in Table P.1, along with the bounds of the 90% confidence intervals (CIs) generated from querying the simulated data sets. The complete Monte Carlo simulated data sets are included in columns 2 through 4 of Table P.2, which is located in Section P.2, where the second comparison method is described.

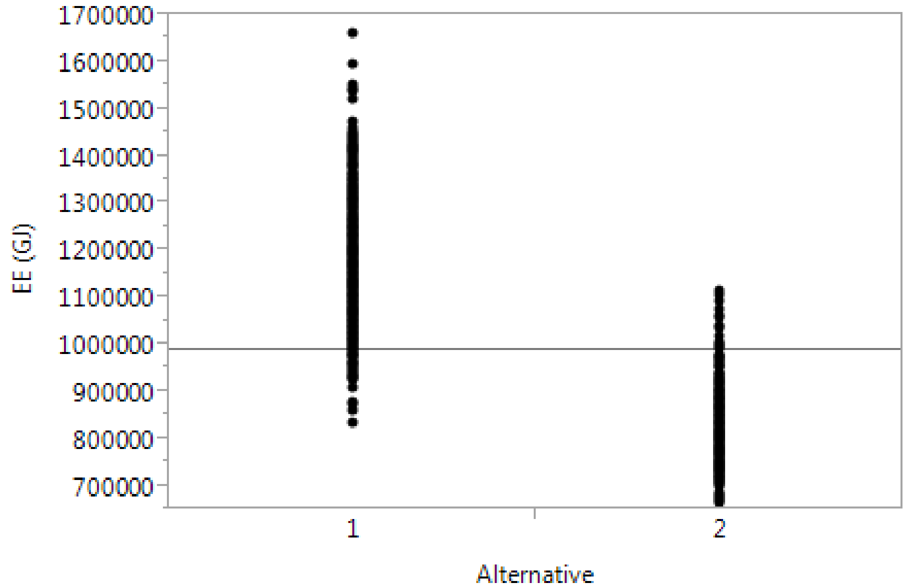
Table P.1 Descriptive statistics and 90% confidence interval of total embodied energy and CO_2 emissions from Monte Carlo simulation for the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives at LPV 111.

Descriptive Statistic	Deep Soil Mixing		Prefabricated Vertical Drains	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Mean	1,173,296	146,886	809,549	63,719
Std Dev.	121,551	11,491	66,619	3,470
Minimum	832,355	115,433	665,101	54,284
Maximum	1,662,152	198,395	1,113,437	80,275
90% CI Low	987,108	129,205	717,214	58,508
90% CI High	1,390,032	167,047	920,944	69,455

Since only two project alternatives were compared (DSM and PVDs), the Wilcoxon Rank Sum test was performed in JMP to compare the total embodied energy and CO_2 emissions for each design alternative. Figure P.1 contains the results from the Wilcoxon Rank Sum test for embodied energy. Figure P.2 contains the results from the Wilcoxon Rank Sum test for CO_2 emissions.

Fit Group

Oneway Analysis of EE (GJ) By Alternative



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
1	1000	1496614	1000500	1496.61	38.419
2	1000	504386	1000500	504.39	-38.419

2-Sample Test, Normal Approximation

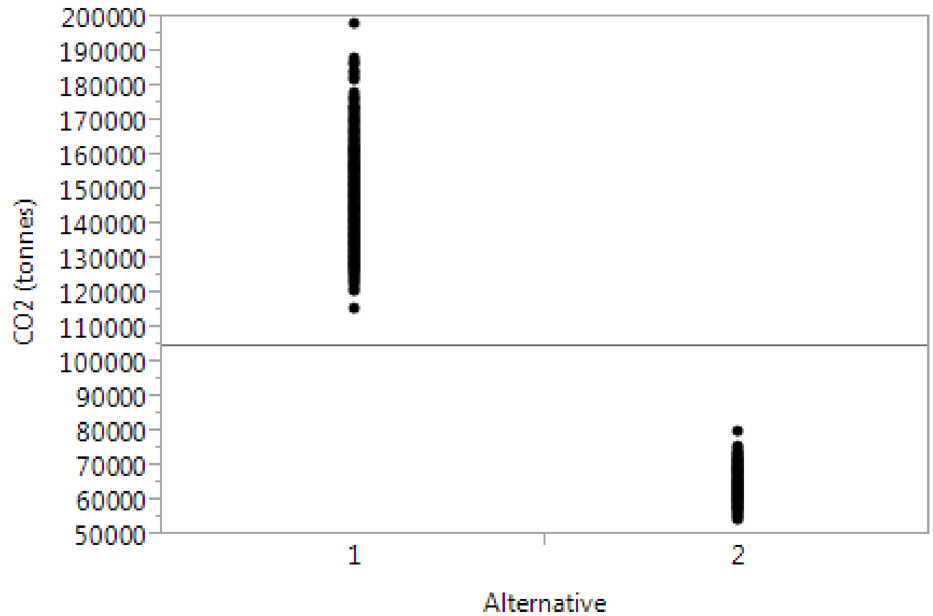
S	Z	Prob>|Z|
504386	-38.4192	<.0001*

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1476.0366	1	<.0001*

Figure P.1 JMP output for the Wilcoxon Rank Sum test comparing the total embodied energy from the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for LPV 111.

Oneway Analysis of CO2 (tonnes) By Alternative



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
1	1000	1500500	1000500	1500.50	38.720
2	1000	500500	1000500	500.50	-38.720

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
500500	-38.7201	<.0001*

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1499.2504	1	<.0001*

Figure P.2 JMP output for the Wilcoxon Rank Sum test comparing the total CO_2 emissions from the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for LPV 111.

In both cases (for embodied energy and CO_2 emissions), the *p*-value is < 0.0001 for the Wilcoxon Rank Sum test. Therefore, the DSM and PVD design alternatives for LPV 111 have significantly different total embodied energy and CO_2 emissions. Based on an examination of the results, it is clear that DSM results in statistically greater total embodied energy and CO_2 emissions than PVDs.

P.2 COMPARISON BY TAKING THE DIFFERENCE

P.2.1 Method

Two design alternatives may be compared following a simple method that does not involve statistical hypothesis testing. Instead, the difference between the Monte Carlo generated embodied energy and CO_2 emissions from each alternative is determined, similar to a method described by de Koning et al. (2010). The differences between each Monte Carlo simulated value of total embodied energy and total CO_2 emissions for each project alternative must be taken. When the Monte Carlo simulation consists of 1,000 values (as recommended in Ch. 6), then there are 1,000 difference values in the difference data sets. When taking the difference, the values should not be organized in any manner (e.g., by ascending or descending value) but should remain in the random order in which they were generated by the Monte Carlo simulation. Organizing or sorting the simulated data would systematically reduce some of the difference values, resulting in much lower variability in the difference data sets.

The mean, standard deviation, maximum and minimum of the difference data sets for total embodied energy and CO_2 emissions are then determined. The difference data are also plotted in histograms. If the histogram centers around zero, then the alternatives are not different (i.e., the difference between them is zero on average). If zero does not fall within the histogram, then one of the alternatives involves more embodied energy and/or CO_2 emissions than the other. The farther the center of the histogram is away from zero, the more likely one alternative is greater than the other. The greater of the two alternatives may be determined based on the sign of the difference.

When the histogram of the difference values overlaps zero in one of the distribution tails, the proportion of the difference values that are greater than or less than zero may be determined by querying the difference data set. The proportion of values greater than or less than zero provides an indication of the strength of any conclusions regarding the difference between alternatives. For example, if 2% of the difference values are less than zero, then there is a 98% chance that one alternative is greater than the other; therefore, the two alternatives are most likely significantly different. If 20% of the values are less than zero, then it is only 80% likely that one alternative is greater than another; therefore, the alternatives are most likely not significantly different.

For the comparison of LPV 111 alternatives presented here, the values (and only the values) from rows 62-1061 of columns CJ and CK of the Monte Carlo worksheet in the SEEAM Spreadsheet Calculator (See Appendices A and B) were copied and pasted into a separate Microsoft Excel workbook. In the SEEAM Spreadsheet Calculator, these values consist of the n = 1,000 Monte Carlo simulated data sets for total embodied energy and CO_2 emissions. Values were copied from analyses of both the DSM and PVD design alternatives at LPV 111 and pasted side-by-side into the same new Microsoft Excel workbook. Then, the difference between the embodied energy and CO_2 emissions for each corresponding value from each alternative (DSM – PVDs) was taken, filling in two new columns in the worksheet (one for the embodied energy difference, and one for the CO_2 emissions difference). Microsoft Excel formulas were used to determine the descriptive statistics of the difference data and the proportion of difference values that are less than zero. Histograms of the difference data sets were also generated. The complete data sets of total embodied energy and CO_2 emissions for project alternatives (DSM, PVDs and the Difference) is included in Table P.2 and extends for 27 pages (Note: columns 2 through 4 in Table P.2 also constitute the data that was used for the statistical testing in JMP Pro for the nonparametric statistical hypothesis testing described in Section P.1).

Table P.2 Data sets from Monte Carlo simulations performed by the SEEAM Spreadsheet Calculator for the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for LPV 111.

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	1,160,107	144,560	800,263	69,038	359,844	75,522
2	1,335,429	158,057	778,298	60,709	557,131	97,348
3	996,205	135,127	787,031	58,363	209,174	76,764
4	1,334,384	143,153	798,508	64,389	535,875	78,764
5	1,427,064	170,021	783,363	63,301	643,701	106,720
6	1,323,695	143,669	765,440	63,598	558,254	80,072
7	1,039,497	159,065	847,454	65,430	192,043	93,634
8	1,164,405	141,475	893,943	57,513	270,462	83,962
9	1,207,596	146,686	813,899	61,676	393,697	85,009
10	1,286,176	151,018	906,448	68,120	379,727	82,898
11	1,089,343	135,028	1,055,280	61,215	34,064	73,814
12	1,470,673	158,092	776,229	61,416	694,444	96,676
13	1,108,060	140,209	824,806	63,191	283,254	77,018
14	1,068,812	128,178	797,408	65,659	271,404	62,520
15	1,270,616	145,937	916,343	64,565	354,273	81,371
16	1,045,073	149,336	786,640	62,464	258,433	86,872
17	1,098,596	136,715	781,561	66,010	317,036	70,705
18	1,231,821	140,889	756,742	62,915	475,079	77,975
19	1,385,862	128,789	782,181	63,480	603,681	65,309
20	1,180,568	143,202	810,942	64,356	369,626	78,845
21	1,302,704	138,965	789,827	72,816	512,877	66,149
22	1,195,411	157,902	805,688	67,212	389,724	90,690
23	1,000,477	148,137	854,802	61,869	145,674	86,268
24	1,097,522	125,036	747,288	60,558	350,234	64,477
25	1,281,614	128,183	854,851	61,914	426,762	66,269
26	1,398,806	169,521	745,678	62,991	653,128	106,530
27	1,254,011	153,736	877,517	64,554	376,494	89,182
28	1,244,384	148,473	934,594	67,383	309,790	81,090
29	1,199,047	143,102	821,433	69,663	377,614	73,439
30	1,253,199	147,551	914,701	65,063	338,497	82,488
31	1,124,571	174,546	806,357	59,597	318,214	114,949
32	1,122,805	133,334	749,181	63,101	373,623	70,234
33	1,340,725	162,109	839,336	62,584	501,389	99,525
34	1,460,949	146,343	787,864	63,713	673,085	82,630
35	1,209,624	146,732	883,791	63,027	325,833	83,706
36	1,139,366	139,191	816,768	63,160	322,598	76,030

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
37	1,053,913	136,319	722,998	60,106	330,915	76,213
38	1,288,195	139,501	813,933	64,634	474,262	74,867
39	1,128,054	133,551	848,695	63,842	279,359	69,709
40	1,060,262	135,051	855,384	70,955	204,878	64,096
41	1,133,498	142,111	754,927	60,685	378,571	81,426
42	1,108,394	137,096	762,853	60,678	345,541	76,418
43	1,194,164	122,496	720,909	61,020	473,255	61,476
44	1,242,575	153,345	857,902	61,431	384,673	91,914
45	1,073,624	133,984	755,440	63,557	318,185	70,426
46	1,271,006	159,272	920,646	67,407	350,360	91,865
47	1,072,881	130,444	736,819	62,383	336,062	68,062
48	1,194,714	136,462	681,088	61,641	513,626	74,821
49	1,181,453	159,256	854,616	60,704	326,837	98,552
50	1,139,517	156,855	918,195	66,152	221,322	90,703
51	1,087,078	145,991	812,817	61,478	274,261	84,513
52	1,272,462	167,151	854,612	62,579	417,850	104,573
53	1,232,823	140,109	780,704	59,609	452,119	80,500
54	1,057,498	159,299	832,761	65,032	224,738	94,266
55	994,588	152,445	854,441	61,751	140,147	90,695
56	1,059,865	145,723	702,990	63,573	356,874	82,150
57	1,001,387	161,161	1,016,913	64,157	-15,526	97,004
58	939,439	147,021	972,031	62,556	-32,593	84,465
59	1,084,526	151,464	724,721	67,192	359,805	84,272
60	1,134,005	161,304	872,512	56,487	261,492	104,817
61	1,125,620	168,179	753,630	60,701	371,989	107,479
62	1,223,418	137,326	787,256	65,381	436,161	71,945
63	1,361,061	148,061	836,939	61,393	524,122	86,669
64	1,157,793	148,000	777,041	68,495	380,752	79,505
65	1,099,764	143,423	776,560	65,797	323,205	77,626
66	1,225,376	142,031	912,774	61,584	312,602	80,447
67	1,390,032	137,220	674,629	66,549	715,403	70,671
68	1,177,328	155,743	842,018	63,114	335,310	92,630
69	1,359,828	149,605	704,705	55,008	655,122	94,597
70	963,977	141,870	841,908	67,189	122,068	74,681
71	1,264,193	147,006	841,354	61,991	422,839	85,016
72	1,159,861	155,131	839,483	61,219	320,378	93,912
73	1,375,935	146,229	868,696	60,472	507,240	85,757
74	1,268,386	151,393	719,602	68,045	548,784	83,348

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
75	1,200,279	156,321	875,216	60,695	325,063	95,626
76	1,242,407	133,887	808,095	60,375	434,312	73,512
77	1,231,512	134,107	824,104	64,603	407,408	69,504
78	1,153,436	155,959	667,595	66,247	485,840	89,712
79	953,715	141,700	834,453	64,325	119,262	77,375
80	1,350,864	151,048	844,815	64,236	506,049	86,811
81	1,274,322	166,947	727,364	62,682	546,958	104,265
82	1,235,456	167,396	816,320	56,142	419,136	111,253
83	1,024,604	132,312	755,439	61,587	269,166	70,725
84	1,145,434	153,708	830,838	63,416	314,597	90,292
85	1,308,839	153,435	887,308	65,268	421,531	88,166
86	1,230,158	161,575	836,425	60,680	393,733	100,895
87	1,101,799	153,216	734,915	62,057	366,885	91,159
88	1,173,859	145,264	846,081	68,611	327,778	76,654
89	1,058,477	140,988	763,953	65,098	294,524	75,890
90	1,311,221	143,954	751,910	58,657	559,311	85,297
91	971,262	160,627	817,569	61,526	153,693	99,100
92	1,132,794	155,754	753,818	64,324	378,976	91,430
93	1,281,300	149,017	686,228	68,606	595,071	80,411
94	1,120,498	156,545	811,407	60,837	309,091	95,707
95	1,104,363	157,488	1,004,728	58,772	99,635	98,716
96	986,788	126,977	772,803	62,742	213,985	64,235
97	1,370,736	123,670	889,669	70,488	481,067	53,182
98	1,354,021	156,991	774,445	64,162	579,575	92,829
99	1,231,874	145,969	856,196	67,495	375,678	78,474
100	1,044,009	149,373	873,266	57,511	170,744	91,862
101	1,201,622	149,750	751,310	54,284	450,312	95,465
102	998,326	184,006	845,297	63,506	153,029	120,500
103	1,189,158	143,511	1,034,991	63,365	154,167	80,145
104	1,235,730	129,746	794,831	65,586	440,899	64,160
105	1,262,584	155,099	746,247	63,999	516,336	91,100
106	1,195,352	156,181	743,180	59,947	452,172	96,234
107	1,284,977	160,743	719,381	62,284	565,597	98,459
108	1,098,178	115,433	879,369	63,026	218,810	52,406
109	1,265,993	141,361	818,523	60,612	447,470	80,749
110	1,062,037	140,863	784,410	63,353	277,627	77,510
111	1,255,508	162,062	665,101	56,230	590,407	105,832
112	1,096,538	147,344	825,644	62,124	270,893	85,220

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
113	1,090,908	168,103	774,497	56,657	316,412	111,446
114	1,162,124	134,739	814,417	60,308	347,706	74,431
115	1,152,450	130,048	867,718	64,031	284,732	66,017
116	1,205,265	141,423	815,417	61,286	389,848	80,137
117	1,286,585	139,218	715,866	64,623	570,719	74,595
118	1,134,529	144,711	856,136	66,902	278,393	77,810
119	1,006,215	130,596	752,051	63,012	254,164	67,584
120	1,107,696	145,133	876,092	64,044	231,604	81,090
121	1,106,711	145,233	874,792	62,939	231,919	82,294
122	1,365,293	151,961	823,669	64,347	541,624	87,615
123	983,301	157,001	780,471	67,212	202,830	89,790
124	1,450,553	143,334	883,707	64,711	566,846	78,623
125	1,125,400	167,110	799,198	66,432	326,202	100,678
126	1,437,959	151,769	832,257	58,710	605,703	93,059
127	1,043,632	155,633	792,785	65,203	250,847	90,430
128	1,195,422	140,750	762,505	59,845	432,917	80,905
129	1,056,607	160,575	821,984	59,087	234,624	101,488
130	1,087,830	135,271	888,419	66,462	199,411	68,810
131	1,153,024	170,696	791,941	62,928	361,082	107,768
132	1,080,047	130,976	731,388	63,452	348,659	67,524
133	985,976	145,524	723,706	62,298	262,270	83,226
134	1,195,935	143,547	799,537	63,128	396,398	80,419
135	1,023,428	132,784	709,754	59,071	313,674	73,713
136	876,561	149,949	868,995	64,108	7,566	85,841
137	1,051,035	150,627	816,587	61,554	234,448	89,073
138	1,009,434	128,519	776,698	64,167	232,736	64,352
139	1,202,940	155,308	746,916	61,657	456,024	93,652
140	989,566	134,447	761,868	65,343	227,699	69,104
141	1,031,301	164,663	813,153	63,588	218,147	101,074
142	1,141,991	145,559	814,357	64,229	327,634	81,330
143	1,170,658	132,851	800,101	67,620	370,557	65,231
144	1,186,596	145,439	783,556	67,823	403,040	77,616
145	1,098,079	158,706	914,247	58,774	183,832	99,931
146	1,048,060	146,871	740,785	68,649	307,274	78,222
147	1,294,753	158,946	743,163	61,887	551,590	97,059
148	1,145,182	143,436	801,521	59,929	343,661	83,507
149	1,334,430	132,375	785,203	60,740	549,227	71,636
150	1,130,431	138,122	853,585	67,951	276,846	70,171

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
151	995,579	170,073	757,374	69,262	238,204	100,810
152	1,270,091	139,101	953,534	62,649	316,557	76,453
153	1,068,036	148,626	705,633	64,072	362,403	84,554
154	1,063,361	141,035	797,908	69,960	265,453	71,076
155	1,300,048	142,324	727,173	61,400	572,875	80,924
156	1,100,990	155,349	801,413	64,159	299,577	91,191
157	1,109,240	144,961	807,930	61,330	301,310	83,631
158	1,278,782	136,377	845,910	64,238	432,872	72,139
159	1,175,836	142,976	825,048	64,194	350,789	78,782
160	939,128	160,531	779,948	63,609	159,180	96,922
161	1,135,256	156,753	827,625	66,993	307,631	89,760
162	1,142,109	148,104	827,076	73,520	315,033	74,583
163	1,011,866	139,962	906,787	61,009	105,078	78,953
164	1,206,765	144,695	762,109	64,875	444,655	79,820
165	1,252,414	163,533	801,391	60,031	451,022	103,502
166	1,119,417	145,957	833,593	59,781	285,824	86,176
167	1,054,297	149,080	745,114	65,031	309,184	84,049
168	1,114,506	169,542	764,866	60,463	349,639	109,078
169	1,063,886	157,376	801,210	61,658	262,676	95,718
170	1,143,732	141,528	811,155	62,855	332,577	78,673
171	1,022,023	170,942	881,551	64,921	140,472	106,021
172	1,205,701	141,620	802,280	61,866	403,421	79,754
173	933,741	175,666	739,836	61,197	193,905	114,469
174	1,039,765	144,920	774,319	61,768	265,446	83,152
175	1,075,306	149,439	834,616	63,623	240,690	85,816
176	1,048,948	171,029	772,051	58,573	276,897	112,457
177	997,873	147,352	780,538	64,774	217,334	82,578
178	1,307,134	136,626	779,173	66,023	527,961	70,602
179	1,186,155	144,546	894,803	66,667	291,352	77,879
180	1,150,339	160,489	753,124	63,172	397,214	97,317
181	1,242,214	137,362	737,038	59,524	505,176	77,838
182	1,317,769	152,498	783,114	61,290	534,656	91,208
183	942,179	156,600	864,135	63,434	78,044	93,166
184	1,215,910	150,773	723,464	60,598	492,447	90,175
185	1,223,550	146,603	774,093	63,447	449,458	83,156
186	1,112,761	140,722	767,111	68,959	345,650	71,762
187	1,204,680	135,088	748,632	69,438	456,048	65,651
188	1,021,921	155,266	974,875	67,562	47,045	87,704

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
189	1,201,261	143,703	794,577	65,934	406,684	77,769
190	1,074,720	148,847	860,688	69,493	214,032	79,355
191	1,016,106	160,190	906,807	57,934	109,300	102,256
192	1,104,226	149,772	971,457	64,180	132,769	85,591
193	1,196,532	148,918	707,367	62,464	489,166	86,453
194	1,164,730	159,905	877,262	63,676	287,468	96,229
195	1,162,820	150,285	776,641	62,031	386,179	88,254
196	1,170,982	158,580	783,319	67,700	387,663	90,880
197	1,440,318	124,137	830,879	65,837	609,439	58,300
198	1,252,733	146,512	779,065	62,670	473,668	83,843
199	1,282,298	138,548	751,579	57,489	530,719	81,059
200	1,446,079	137,519	817,053	62,223	629,027	75,295
201	1,110,847	150,549	892,834	65,651	218,013	84,899
202	1,349,633	128,720	756,397	63,496	593,236	65,225
203	1,073,097	131,617	908,463	60,739	164,634	70,878
204	979,298	147,222	909,054	64,292	70,244	82,929
205	984,993	139,974	742,811	62,989	242,183	76,985
206	1,153,892	138,642	713,256	61,007	440,636	77,635
207	1,407,042	127,324	820,826	65,602	586,216	61,722
208	1,076,694	148,492	812,174	61,436	264,520	87,056
209	1,129,389	127,213	917,753	64,714	211,635	62,499
210	1,267,478	148,101	763,670	60,065	503,808	88,036
211	1,153,894	152,962	790,438	71,343	363,456	81,619
212	1,209,435	144,671	758,094	60,009	451,341	84,662
213	1,378,587	144,845	796,070	60,220	582,517	84,625
214	994,819	178,138	741,786	66,965	253,032	111,173
215	986,653	146,701	844,980	69,987	141,673	76,714
216	1,231,006	153,478	734,587	62,591	496,420	90,886
217	1,101,658	148,800	904,166	66,190	197,492	82,610
218	1,146,703	161,518	793,409	67,318	353,293	94,199
219	1,242,276	150,775	864,605	66,571	377,672	84,205
220	1,272,373	151,935	798,245	58,463	474,128	93,472
221	1,154,147	163,565	762,758	65,212	391,389	98,353
222	1,081,579	130,244	784,134	63,036	297,445	67,208
223	1,381,632	153,720	854,754	65,075	526,878	88,645
224	1,020,948	134,013	900,762	68,851	120,186	65,162
225	1,193,848	134,328	737,914	63,101	455,934	71,227
226	1,143,828	130,112	843,863	63,262	299,965	66,850

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
227	1,141,672	162,502	680,359	63,179	461,313	99,323
228	1,097,376	137,478	814,623	60,517	282,753	76,960
229	1,278,310	132,206	753,908	60,743	524,402	71,463
230	1,172,200	143,028	779,521	64,658	392,679	78,370
231	1,200,587	150,549	724,798	66,955	475,790	83,594
232	1,207,430	134,709	801,478	63,081	405,952	71,628
233	1,067,701	136,938	761,126	64,688	306,575	72,250
234	1,228,794	159,301	843,436	62,198	385,358	97,102
235	1,067,407	151,805	850,830	65,229	216,577	86,576
236	1,098,479	140,555	776,007	64,928	322,472	75,626
237	1,331,111	150,281	768,657	63,568	562,454	86,713
238	1,120,136	148,678	791,437	58,852	328,700	89,826
239	1,086,709	152,738	809,609	67,060	277,099	85,678
240	1,059,776	144,926	814,020	61,214	245,756	83,712
241	1,441,652	133,314	763,870	59,849	677,782	73,465
242	1,000,397	163,420	768,148	71,437	232,250	91,984
243	1,011,070	127,634	735,687	66,974	275,383	60,660
244	1,209,659	140,613	876,092	63,042	333,566	77,572
245	1,108,851	146,471	730,310	62,015	378,542	84,456
246	1,061,977	159,410	742,754	60,540	319,224	98,871
247	1,363,762	138,848	885,236	66,678	478,527	72,171
248	1,210,659	143,844	717,214	73,935	493,445	69,909
249	1,158,069	148,541	801,309	65,444	356,760	83,098
250	1,119,320	155,920	972,232	60,430	147,088	95,490
251	973,303	144,576	779,690	61,518	193,614	83,058
252	1,257,534	128,681	974,071	68,672	283,463	60,009
253	1,018,176	154,302	809,161	66,098	209,015	88,204
254	1,097,650	141,617	740,098	67,422	357,552	74,195
255	1,017,690	159,579	845,080	66,374	172,610	93,205
256	1,256,536	152,495	908,217	66,733	348,319	85,762
257	1,536,519	159,737	865,752	57,998	670,768	101,739
258	1,294,044	130,845	782,598	63,227	511,447	67,618
259	1,081,962	158,065	755,686	66,536	326,276	91,529
260	1,117,946	176,367	794,947	58,885	322,999	117,481
261	1,066,796	141,130	771,968	70,408	294,827	70,722
262	1,370,571	138,646	746,870	58,458	623,701	80,188
263	1,031,359	143,070	992,141	65,965	39,218	77,105
264	1,147,861	125,706	839,390	66,746	308,470	58,960

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
265	1,275,050	138,856	791,134	59,784	483,916	79,072
266	1,257,585	139,141	750,332	68,968	507,254	70,173
267	1,326,353	135,300	845,565	61,827	480,789	73,474
268	1,086,154	155,020	819,751	60,582	266,403	94,438
269	1,223,181	138,407	917,791	73,704	305,389	64,702
270	1,216,824	138,971	862,804	66,226	354,020	72,745
271	1,061,992	156,345	863,257	63,192	198,734	93,153
272	1,129,302	156,849	820,056	62,599	309,246	94,249
273	1,173,822	166,188	762,343	54,580	411,479	111,608
274	1,024,668	146,887	765,717	68,513	258,950	78,375
275	1,166,599	141,121	762,389	67,550	404,210	73,572
276	1,280,943	142,683	884,917	68,978	396,026	73,705
277	1,338,730	161,770	778,137	62,756	560,594	99,014
278	1,083,254	143,776	818,848	60,606	264,406	83,170
279	1,263,262	135,945	940,276	62,104	322,986	73,841
280	1,070,870	156,538	787,214	60,770	283,655	95,768
281	1,178,098	150,946	889,407	64,510	288,691	86,435
282	1,059,220	142,058	830,554	67,308	228,666	74,750
283	1,314,440	148,369	806,737	72,100	507,703	76,268
284	1,103,465	147,901	736,589	61,931	366,876	85,970
285	1,439,639	151,395	891,088	62,056	548,550	89,340
286	1,162,470	124,789	782,090	60,047	380,380	64,741
287	1,257,760	155,400	874,673	57,738	383,087	97,662
288	1,089,015	130,475	733,837	65,285	355,178	65,191
289	1,105,126	142,886	792,158	67,626	312,969	75,260
290	1,045,901	147,598	872,457	65,283	173,444	82,315
291	949,659	130,854	830,402	67,616	119,257	63,238
292	1,113,445	153,821	743,479	64,878	369,966	88,943
293	1,347,087	137,940	745,745	59,247	601,342	78,693
294	1,027,928	141,757	770,426	65,975	257,503	75,782
295	1,087,537	149,207	811,897	62,805	275,640	86,402
296	1,045,014	141,171	909,706	61,754	135,308	79,416
297	1,286,416	131,949	874,038	66,713	412,377	65,236
298	1,324,150	145,483	756,879	65,775	567,271	79,708
299	1,121,741	132,843	766,719	61,721	355,022	71,122
300	1,180,019	155,120	750,615	67,352	429,405	87,768
301	1,144,311	164,063	848,812	65,649	295,499	98,414
302	1,258,136	166,142	786,714	59,199	471,423	106,943

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
303	1,251,382	137,303	745,731	62,732	505,651	74,570
304	1,120,376	150,642	848,631	66,451	271,745	84,190
305	1,255,955	142,331	699,773	62,736	556,181	79,595
306	1,117,902	152,991	993,314	66,421	124,588	86,570
307	1,195,366	149,860	841,450	65,050	353,917	84,810
308	1,138,765	159,876	854,608	62,945	284,158	96,931
309	1,106,461	145,756	751,785	62,107	354,677	83,650
310	1,268,466	130,431	896,376	64,818	372,091	65,613
311	1,163,036	162,564	707,387	59,910	455,650	102,653
312	1,120,231	146,972	847,624	58,707	272,606	88,265
313	1,182,951	163,055	714,960	66,241	467,990	96,814
314	1,159,073	140,634	825,038	63,167	334,034	77,466
315	1,177,369	171,208	895,780	58,827	281,589	112,382
316	1,042,645	157,458	733,614	64,243	309,031	93,215
317	1,260,393	151,658	877,214	60,982	383,179	90,677
318	1,171,590	144,311	845,344	65,060	326,246	79,251
319	976,350	157,030	857,918	65,474	118,431	91,556
320	1,029,809	150,001	772,299	66,537	257,510	83,464
321	1,131,274	146,870	819,662	60,532	311,612	86,338
322	1,303,676	149,875	878,299	59,026	425,377	90,849
323	1,112,473	144,267	812,320	61,915	300,153	82,353
324	1,385,962	145,028	778,723	57,685	607,239	87,343
325	1,036,328	134,052	1,105,967	59,183	-69,639	74,869
326	1,153,476	146,844	803,150	68,082	350,326	78,762
327	1,188,164	157,579	870,470	58,151	317,694	99,428
328	977,555	148,778	760,978	60,847	216,577	87,931
329	1,151,530	149,712	883,987	65,755	267,543	83,956
330	1,113,861	137,976	750,825	60,150	363,036	77,827
331	1,199,161	173,435	830,023	57,818	369,138	115,617
332	1,233,073	144,840	767,814	64,573	465,259	80,266
333	1,257,208	142,575	767,360	65,252	489,847	77,323
334	1,145,601	136,937	820,631	64,372	324,970	72,565
335	1,116,038	144,766	796,896	62,274	319,142	82,492
336	1,137,400	142,267	859,789	63,853	277,612	78,414
337	1,190,052	130,016	794,478	60,508	395,574	69,509
338	1,219,676	149,848	879,608	61,392	340,069	88,456
339	1,055,678	138,745	793,471	64,659	262,208	74,086
340	1,223,585	140,498	826,935	66,182	396,650	74,316

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
341	1,325,432	136,696	775,777	64,412	549,656	72,284
342	1,220,631	143,906	748,599	64,431	472,032	79,474
343	1,040,784	156,064	860,705	68,700	180,078	87,364
344	1,335,299	132,696	762,361	65,267	572,939	67,429
345	1,331,298	141,354	812,527	64,277	518,772	77,077
346	1,185,955	165,563	759,461	58,054	426,493	107,509
347	1,115,891	150,389	749,694	62,279	366,197	88,110
348	1,032,489	149,146	769,356	61,963	263,132	87,183
349	1,302,323	141,209	812,911	70,452	489,412	70,757
350	1,281,741	162,085	752,097	57,195	529,644	104,891
351	988,013	149,266	705,656	61,501	282,357	87,766
352	1,119,022	145,911	785,551	65,600	333,471	80,311
353	1,110,031	153,057	741,512	63,689	368,519	89,369
354	1,142,708	139,188	753,779	68,704	388,930	70,484
355	1,091,677	140,655	809,635	66,106	282,042	74,549
356	1,245,351	145,746	799,266	66,911	446,085	78,835
357	1,121,026	151,807	920,413	70,067	200,613	81,739
358	1,060,953	132,690	789,935	57,457	271,018	75,233
359	959,062	143,052	726,642	62,568	232,420	80,484
360	1,423,965	172,460	794,417	65,157	629,548	107,303
361	1,164,187	142,492	1,000,552	63,013	163,635	79,478
362	1,224,858	139,882	712,092	62,064	512,765	77,818
363	1,286,117	146,287	730,420	66,102	555,697	80,185
364	1,130,744	158,507	772,517	64,035	358,228	94,472
365	1,125,130	163,515	759,831	60,910	365,299	102,605
366	1,140,194	127,888	834,244	64,060	305,949	63,829
367	1,348,560	128,288	763,759	62,846	584,801	65,442
368	1,333,691	138,433	782,872	64,367	550,819	74,066
369	1,122,949	154,152	839,222	62,804	283,727	91,348
370	1,109,775	140,596	919,295	59,632	190,480	80,963
371	1,109,660	144,928	835,373	65,929	274,287	78,999
372	1,400,316	135,705	747,197	60,960	653,119	74,745
373	1,130,464	144,143	854,925	60,648	275,540	83,495
374	1,089,173	182,457	779,825	64,568	309,348	117,889
375	1,412,057	131,364	788,350	64,695	623,707	66,668
376	1,244,595	153,691	851,139	59,337	393,456	94,354
377	1,270,661	162,242	816,324	62,819	454,337	99,423
378	1,167,540	149,616	782,703	60,703	384,837	88,913

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
379	1,067,067	139,708	747,268	65,536	319,800	74,171
380	1,205,278	148,866	897,153	61,962	308,125	86,904
381	1,314,413	171,821	799,233	65,309	515,180	106,512
382	1,219,588	150,111	722,426	64,664	497,161	85,447
383	1,520,151	186,794	719,283	66,911	800,869	119,883
384	1,229,659	150,032	916,877	64,410	312,782	85,622
385	1,280,591	148,120	726,227	64,298	554,364	83,823
386	1,129,484	134,547	803,835	67,290	325,649	67,258
387	1,088,275	135,808	722,739	63,064	365,536	72,744
388	1,106,516	152,872	734,232	60,675	372,283	92,197
389	1,198,733	140,684	908,573	66,063	290,160	74,621
390	1,066,943	160,627	887,725	60,962	179,218	99,664
391	943,394	133,448	830,933	73,237	112,461	60,211
392	1,267,742	144,759	1,014,963	67,517	252,779	77,242
393	1,210,943	161,723	829,685	63,217	381,258	98,505
394	1,188,248	148,909	721,647	60,246	466,601	88,664
395	1,239,783	141,705	758,107	61,172	481,677	80,533
396	1,133,988	144,992	730,787	60,759	403,201	84,233
397	1,311,380	145,357	748,100	80,275	563,280	65,082
398	1,407,793	141,355	811,627	65,229	596,166	76,125
399	1,125,713	158,262	745,691	64,844	380,021	93,418
400	954,160	140,948	799,835	62,135	154,325	78,813
401	1,405,127	149,757	850,120	62,569	555,007	87,187
402	1,273,603	173,469	733,460	66,026	540,142	107,443
403	1,111,778	160,240	859,965	59,285	251,813	100,954
404	1,009,710	143,099	778,552	59,882	231,158	83,217
405	1,068,641	130,346	903,450	65,842	165,191	64,504
406	1,305,733	137,257	794,563	67,627	511,170	69,630
407	1,215,664	144,205	838,989	61,298	376,675	82,906
408	1,306,333	137,098	745,360	72,283	560,973	64,815
409	963,110	142,923	749,577	62,408	213,533	80,514
410	1,312,527	136,694	818,111	61,493	494,416	75,201
411	1,268,943	141,912	827,357	64,258	441,586	77,654
412	1,214,245	151,882	834,488	64,664	379,757	87,218
413	1,098,090	139,514	777,710	68,348	320,381	71,166
414	1,037,439	167,565	776,965	61,462	260,473	106,103
415	1,261,709	152,492	744,628	64,267	517,082	88,225
416	1,143,987	145,732	801,058	69,434	342,930	76,298

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
417	1,036,393	134,625	721,342	59,359	315,051	75,266
418	1,161,778	160,291	756,008	61,829	405,770	98,462
419	1,236,951	153,626	748,269	65,596	488,683	88,030
420	1,268,851	162,742	815,010	64,486	453,841	98,256
421	1,281,416	156,701	775,626	65,990	505,790	90,710
422	1,058,089	145,486	760,832	58,461	297,257	87,025
423	1,401,646	145,204	768,984	64,977	632,662	80,227
424	1,042,222	144,632	851,093	62,044	191,129	82,588
425	1,100,535	149,716	970,845	66,036	129,691	83,680
426	1,311,088	143,235	777,635	63,167	533,453	80,068
427	1,012,347	163,574	820,757	70,764	191,590	92,810
428	1,014,853	133,359	833,392	67,949	181,460	65,411
429	1,271,184	130,419	743,357	64,878	527,827	65,542
430	1,325,568	134,136	816,333	64,104	509,235	70,032
431	1,025,225	123,987	852,629	63,102	172,596	60,886
432	1,202,356	134,300	761,321	63,633	441,035	70,667
433	1,242,010	142,638	779,961	57,425	462,049	85,213
434	1,180,865	154,942	845,942	68,951	334,923	85,991
435	1,294,187	155,026	797,522	65,558	496,664	89,468
436	1,219,219	138,819	808,966	63,586	410,252	75,233
437	1,135,866	145,756	723,240	71,483	412,625	74,272
438	1,032,060	146,862	724,753	67,978	307,307	78,884
439	1,234,386	151,430	905,839	67,742	328,547	83,688
440	1,290,512	150,476	799,193	58,035	491,319	92,441
441	1,209,045	156,162	847,143	58,462	361,902	97,700
442	1,310,496	136,712	753,239	68,870	557,257	67,842
443	1,265,995	138,592	768,767	61,936	497,228	76,656
444	1,099,688	148,961	700,253	57,542	399,436	91,419
445	1,306,116	143,457	848,755	60,970	457,361	82,487
446	1,449,199	143,079	810,411	64,229	638,788	78,850
447	1,324,158	150,644	756,090	61,410	568,068	89,234
448	1,030,596	148,568	835,310	61,523	195,286	87,045
449	1,248,716	142,734	843,827	66,699	404,888	76,035
450	1,205,265	152,601	865,308	63,831	339,957	88,770
451	950,135	167,472	752,585	56,644	197,551	110,828
452	1,090,077	142,373	876,249	65,593	213,828	76,780
453	1,220,876	133,799	828,953	64,354	391,923	69,444
454	1,158,655	144,576	777,754	67,281	380,900	77,295

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
455	1,234,592	146,362	806,203	69,994	428,389	76,368
456	1,093,537	146,004	836,390	60,457	257,147	85,547
457	982,643	166,259	816,069	61,887	166,574	104,372
458	1,039,858	167,633	737,867	68,606	301,991	99,027
459	1,092,630	131,576	782,919	61,733	309,711	69,843
460	987,425	128,288	742,778	62,866	244,646	65,423
461	1,364,136	131,214	848,040	61,214	516,097	70,000
462	1,351,165	150,050	713,975	65,710	637,190	84,339
463	1,270,587	135,580	764,712	62,589	505,875	72,991
464	1,162,054	154,730	819,043	64,859	343,011	89,870
465	1,150,432	134,245	766,583	68,510	383,850	65,735
466	1,252,388	148,726	756,826	64,042	495,561	84,684
467	1,110,747	137,362	875,147	67,211	235,600	70,150
468	1,059,384	138,698	874,131	63,865	185,252	74,833
469	947,568	132,470	743,984	69,149	203,584	63,321
470	1,301,187	141,542	791,909	67,902	509,278	73,640
471	1,241,013	166,675	703,913	62,759	537,100	103,915
472	1,259,108	135,390	863,707	64,783	395,401	70,607
473	1,301,608	155,526	727,627	65,517	573,981	90,009
474	980,294	123,044	795,641	60,425	184,653	62,619
475	1,255,180	123,748	804,543	58,102	450,636	65,646
476	1,118,346	160,526	929,361	63,930	188,985	96,597
477	1,229,717	132,253	854,719	59,722	374,999	72,531
478	1,339,423	141,120	822,786	63,587	516,637	77,533
479	1,043,529	141,777	713,092	70,605	330,437	71,171
480	1,218,906	147,100	771,249	60,501	447,657	86,599
481	1,042,150	153,206	850,437	67,016	191,714	86,190
482	1,343,967	148,906	743,520	59,266	600,447	89,640
483	1,287,684	145,350	821,843	66,492	465,841	78,858
484	1,153,371	144,860	774,288	64,990	379,082	79,869
485	1,149,853	155,524	828,167	63,947	321,686	91,577
486	1,243,089	144,611	798,784	64,564	444,305	80,047
487	1,132,220	153,745	758,225	67,753	373,995	85,992
488	1,196,379	145,115	782,154	58,515	414,225	86,600
489	1,223,077	150,326	869,624	65,551	353,453	84,775
490	930,931	148,217	837,663	60,408	93,268	87,809
491	1,296,190	134,678	845,069	62,887	451,120	71,791
492	1,129,020	147,133	819,982	66,592	309,037	80,542

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
493	1,178,973	133,974	908,788	70,542	270,185	63,432
494	1,426,118	141,239	766,808	59,226	659,310	82,013
495	1,146,387	133,848	769,635	58,846	376,752	75,002
496	1,391,486	145,061	871,919	60,807	519,567	84,255
497	1,086,517	145,455	796,442	68,315	290,075	77,140
498	1,358,268	147,815	869,350	60,795	488,918	87,020
499	1,133,763	151,164	835,438	66,139	298,325	85,025
500	1,241,024	162,377	846,519	61,693	394,505	100,684
501	1,299,865	152,483	839,998	60,461	459,867	92,022
502	983,610	140,890	781,780	65,178	201,830	75,711
503	1,089,606	139,145	799,521	67,221	290,085	71,924
504	1,217,263	154,703	833,533	68,647	383,731	86,056
505	1,094,423	151,958	839,184	62,870	255,239	89,088
506	1,319,530	125,895	817,263	63,309	502,268	62,586
507	1,188,115	150,938	806,667	66,323	381,448	84,615
508	1,320,164	144,730	960,820	64,704	359,344	80,026
509	1,046,875	146,088	801,703	65,227	245,171	80,861
510	1,112,663	153,767	957,079	62,576	155,584	91,191
511	1,202,450	160,987	760,233	69,653	442,217	91,334
512	1,304,171	166,472	768,884	59,231	535,287	107,241
513	1,106,394	148,897	827,584	64,777	278,810	84,120
514	1,141,202	144,713	884,578	61,015	256,624	83,698
515	1,269,880	152,680	760,993	62,366	508,887	90,313
516	1,310,984	133,935	903,817	69,207	407,166	64,728
517	1,052,237	141,587	757,916	56,222	294,321	85,365
518	1,104,698	157,377	811,001	60,427	293,697	96,951
519	872,831	151,192	666,478	64,562	206,353	86,630
520	1,127,226	146,184	735,363	60,028	391,863	86,156
521	1,155,040	138,932	936,728	63,915	218,312	75,017
522	1,105,601	143,572	789,044	68,422	316,558	75,150
523	1,159,103	166,730	752,679	59,691	406,424	107,039
524	992,465	159,216	681,316	67,001	311,150	92,215
525	984,152	131,620	787,577	66,440	196,575	65,181
526	1,449,377	157,689	783,412	65,415	665,965	92,273
527	1,138,355	122,505	715,787	73,451	422,568	49,054
528	1,058,594	150,646	759,430	66,963	299,164	83,684
529	1,292,332	137,440	857,443	65,173	434,890	72,267
530	996,919	158,625	746,379	63,220	250,539	95,406

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
531	1,143,285	143,954	700,913	64,621	442,373	79,333
532	1,151,882	138,279	798,679	64,111	353,203	74,168
533	1,384,349	143,309	850,544	64,482	533,805	78,827
534	1,137,489	137,925	751,476	59,396	386,014	78,529
535	1,196,663	141,271	804,836	62,279	391,827	78,992
536	1,237,854	166,307	832,430	72,247	405,423	94,060
537	1,359,999	142,472	817,961	58,375	542,038	84,097
538	1,013,840	159,555	1,113,437	62,675	-99,596	96,879
539	1,232,601	139,012	815,024	58,943	417,577	80,069
540	977,328	154,317	708,539	68,541	268,789	85,777
541	1,187,872	150,288	812,595	62,642	375,277	87,646
542	1,173,072	128,783	776,612	60,650	396,461	68,133
543	1,291,466	153,200	865,874	59,716	425,592	93,484
544	1,344,358	158,461	772,921	61,904	571,437	96,557
545	1,023,915	150,765	790,473	63,781	233,442	86,984
546	1,244,771	142,991	806,962	67,343	437,809	75,649
547	1,066,362	141,600	762,223	71,346	304,138	70,254
548	1,094,176	159,992	821,502	58,098	272,674	101,894
549	1,304,124	137,967	819,280	61,340	484,844	76,626
550	1,209,254	134,159	844,119	59,587	365,135	74,572
551	1,109,909	146,020	813,902	60,944	296,007	85,076
552	1,141,211	142,153	749,148	62,238	392,063	79,915
553	1,239,964	140,826	719,056	63,104	520,908	77,723
554	1,313,536	150,191	786,819	64,569	526,717	85,622
555	1,421,482	144,133	876,712	62,055	544,770	82,078
556	1,212,946	160,685	762,959	63,091	449,986	97,594
557	1,046,057	153,648	742,103	69,251	303,954	84,397
558	1,301,259	149,720	705,176	58,472	596,083	91,248
559	1,200,343	128,938	822,027	65,723	378,316	63,215
560	1,156,909	149,442	755,274	62,018	401,635	87,424
561	1,232,695	173,425	831,054	57,798	401,641	115,627
562	1,173,527	140,140	788,133	72,487	385,394	67,653
563	1,133,572	153,046	844,978	66,631	288,594	86,415
564	1,170,541	162,840	811,774	64,876	358,767	97,965
565	1,128,609	146,407	800,208	61,976	328,401	84,431
566	1,101,360	134,327	773,598	65,990	327,762	68,337
567	1,272,566	150,060	816,013	64,218	456,553	85,841
568	1,092,228	140,403	797,278	64,606	294,950	75,797

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
569	1,179,098	145,673	806,544	67,260	372,554	78,414
570	1,056,539	135,822	676,450	63,050	380,090	72,772
571	1,170,679	154,110	935,257	64,679	235,422	89,431
572	1,079,904	142,024	704,588	62,545	375,316	79,479
573	1,223,365	139,950	1,092,315	62,590	131,050	77,360
574	1,205,812	151,643	794,512	67,836	411,300	83,807
575	1,168,718	155,785	794,146	66,493	374,573	89,293
576	1,133,351	154,908	848,882	64,702	284,469	90,205
577	1,183,707	133,675	749,902	68,443	433,805	65,232
578	1,118,147	132,011	728,827	67,038	389,319	64,973
579	1,210,058	142,728	822,997	66,209	387,060	76,519
580	1,257,501	147,219	768,736	68,038	488,766	79,181
581	1,125,041	161,432	746,486	60,624	378,556	100,808
582	1,101,937	147,435	756,556	62,123	345,381	85,312
583	1,281,150	168,665	824,469	67,508	456,681	101,157
584	1,142,542	132,016	797,810	61,590	344,731	70,426
585	1,067,085	132,251	809,469	61,533	257,615	70,718
586	1,011,471	140,244	784,108	58,916	227,363	81,328
587	1,086,726	145,899	824,432	67,929	262,294	77,969
588	1,286,137	159,710	771,952	63,491	514,185	96,219
589	1,184,923	129,712	808,460	68,317	376,463	61,395
590	1,232,471	139,966	747,536	64,796	484,935	75,169
591	991,710	156,971	892,124	63,034	99,586	93,936
592	1,202,464	130,321	744,088	63,507	458,376	66,815
593	1,291,201	143,444	745,200	62,288	546,001	81,156
594	1,191,854	138,105	819,041	64,128	372,813	73,977
595	1,240,206	132,773	819,041	66,096	421,164	66,676
596	1,278,339	145,429	766,023	62,803	512,316	82,626
597	962,414	141,326	783,397	61,143	179,016	80,184
598	1,086,637	145,845	848,753	61,476	237,884	84,369
599	1,359,745	141,590	864,532	67,135	495,213	74,455
600	1,121,021	136,597	788,258	58,819	332,762	77,778
601	1,137,714	127,969	822,939	59,504	314,775	68,464
602	1,204,302	144,890	790,063	70,277	414,238	74,612
603	1,043,257	139,040	735,625	61,817	307,632	77,223
604	1,397,039	136,929	884,799	66,684	512,240	70,245
605	1,162,834	153,136	880,643	58,200	282,191	94,936
606	1,133,864	135,379	809,770	63,900	324,094	71,480

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
607	984,516	169,812	797,444	60,770	187,071	109,042
608	1,264,172	120,431	847,808	59,138	416,364	61,293
609	1,326,110	145,136	818,273	64,942	507,837	80,193
610	1,218,997	157,789	771,481	62,893	447,516	94,895
611	1,425,199	158,252	889,621	62,303	535,578	95,948
612	1,257,569	134,057	880,845	60,904	376,723	73,153
613	1,074,883	142,786	704,003	61,279	370,880	81,508
614	1,156,317	144,835	881,515	64,110	274,802	80,725
615	1,190,545	174,609	719,790	65,621	470,755	108,988
616	1,178,935	142,395	812,564	57,513	366,371	84,882
617	1,373,800	149,567	718,020	62,627	655,780	86,940
618	992,442	135,026	801,325	62,623	191,117	72,402
619	1,114,035	156,739	781,383	61,424	332,652	95,315
620	1,662,152	140,381	707,747	64,766	954,405	75,615
621	1,123,285	159,858	877,094	63,657	246,191	96,201
622	1,089,751	145,760	858,066	67,190	231,685	78,570
623	1,219,562	145,548	751,278	57,848	468,284	87,700
624	1,287,077	136,543	833,931	59,006	453,146	77,537
625	1,147,922	160,036	798,984	63,335	348,938	96,701
626	1,411,179	168,014	799,973	59,620	611,206	108,393
627	1,095,134	135,198	823,509	60,812	271,625	74,386
628	1,351,262	138,946	920,944	59,422	430,318	79,524
629	1,125,202	156,339	786,378	60,885	338,824	95,454
630	1,196,330	144,755	800,895	60,863	395,435	83,892
631	1,440,374	143,094	789,043	62,237	651,331	80,857
632	1,187,373	143,114	755,506	67,842	431,867	75,272
633	1,333,887	161,182	752,522	59,093	581,364	102,089
634	1,152,417	182,131	917,684	70,352	234,733	111,779
635	999,607	137,731	766,867	62,735	232,740	74,996
636	1,154,791	152,458	760,605	61,049	394,186	91,409
637	1,197,471	136,751	697,129	60,150	500,342	76,601
638	1,181,137	145,329	808,355	66,714	372,782	78,615
639	1,101,374	145,333	806,639	60,022	294,735	85,311
640	1,128,977	139,180	881,831	68,828	247,146	70,353
641	1,068,080	148,669	844,810	65,237	223,269	83,432
642	1,235,820	134,121	738,270	63,072	497,550	71,048
643	1,135,898	144,390	821,322	58,601	314,576	85,789
644	1,229,684	161,140	778,800	60,054	450,884	101,087

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
645	1,134,435	150,093	836,596	59,550	297,839	90,542
646	1,060,540	138,942	807,715	69,194	252,825	69,749
647	1,092,116	156,518	752,294	58,345	339,822	98,173
648	1,277,633	136,387	815,827	62,168	461,806	74,219
649	1,226,436	161,880	770,137	63,475	456,300	98,405
650	1,126,249	145,911	849,731	60,733	276,517	85,178
651	1,089,517	130,485	728,634	65,217	360,884	65,268
652	1,209,392	152,817	809,963	60,640	399,429	92,177
653	1,347,589	151,499	800,879	60,078	546,710	91,421
654	1,144,674	133,319	790,276	60,304	354,399	73,015
655	1,399,909	134,532	776,145	65,308	623,765	69,224
656	1,199,358	173,924	891,157	58,396	308,202	115,528
657	1,251,681	178,046	757,623	59,241	494,057	118,806
658	1,268,639	159,934	768,276	65,845	500,363	94,089
659	1,057,400	160,678	900,262	70,510	157,138	90,169
660	1,173,373	150,961	979,919	61,732	193,454	89,229
661	1,342,743	150,398	788,131	58,508	554,612	91,890
662	1,198,233	155,408	965,709	62,112	232,525	93,296
663	1,549,163	149,517	773,147	68,101	776,016	81,417
664	983,833	125,608	752,425	62,915	231,407	62,692
665	1,089,667	138,483	772,443	63,248	317,224	75,235
666	1,251,265	141,904	819,471	65,856	431,795	76,048
667	1,183,975	139,538	916,259	67,340	267,716	72,198
668	1,215,981	156,512	866,580	67,875	349,401	88,637
669	1,154,001	139,633	909,171	58,680	244,830	80,953
670	1,056,627	163,915	758,714	64,511	297,913	99,405
671	1,046,016	162,421	864,950	75,086	181,066	87,336
672	1,031,555	140,784	810,828	67,102	220,727	73,682
673	1,173,337	143,065	835,332	75,474	338,006	67,591
674	1,206,500	145,690	853,860	67,121	352,640	78,568
675	1,254,259	141,074	783,041	67,702	471,218	73,373
676	1,050,748	146,974	716,781	61,304	333,967	85,670
677	1,154,135	153,611	923,662	61,792	230,473	91,819
678	1,285,351	159,332	755,582	61,402	529,768	97,930
679	1,005,808	132,811	830,683	67,486	175,125	65,325
680	1,149,411	155,407	803,448	66,837	345,963	88,571
681	1,408,866	143,138	751,470	64,007	657,396	79,131
682	1,032,735	169,551	811,539	60,165	221,196	109,385

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
683	1,123,097	140,528	806,993	66,969	316,103	73,560
684	1,193,539	146,202	835,342	60,861	358,197	85,341
685	1,001,394	150,988	786,148	66,422	215,246	84,565
686	1,138,232	147,111	1,075,697	62,042	62,535	85,069
687	1,072,294	166,496	799,032	62,830	273,262	103,666
688	1,369,690	141,559	833,621	62,431	536,069	79,128
689	1,350,961	141,799	733,088	69,284	617,873	72,515
690	1,265,210	137,564	932,505	58,278	332,705	79,286
691	1,188,643	150,272	754,856	65,060	433,787	85,212
692	1,092,981	146,613	992,809	63,603	100,172	83,010
693	1,245,034	139,071	725,201	66,325	519,833	72,746
694	1,386,289	147,958	990,163	59,624	396,126	88,333
695	1,347,726	129,523	737,311	66,796	610,415	62,726
696	1,350,195	142,282	754,475	59,330	595,719	82,952
697	961,261	150,182	771,945	63,492	189,316	86,691
698	1,273,710	145,753	800,076	66,780	473,634	78,973
699	1,201,258	126,344	816,642	60,636	384,616	65,708
700	1,255,711	125,754	779,144	60,120	476,567	65,634
701	1,036,371	155,490	837,435	59,589	198,937	95,902
702	1,359,298	154,368	847,366	61,917	511,932	92,451
703	1,020,244	150,858	760,744	59,815	259,500	91,043
704	1,278,944	155,513	792,206	59,377	486,738	96,137
705	1,126,134	145,796	1,037,969	61,737	88,165	84,059
706	1,102,685	147,280	844,731	63,093	257,954	84,187
707	1,207,160	134,876	973,539	65,912	233,621	68,965
708	1,052,090	143,517	889,787	71,273	162,303	72,245
709	1,280,695	139,516	852,568	65,714	428,127	73,802
710	1,133,847	137,889	801,006	62,866	332,841	75,023
711	1,379,857	147,355	773,316	66,336	606,541	81,019
712	1,409,573	161,826	887,821	60,137	521,752	101,690
713	1,176,734	147,319	729,097	66,212	447,637	81,106
714	1,229,482	147,282	777,257	59,980	452,225	87,302
715	1,370,239	139,686	794,336	61,186	575,903	78,499
716	1,103,667	138,111	845,377	70,802	258,290	67,309
717	1,449,145	141,597	852,899	63,619	596,245	77,978
718	1,196,293	157,509	734,543	68,017	461,750	89,491
719	1,041,216	132,152	872,825	62,069	168,390	70,083
720	906,442	161,460	761,587	60,187	144,855	101,273

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
721	1,005,032	131,230	811,058	64,233	193,974	66,997
722	1,071,951	154,072	790,507	60,836	281,444	93,236
723	989,048	127,927	834,495	55,045	154,553	72,882
724	1,273,078	145,276	793,405	59,066	479,673	86,210
725	1,063,759	148,127	901,808	55,414	161,951	92,713
726	1,105,369	147,489	907,270	62,254	198,099	85,235
727	1,123,522	164,443	891,012	65,879	232,510	98,564
728	1,157,730	157,329	904,465	68,279	253,265	89,051
729	1,164,022	137,080	753,538	64,304	410,484	72,776
730	1,088,550	130,455	747,568	67,892	340,982	62,564
731	1,190,802	156,878	788,881	63,891	401,921	92,988
732	1,225,852	149,800	803,545	63,374	422,307	86,426
733	1,351,534	166,776	766,147	71,619	585,387	95,157
734	1,198,106	144,935	764,802	62,180	433,304	82,755
735	1,211,071	138,551	802,313	61,181	408,758	77,370
736	1,595,729	151,753	798,934	63,712	796,795	88,041
737	1,337,914	159,227	803,364	64,613	534,550	94,614
738	1,178,720	132,686	817,683	64,386	361,037	68,301
739	1,268,682	155,026	773,791	60,929	494,891	94,097
740	1,019,422	145,676	863,644	68,013	155,778	77,663
741	1,421,174	128,606	826,819	64,168	594,356	64,438
742	1,401,943	147,732	828,040	65,424	573,903	82,308
743	1,145,618	137,374	735,922	63,472	409,696	73,902
744	1,472,001	138,846	818,975	62,241	653,026	76,604
745	1,217,650	155,952	709,450	61,820	508,200	94,132
746	1,229,129	148,850	875,791	70,102	353,338	78,748
747	988,767	162,566	828,215	65,777	160,552	96,789
748	1,197,028	145,599	840,959	61,961	356,069	83,638
749	1,090,835	144,472	771,731	66,994	319,104	77,478
750	1,160,177	162,690	761,836	65,731	398,341	96,959
751	1,117,674	159,277	837,713	65,479	279,961	93,797
752	1,135,334	173,019	760,520	64,005	374,814	109,014
753	1,199,009	131,954	823,321	58,996	375,688	72,958
754	1,238,725	154,661	802,907	62,731	435,818	91,930
755	971,576	137,417	744,182	64,066	227,395	73,351
756	1,298,511	153,054	809,257	59,325	489,255	93,729
757	1,384,129	138,097	858,204	61,079	525,926	77,017
758	1,232,382	130,747	868,385	63,327	363,997	67,421

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
759	1,391,754	137,637	877,041	65,464	514,714	72,172
760	1,278,875	148,627	802,749	60,519	476,125	88,108
761	1,174,933	150,921	713,306	67,450	461,627	83,471
762	1,255,926	141,938	751,408	60,038	504,518	81,899
763	1,149,477	159,063	775,320	66,755	374,157	92,308
764	1,213,387	151,068	806,103	63,758	407,283	87,310
765	1,152,399	132,767	840,153	67,865	312,246	64,902
766	1,107,252	136,896	721,797	61,861	385,454	75,035
767	1,211,980	123,079	784,214	64,381	427,766	58,698
768	1,172,272	152,717	789,350	62,217	382,922	90,500
769	1,052,502	146,605	831,079	61,388	221,423	85,217
770	930,876	172,706	804,183	62,371	126,693	110,336
771	861,292	135,010	749,991	60,504	111,301	74,506
772	1,135,106	161,211	971,740	68,326	163,366	92,885
773	1,201,085	149,769	724,667	67,575	476,418	82,193
774	1,075,741	155,818	793,277	58,449	282,463	97,368
775	1,230,044	137,880	779,032	64,587	451,012	73,293
776	1,061,386	142,096	714,978	56,003	346,407	86,093
777	1,095,947	170,209	719,904	68,161	376,043	102,048
778	1,266,843	187,847	762,073	63,016	504,770	124,831
779	1,143,182	157,343	779,361	68,507	363,822	88,836
780	1,230,255	131,131	790,626	67,854	439,629	63,276
781	1,433,124	145,318	754,952	64,129	678,172	81,189
782	1,140,293	132,738	804,123	67,474	336,170	65,264
783	1,328,962	156,061	739,073	64,505	589,889	91,556
784	1,251,678	142,875	760,194	64,288	491,484	78,587
785	1,114,953	132,679	757,787	62,881	357,166	69,798
786	1,139,829	142,430	766,174	64,258	373,655	78,172
787	1,223,095	147,142	765,366	65,201	457,730	81,941
788	1,199,894	155,804	768,225	61,407	431,669	94,397
789	1,124,000	133,355	749,978	60,209	374,022	73,146
790	1,145,964	154,320	800,858	67,302	345,106	87,018
791	1,204,364	143,122	781,840	62,557	422,524	80,565
792	1,162,637	149,173	781,570	63,069	381,067	86,104
793	1,066,070	135,305	949,861	66,146	116,209	69,159
794	1,061,486	137,039	797,313	64,316	264,173	72,723
795	1,250,056	129,417	797,232	63,609	452,823	65,808
796	1,254,923	164,146	756,532	65,143	498,391	99,003

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
797	1,028,760	127,306	768,871	58,945	259,889	68,361
798	1,217,833	166,067	771,816	69,713	446,017	96,354
799	1,392,875	137,717	792,915	59,948	599,960	77,769
800	1,165,645	161,779	1,016,299	63,733	149,346	98,046
801	1,302,944	149,511	910,816	64,596	392,128	84,915
802	977,934	137,911	895,637	60,765	82,297	77,146
803	1,228,623	145,108	720,091	62,902	508,532	82,206
804	1,054,570	163,029	744,698	64,491	309,872	98,538
805	1,185,622	142,140	968,029	61,699	217,593	80,441
806	1,291,695	139,152	782,487	62,163	509,209	76,989
807	1,277,024	157,017	897,500	71,602	379,525	85,416
808	1,052,822	151,395	779,900	64,583	272,922	86,813
809	1,417,306	159,503	972,303	64,612	445,003	94,891
810	1,080,626	148,775	804,249	64,345	276,378	84,429
811	1,000,046	160,326	820,033	69,455	180,013	90,871
812	1,280,774	153,896	713,976	65,485	566,798	88,411
813	1,067,563	144,530	815,824	62,237	251,739	82,293
814	1,243,138	148,236	707,055	58,138	536,083	90,098
815	1,237,663	198,395	804,130	63,396	433,533	134,999
816	1,037,916	154,660	820,070	61,989	217,846	92,670
817	1,111,621	160,640	815,391	59,422	296,230	101,218
818	1,037,364	154,050	853,802	72,657	183,562	81,392
819	972,243	139,356	730,352	66,620	241,891	72,737
820	1,035,652	176,460	840,529	64,082	195,124	112,377
821	1,308,819	137,749	784,254	59,983	524,565	77,766
822	1,007,227	173,805	814,411	63,176	192,816	110,629
823	1,223,922	148,471	835,809	61,398	388,113	87,073
824	973,508	135,642	763,661	60,850	209,847	74,792
825	987,108	146,143	896,153	68,176	90,955	77,967
826	978,782	131,952	713,340	65,904	265,442	66,048
827	1,179,464	141,788	830,860	57,604	348,604	84,184
828	1,048,048	146,861	743,990	68,532	304,058	78,329
829	1,122,781	150,627	769,720	66,915	353,061	83,713
830	1,164,283	158,389	857,837	62,463	306,447	95,926
831	1,175,020	147,883	863,494	63,608	311,526	84,275
832	1,312,345	157,975	885,403	65,505	426,942	92,470
833	1,170,921	148,870	736,691	60,260	434,229	88,611
834	987,509	144,426	818,689	60,835	168,821	83,591

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
835	1,417,946	137,574	779,706	57,166	638,239	80,408
836	1,427,379	150,745	741,715	65,019	685,663	85,726
837	1,379,460	154,744	959,664	63,760	419,796	90,985
838	1,299,440	155,398	998,879	67,598	300,561	87,800
839	1,322,496	156,551	731,192	63,195	591,304	93,356
840	1,064,156	150,872	854,725	64,629	209,432	86,242
841	1,252,835	149,068	803,297	66,322	449,538	82,747
842	983,338	133,239	869,401	68,448	113,937	64,791
843	1,055,572	144,909	787,348	67,002	268,225	77,908
844	1,081,315	131,931	774,651	63,988	306,663	67,943
845	1,045,161	150,772	919,656	59,511	125,505	91,261
846	1,127,781	153,669	794,179	61,982	333,602	91,687
847	1,300,008	146,109	817,126	67,311	482,883	78,798
848	1,127,912	149,248	821,194	64,205	306,718	85,043
849	1,285,580	151,322	801,243	64,565	484,337	86,757
850	1,054,868	134,523	747,194	59,874	307,673	74,650
851	1,089,011	129,205	803,448	64,728	285,563	64,477
852	1,191,719	140,480	793,920	66,456	397,800	74,024
853	1,317,937	153,000	931,348	63,628	386,589	89,372
854	1,300,690	131,228	816,422	62,004	484,268	69,224
855	1,228,645	153,231	709,237	63,878	519,408	89,353
856	1,300,809	138,414	881,838	64,031	418,971	74,383
857	989,155	125,552	917,425	66,882	71,731	58,669
858	1,227,574	148,408	802,600	62,069	424,974	86,339
859	1,103,243	157,101	824,538	62,888	278,704	94,214
860	1,253,696	144,353	801,459	66,770	452,237	77,583
861	1,267,032	134,934	830,877	63,218	436,154	71,716
862	1,084,066	141,714	811,355	67,492	272,711	74,222
863	1,026,058	141,043	727,375	71,164	298,684	69,878
864	1,108,873	147,432	820,775	64,222	288,098	83,211
865	1,286,769	167,047	880,088	62,831	406,681	104,217
866	989,064	143,155	846,960	69,023	142,104	74,132
867	974,244	161,656	758,272	59,628	215,971	102,028
868	1,263,029	147,832	790,065	58,860	472,965	88,972
869	1,126,360	154,146	831,356	61,155	295,004	92,990
870	1,129,144	140,416	765,455	70,711	363,689	69,705
871	1,236,277	134,342	882,667	72,360	353,611	61,982
872	996,513	141,171	810,122	65,708	186,391	75,463

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
873	1,287,929	150,913	883,346	66,565	404,583	84,348
874	1,136,598	144,908	804,812	64,421	331,786	80,487
875	1,145,410	147,093	670,846	66,082	474,564	81,011
876	1,183,815	124,119	739,534	73,863	444,282	50,256
877	1,046,670	147,324	705,200	64,360	341,470	82,964
878	1,235,149	154,591	876,154	62,616	358,995	91,975
879	1,077,808	160,327	745,355	63,436	332,453	96,891
880	1,119,499	142,904	695,668	63,661	423,831	79,242
881	1,288,465	149,316	861,157	60,593	427,308	88,723
882	1,042,330	123,102	766,583	67,461	275,747	55,641
883	1,277,600	140,889	723,655	64,716	553,945	76,172
884	1,174,680	143,400	927,125	58,499	247,555	84,901
885	1,032,842	164,404	800,156	59,912	232,686	104,492
886	1,274,082	148,029	844,393	61,799	429,689	86,230
887	1,211,849	135,994	846,834	75,180	365,015	60,813
888	1,134,267	138,618	764,614	64,699	369,653	73,919
889	1,087,764	171,120	869,765	62,505	217,999	108,615
890	1,414,371	149,147	805,178	63,117	609,193	86,030
891	1,205,841	134,043	797,406	69,083	408,434	64,960
892	925,931	144,665	881,208	63,083	44,723	81,582
893	1,140,132	152,493	743,236	65,962	396,896	86,531
894	1,206,512	146,070	914,815	60,092	291,696	85,978
895	1,120,282	147,172	769,658	61,790	350,624	85,382
896	1,100,392	137,794	1,062,343	60,124	38,049	77,671
897	1,262,562	130,002	805,033	62,623	457,529	67,379
898	1,279,729	131,221	783,750	67,813	495,979	63,408
899	1,273,064	154,414	822,485	62,939	450,579	91,475
900	1,097,614	142,462	724,602	60,834	373,012	81,629
901	1,168,267	134,379	755,603	65,709	412,663	68,669
902	1,333,859	150,753	1,015,219	60,772	318,640	89,981
903	988,376	155,663	766,226	59,747	222,150	95,916
904	1,168,885	153,273	741,499	67,436	427,387	85,837
905	1,118,032	137,246	797,174	64,795	320,858	72,451
906	996,957	158,328	913,037	61,166	83,919	97,162
907	1,001,711	139,393	797,508	64,162	204,203	75,231
908	1,091,713	148,972	767,444	60,916	324,269	88,056
909	1,118,838	153,268	888,449	61,704	230,390	91,564
910	1,075,493	149,287	704,974	61,445	370,520	87,842

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
911	1,125,395	152,727	814,630	61,987	310,765	90,739
912	1,302,135	150,618	774,479	64,179	527,656	86,438
913	1,119,956	121,403	829,524	60,365	290,432	61,038
914	1,224,841	123,966	703,474	67,290	521,368	56,676
915	1,138,511	153,601	834,607	60,432	303,904	93,170
916	1,256,631	133,022	828,750	59,601	427,881	73,421
917	1,075,367	153,509	891,312	65,280	184,055	88,229
918	1,034,205	169,294	788,849	59,697	245,356	109,597
919	1,175,220	153,412	777,789	58,517	397,431	94,895
920	1,005,304	128,969	764,671	60,559	240,633	68,410
921	976,123	128,224	790,429	61,327	185,694	66,897
922	1,232,057	130,614	864,734	56,491	367,323	74,123
923	1,053,635	140,768	773,978	60,735	279,656	80,033
924	1,080,606	145,159	890,974	70,404	189,631	74,756
925	1,244,385	147,801	782,277	67,673	462,109	80,128
926	1,256,523	149,417	802,930	61,474	453,593	87,943
927	1,109,950	148,895	921,064	60,917	188,885	87,978
928	1,027,381	145,476	779,652	62,266	247,729	83,210
929	1,123,168	139,714	800,618	60,572	322,550	79,142
930	1,208,987	150,267	753,019	59,050	455,968	91,217
931	1,332,938	144,638	790,046	63,621	542,892	81,017
932	1,340,436	162,165	786,915	63,913	553,521	98,252
933	1,416,451	126,692	845,332	59,808	571,119	66,884
934	1,197,825	142,090	854,749	60,995	343,076	81,095
935	1,100,512	148,165	751,968	62,341	348,544	85,825
936	1,343,779	184,555	799,932	60,646	543,847	123,909
937	1,100,492	142,356	893,802	64,286	206,690	78,070
938	1,200,827	135,213	840,645	63,437	360,182	71,776
939	1,342,686	136,113	714,895	63,407	627,790	72,706
940	1,072,690	139,506	840,810	58,667	231,880	80,838
941	1,220,550	147,531	797,561	59,970	422,989	87,561
942	1,094,067	125,993	797,178	62,204	296,889	63,789
943	1,234,878	161,335	764,797	65,638	470,081	95,697
944	1,056,390	129,685	878,675	61,542	177,715	68,142
945	1,101,554	142,271	808,652	69,307	292,901	72,964
946	1,181,392	163,143	747,416	63,888	433,975	99,256
947	1,090,647	156,212	798,227	59,698	292,421	96,514
948	1,241,396	133,597	744,391	66,462	497,005	67,135

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
949	1,022,761	146,833	783,734	63,926	239,027	82,907
950	1,176,673	143,034	736,536	61,658	440,137	81,376
951	1,092,857	168,705	878,435	64,625	214,422	104,080
952	1,119,576	148,956	795,859	64,125	323,717	84,832
953	1,048,566	156,005	901,047	63,189	147,520	92,816
954	1,247,969	144,528	807,294	69,312	440,675	75,216
955	1,024,183	141,111	823,276	64,197	200,907	76,913
956	1,289,671	176,810	795,752	63,250	493,919	113,560
957	1,211,247	169,625	814,837	65,430	396,410	104,195
958	1,004,217	145,878	859,459	61,103	144,758	84,775
959	1,143,039	186,367	873,966	62,914	269,073	123,453
960	1,093,418	146,814	919,282	64,205	174,136	82,608
961	1,154,307	149,111	860,216	69,974	294,091	79,138
962	1,144,274	153,041	801,080	64,903	343,193	88,138
963	1,360,522	150,475	850,968	63,661	509,553	86,814
964	1,393,590	149,276	870,616	68,487	522,974	80,788
965	1,424,212	165,130	791,565	65,091	632,646	100,039
966	1,132,803	142,085	740,539	64,628	392,264	77,458
967	1,542,246	132,676	994,756	59,754	547,490	72,922
968	1,152,259	143,767	813,473	62,417	338,786	81,350
969	1,325,427	135,431	938,138	67,899	387,288	67,532
970	1,064,440	130,938	953,677	68,357	110,763	62,580
971	1,225,529	143,535	899,159	62,935	326,371	80,600
972	1,019,616	145,232	714,964	65,036	304,652	80,196
973	1,123,425	135,906	761,540	68,669	361,885	67,236
974	1,127,883	126,441	753,663	61,374	374,220	65,067
975	1,110,054	138,431	990,562	60,435	119,492	77,996
976	1,020,006	134,855	785,799	61,292	234,207	73,563
977	1,109,924	153,123	747,198	64,656	362,725	88,466
978	1,085,624	143,401	877,024	65,853	208,600	77,548
979	1,199,918	125,815	798,957	63,810	400,961	62,004
980	1,205,132	143,337	832,446	60,154	372,686	83,183
981	1,419,531	157,281	778,529	61,368	641,002	95,913
982	1,200,594	121,513	761,722	61,909	438,872	59,604
983	1,388,011	145,253	832,155	62,547	555,856	82,706
984	1,244,364	157,416	750,926	68,852	493,438	88,564
985	1,032,999	140,505	780,366	69,008	252,634	71,496
986	1,186,675	127,451	807,537	61,643	379,138	65,807

Calculation No.	LPV 111 DSM		LPV 111 PVDs		Difference (DSM-PVD)	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
987	1,098,215	139,651	829,056	61,494	269,159	78,157
988	1,081,287	165,042	765,807	59,201	315,480	105,841
989	1,165,219	137,859	868,019	68,623	297,199	69,235
990	1,230,322	147,731	845,866	71,057	384,456	76,674
991	1,066,310	146,123	782,277	67,277	284,033	78,846
992	1,206,622	149,418	705,080	73,413	501,542	76,006
993	1,034,443	162,692	751,828	63,284	282,614	99,408
994	1,078,661	154,150	856,706	68,909	221,954	85,241
995	1,273,691	153,490	879,854	64,979	393,837	88,512
996	1,012,193	151,473	799,550	65,198	212,643	86,275
997	928,326	151,715	801,239	62,159	127,088	89,555
998	1,156,779	138,364	815,405	60,593	341,374	77,771
999	1,101,467	136,502	824,323	66,975	277,143	69,527
1000	832,355	157,681	759,643	62,618	72,712	95,063

P.2.2 Results

Descriptive statistics of the difference data sets for LPV 111 design alternatives (DSM – PVD) are shown in Table P.3. Histograms of the difference data sets for total embodied energy and CO_2 emissions are shown in Figure P.3 and Figure P.4, respectively.

Table P.3 Descriptive statistics of the difference in total embodied energy and CO_2 emissions between Monte Carlo simulations for the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for LPV 111.

Descriptive Statistic	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
Mean	363,747	83,167
Std. Dev.	137,838	12,209
Minimum	-99,596	49,054
Maximum	954,405	134,999
% < 0	0.4%	0.0%

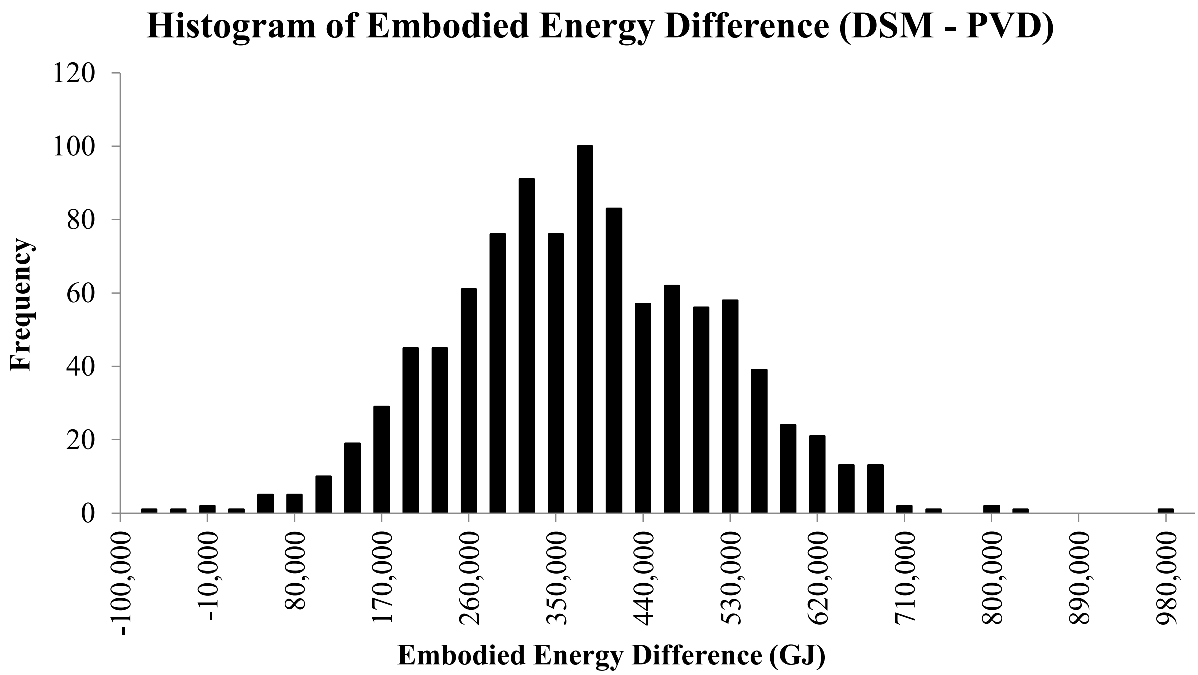


Figure P.3 Histogram of the embodied energy difference data set. The data set was generated by subtracting corresponding values in the Monte Carlo simulated data sets from the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for LPV 111.

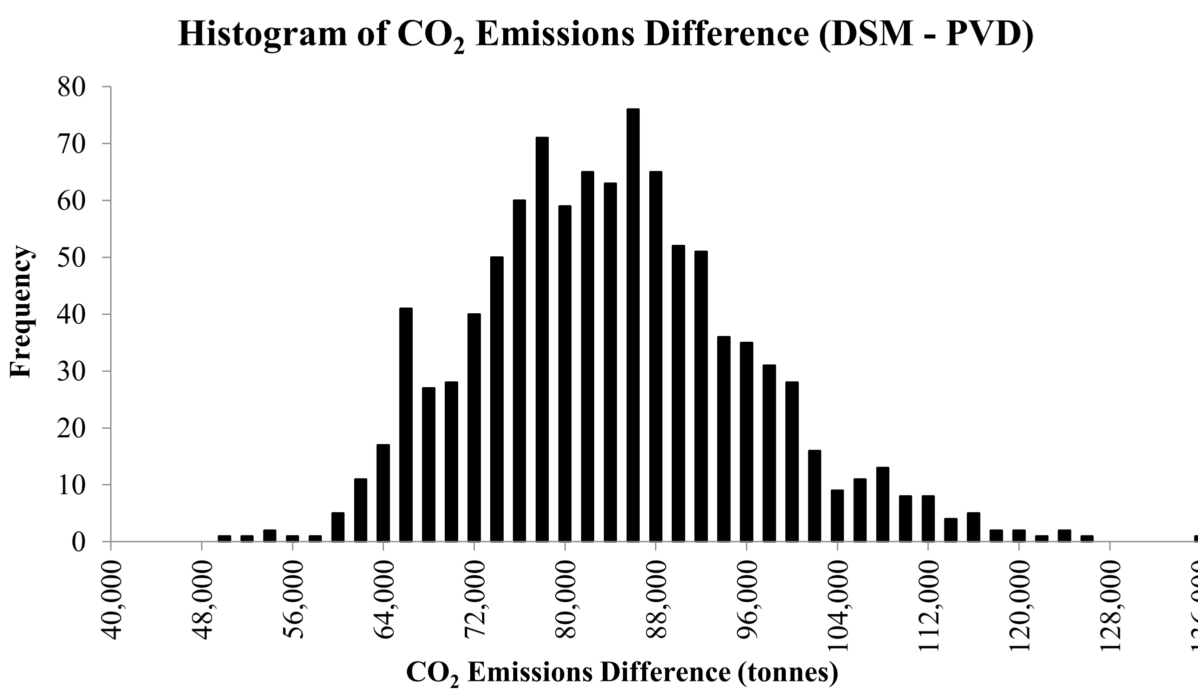


Figure P.4 Histogram of the CO_2 emissions difference data set. The data set was generated by subtracting corresponding values in the Monte Carlo simulated data sets from the Deep Soil Mixing and Prefabricated Vertical Drains design alternatives for LPV 111.

In this case, the embodied energy histogram (Figure P.3) mostly lies on the positive side of zero; however, the left tail of the distribution of values shown in the histogram does extend below zero. Since only the extreme tail of the difference histogram falls below zero, it is reasonable to conclude the DSM alternative for LPV 111 is responsible for more embodied energy than the PVD alternative (the difference taken was DSM – PVDs, therefore a positive difference indicates DSM > PVDs). This is confirmed by the fact that only 0.4% of the embodied energy difference data (4 out of 1,000 values) are less than zero (see Table P.3). The CO_2 histogram (Figure P.4) lies completely on the positive side of zero, which indicates the DSM design alternative for LPV 111 is responsible for more CO_2 emissions than the PVD design alternative (again, the difference taken was DSM – PVDs, therefore a positive difference in CO_2 emissions indicates DSM > PVDs).

P.3 SUMMARY AND CONCLUSION

Two different methods of comparing the results of Monte Carlo simulations that follow the SEEAM method for estimating the total embodied energy and CO_2 emissions associated with different project alternatives with uncertainty were described and demonstrated in this Appendix. The first method involved conducting nonparametric statistical hypothesis tests using the Monte Carlo simulated data to compare alternatives. The second involved taking the difference between corresponding values in the Monte Carlo simulated data sets from each alternative, in order to generate data sets of the difference. In this method, whether or not the alternatives are significantly different is indicated by where a histogram of the difference data plots relative to zero.

Both methods were demonstrated by comparing the total embodied energy and CO_2 emissions from the DSM and PVD design alternatives for LPV 111. Both methods lead to the same conclusions; the DSM design alternative results in significantly more embodied energy and CO_2 emissions than the PVD design alternative.

Using statistical comparison methods is important for drawing conclusions regarding differences in total embodied energy and CO_2 emissions because design alternatives that have different mean values (or deterministic results) may not actually be different from each other in the presence of uncertainty. This is especially important for the design decision process if the project alternatives have significantly different costs and/or performance characteristics.

P.4 REFERENCES

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Appendix Q: Supporting Analysis for the Influence of Material Haul Distance on Estimated Embodied Energy and CO_2 Emissions from the SEEAM

This Appendix contains supporting analysis and data for the discussion on the influence of material haul distance on total embodied energy and CO_2 emissions for ground improvement projects presented in Ch. 7.

Q.1 PEARSON HALL HAUL DISTANCE ANALYSIS

For the analysis of the influence of material haul distance on the total embodied energy and CO_2 emissions associated with rammed aggregate columns construction at Pearson Hall, the method described in Ch. 7 was followed to determine total embodied energy and CO_2 emissions with increasing haul distance. Construction details and quantities for the project are described in Chs. 6 – 7 and Appendix L. The output from each of the four SEEAM analyses using different material haul distances are not completely presented in Ch. 7 or in this Appendix, however, key elements of the SEEAM analysis results are included. The complete SEEAM results may be easily reproduced with the SEEAM Spreadsheet Calculator (Appendices A and B), using the quantities from Appendix L and varying the haul distances for aggregate materials as shown in Table 7.1.

Table Q.1 presents the results of total embodied energy and CO_2 emissions for rammed aggregate columns at Pearson Hall from the SEEAM analyses with haul distances defined by different distance multiples, *M*. *M* is the ratio of the selected haul distance to the actual distance used in construction (the base distance), see Ch. 7. The resulting total embodied energy and CO_2 emissions presented in this Appendix are actually the analytically computed mean values generated by the SEEAM Spreadsheet Calculator. The standard deviations are not reported here. The tabulated information in Table Q.1 corresponds to Figure 7.1. Actual distances used in the SEEAM analysis are shown in Table 7.1.

Table Q.1 Results from SEEAM analysis of Rammed Aggregate Columns at Pearson Hall with different material haul distances.

Distance Multiple, *M*	Embodied Energy (GJ)	% Increase over Minimum Distance Embodied Energy	CO_2 Emissions (tonnes)	% Increase over Minimum Distance CO_2 Emissions
1.0	1,930	0%	232	0%
3.1	2,130	10%	247	6%
5.3	2,320	20%	262	13%
9.6	2,740	42%	294	26%

Tables Q.2 and Q.3 show the proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation with increasing distance multiple, *M* for Pearson Hall. The tabulated information corresponds to Figure 7.2. Actual distances from the SEEAM analysis are shown in Table 7.1.

Table Q.2 Proportion of total embodied energy for Rammed Aggregate Columns at Pearson Hall due to materials, materials transportation, site operations and waste transportation by distance multiple, *M*.

Distance Multiple, *M*	Materials	Material Transport	Site Operations	Waste Transport
1.0	64%	5%	25%	6%
3.1	58%	14%	23%	5%
5.3	53%	21%	21%	5%
9.6	45%	33%	18%	4%

Table Q.3 Proportion of total CO_2 emissions for Rammed Aggregate Columns at Pearson Hall due to materials, materials transportation, site operations and waste transportation by distance multiple, *M*.

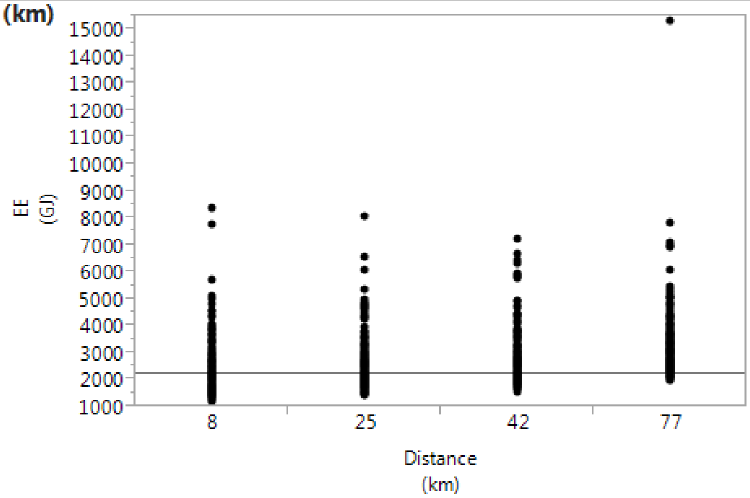
Distance Multiple, *M*	Materials	Material Transport	Site Operations	Waste Transport
1.0	78%	3%	16%	4%
3.1	73%	9%	15%	3%
5.3	69%	14%	14%	3%
9.6	61%	23%	12%	3%

In addition to the analysis presented in Ch. 7 and in the preceding tables, the SEEAM Spreadsheet Calculator was used to conduct a Monte Carlo simulation for total embodied energy and CO_2 emissions for each multiple of the as-built material haul distances. Nonparametric statistical hypothesis tests were then conducted on the simulated data sets to determine whether or not all distance multiples (M) resulted in significantly different total embodied energy and CO_2 emissions for the rammed aggregate columns at Pearson Hall. Nonparametric tests were selected because the actual distribution of the results is unknown. To begin, the nonparametric Kruskal-Wallis test (Kruskal and Wallis 1952) was used to check for differences with a significance level, $\alpha = 0.05$.

The Kruskal-Wallis test yielded $p < 0.0001$, indicating differences exist. Therefore, the nonparametric Steel-Dwass method of multiple comparisons was used to check for differences between the embodied energy and CO_2 emissions assessment results for each different set of haul distances (i.e., each different distance multiple, M). The Steel-Dwass method was originally proposed independently by Steel (1960) and Dwass (1960), and was further elaborated on by Critchlow and Fligner (1991). The Steel-Dwass comparisons revealed that all distances result in significantly different total embodied energy and CO_2 emissions for the rammed aggregate columns at Pearson Hall, with 8 km (the base distance, $M = 1$) resulting in the least total embodied energy and CO_2 emissions and 77 km ($M = 9.6$) resulting in the most embodied energy and CO_2 emissions. All statistical testing was performed using JMP Pro (SAS Institute 2013). The JMP output is shown in Figures Q.1 and Q.2. The levels correspond to the material haul distance, in km (as shown in Table 7.1).

Fit Group

Oneway Analysis of EE (GJ) By Distance (km)



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
8	1000	1150695	2000500	1150.70	-26.870
25	1000	1647961	2000500	1647.96	-11.147
42	1000	2150170	2000500	2150.17	4.732
77	1000	3053175	2000500	3053.17	33.284

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1482.3633	3	<.0001*

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*	Alpha
2.56903	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
77	8	806.7890	25.82633	31.23901	<.0001*	806.0000	769.0000	844.0000
77	25	720.8340	25.82633	27.91082	<.0001*	604.0000	566.0000	643.0000
77	42	577.7230	25.82632	22.36954	<.0001*	412.0000	375.0000	450.0000
42	8	564.4630	25.82632	21.85611	<.0001*	393.0000	355.0000	432.0000
25	8	328.3550	25.82632	12.71397	<.0001*	201.0000	163.0000	240.0000
42	25	312.5980	25.82632	12.10385	<.0001*	192.0000	154.0000	231.0000

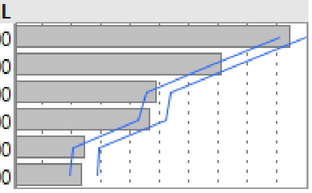
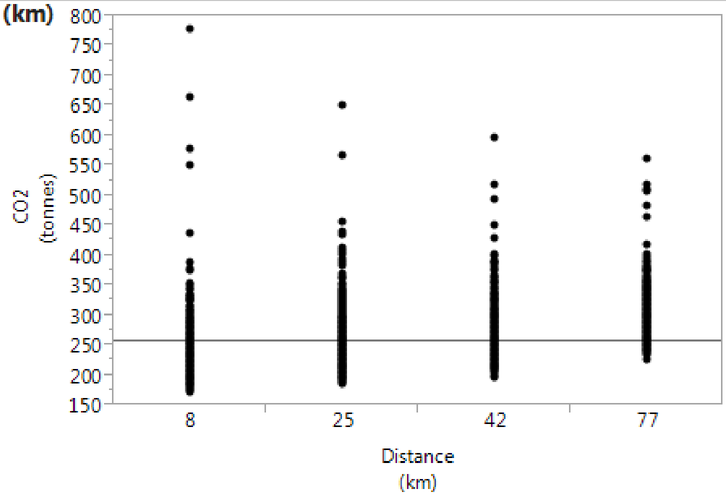


Figure Q.1 Statistical comparison of *n* = 1,000 Monte Carlo simulated data sets of total embodied energy for Rammed Aggregate Columns at Pearson Hall with different material haul distances.

Oneway Analysis of CO2 (tonnes) By Distance (km)



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
8	1000	1116606	2000500	1116.61	-27.949
25	1000	1609828	2000500	1609.83	-12.353
42	1000	2183029	2000500	2183.03	5.772
77	1000	3092538	2000500	3092.54	34.530

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1619.5385	3	<.0001*

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*	Alpha
2.56903	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
77	8	853.1410	25.82553	33.03480	<.0001*	61.00000	58.00000	64.00000
77	25	765.0180	25.82529	29.62283	<.0001*	46.00000	43.00000	49.00000
42	8	590.9850	25.82487	22.88433	<.0001*	31.00000	28.00000	34.00000
77	42	565.9130	25.82490	21.91346	<.0001*	30.00000	27.00000	33.00000
42	25	339.9850	25.82438	13.16528	<.0001*	16.00000	13.00000	19.00000
25	8	323.6590	25.82442	12.53306	<.0001*	15.00000	12.00000	18.00000

Figure Q.2 Statistical comparison of *n* = 1,000 Monte Carlo simulated data sets of total CO_2 emissions for Rammed Aggregate Columns at Pearson Hall with different material haul distances.

The raw data from the Monte Carlo simulations for different material haul distances at Pearson Hall is included in Table Q.4. The table extends for 28 pages to present all 1,000 simulated data values.

Table Q.4 Monte Carlo simulated data for different material haul distances for Rammed Aggregate Columns construction at Pearson Hall.

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	1,866	221	2,704	221	3,863	253	3,465	320
2	1,737	231	2,124	251	1,966	244	2,446	298
3	1,581	189	1,910	263	3,081	246	2,483	299
4	1,782	308	2,007	296	1,810	290	2,967	278
5	1,910	221	2,228	227	1,741	225	2,492	285
6	1,626	239	1,998	246	2,369	240	2,462	295
7	1,801	237	1,784	221	2,024	327	2,651	299
8	2,070	221	1,832	254	2,859	311	2,491	290
9	1,867	209	1,906	221	3,073	236	2,612	297
10	2,775	238	2,235	219	5,923	239	3,772	285
11	2,932	211	1,909	248	2,141	346	2,405	273
12	1,678	186	2,290	238	2,305	256	3,781	296
13	2,056	215	2,157	247	2,109	247	2,389	232
14	1,817	215	2,020	223	1,836	248	2,348	283
15	1,804	217	1,987	253	2,208	257	4,323	292
16	2,599	377	1,656	231	1,534	275	2,309	241
17	2,043	222	3,510	215	1,923	267	2,396	350
18	3,089	296	2,323	222	2,645	256	2,461	298
19	1,499	214	2,264	246	2,837	229	3,722	272
20	1,898	239	2,501	196	1,927	310	7,791	296
21	3,500	282	1,992	252	2,401	217	2,436	339
22	1,861	378	4,830	240	1,773	283	2,368	287
23	2,001	293	2,024	205	3,365	270	3,198	309
24	2,234	195	2,566	264	2,317	224	2,955	281
25	1,661	189	1,664	200	3,617	220	2,553	359
26	1,475	267	2,516	215	1,960	265	2,952	263
27	2,301	219	1,828	260	2,111	308	2,801	341
28	1,937	241	1,789	204	3,080	272	3,009	339
29	1,647	195	2,306	242	2,497	236	2,717	281
30	1,691	211	1,744	230	2,665	266	2,478	284
31	2,645	235	2,192	217	2,318	291	2,352	288
32	1,942	237	1,898	223	7,216	273	3,359	270
33	1,679	217	1,746	220	2,023	255	2,406	276
34	1,903	218	1,681	260	2,572	268	2,524	299
35	1,329	237	2,077	224	2,070	288	2,732	256

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
36	2,114	268	2,794	236	2,356	291	2,496	257
37	2,176	194	1,615	226	3,047	240	2,566	281
38	1,541	242	1,881	198	1,865	366	2,238	281
39	1,477	282	2,061	214	2,274	251	2,932	251
40	1,454	219	2,168	238	2,260	258	2,550	299
41	1,391	201	1,927	234	1,813	242	2,997	279
42	4,077	203	1,796	289	1,917	277	2,646	259
43	1,277	201	1,774	209	2,725	284	2,568	261
44	1,737	207	1,863	277	2,085	289	2,546	286
45	1,691	206	1,619	288	2,990	283	2,312	333
46	1,669	235	1,989	208	1,756	251	2,473	265
47	2,113	212	2,052	266	1,946	259	1,964	237
48	1,867	223	2,365	257	2,239	251	2,894	303
49	2,307	249	1,810	287	2,277	312	2,390	310
50	1,428	197	2,052	269	3,700	266	2,646	263
51	2,455	223	2,138	212	2,087	245	2,293	301
52	1,814	219	4,729	188	2,981	308	2,576	355
53	1,771	243	2,564	209	2,481	220	2,404	248
54	1,942	208	1,808	224	2,034	249	2,812	249
55	1,464	202	2,013	213	2,687	273	2,464	291
56	1,399	242	2,420	210	2,805	297	2,779	291
57	1,748	248	2,044	237	2,082	255	2,268	292
58	1,556	218	1,878	284	2,082	284	2,253	324
59	2,143	240	1,768	224	2,698	284	2,359	296
60	1,684	438	2,373	234	1,830	284	2,372	296
61	1,446	199	2,923	283	2,609	287	3,867	270
62	3,323	252	1,685	237	2,312	297	3,178	275
63	2,638	216	1,744	238	2,015	278	2,648	300
64	1,665	246	2,196	216	1,943	228	2,698	259
65	1,984	187	2,753	264	2,888	265	2,416	275
66	1,973	185	1,981	337	2,127	219	2,783	286
67	1,490	274	2,056	226	2,548	252	2,917	268
68	2,259	204	2,700	224	2,296	250	2,535	303
69	2,721	196	1,618	210	2,097	258	2,373	295
70	1,821	206	2,083	209	2,041	235	2,841	275
71	1,481	388	1,737	281	1,895	251	3,150	273
72	1,783	289	2,660	218	2,481	249	2,973	302

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
73	2,010	223	1,960	331	2,891	256	2,674	248
74	1,764	210	3,270	233	1,815	242	3,165	368
75	1,653	174	1,507	238	1,973	222	2,890	258
76	2,094	222	2,068	264	2,260	243	3,087	327
77	2,450	223	1,997	214	1,775	266	2,607	280
78	1,751	237	2,100	266	2,204	287	2,865	302
79	2,184	243	2,080	235	2,049	235	2,744	273
80	4,823	220	1,756	227	2,239	248	2,159	280
81	1,444	200	4,889	214	2,286	272	2,575	303
82	2,236	219	1,844	209	2,130	264	2,845	336
83	1,749	665	1,735	282	1,942	268	2,337	283
84	1,676	227	1,755	218	2,144	246	2,687	257
85	1,685	232	2,046	224	2,987	313	2,115	290
86	1,741	220	1,679	256	1,865	232	3,117	388
87	1,413	229	4,344	220	2,287	246	3,285	390
88	2,929	246	1,733	255	2,301	387	3,898	278
89	1,819	202	3,139	246	2,472	229	2,315	289
90	1,936	279	2,443	237	1,621	243	2,560	259
91	2,618	209	1,759	267	2,592	322	7,811	272
92	1,658	260	2,281	261	2,349	245	2,418	297
93	4,994	242	2,875	247	3,917	229	3,019	266
94	1,635	232	1,691	247	2,832	242	2,891	304
95	1,729	253	1,768	230	2,925	252	2,409	279
96	1,825	267	2,203	226	2,075	257	2,555	278
97	2,959	206	1,910	201	2,207	269	2,575	321
98	1,454	186	1,904	213	2,412	261	2,683	261
99	3,630	246	2,013	259	2,151	229	2,602	281
100	1,633	197	1,887	237	2,374	238	2,548	314
101	1,536	204	2,073	211	2,771	289	3,180	294
102	1,497	272	3,557	238	2,170	300	2,384	297
103	2,097	247	1,838	245	1,899	248	2,557	333
104	1,650	245	1,527	241	2,158	274	2,500	326
105	1,670	196	2,569	240	1,815	250	2,738	279
106	1,614	190	1,558	283	1,741	265	2,916	316
107	1,967	223	1,678	208	2,521	254	2,255	279
108	4,383	243	2,548	228	2,308	302	2,549	295
109	2,592	202	2,258	237	1,764	234	2,311	280

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
110	1,794	258	2,103	242	2,349	246	2,385	287
111	1,826	199	2,569	226	3,773	262	2,130	305
112	1,597	195	2,636	229	3,598	276	2,754	262
113	1,517	306	4,603	245	2,224	227	3,002	294
114	1,850	231	1,870	267	1,880	227	2,683	300
115	1,737	302	1,999	240	2,169	212	2,628	302
116	1,894	260	1,873	234	2,253	268	2,597	268
117	1,663	250	2,067	394	1,839	255	2,630	284
118	2,029	251	2,315	243	2,585	264	2,571	264
119	1,471	228	1,571	241	2,306	318	2,522	268
120	1,570	197	2,261	286	2,108	239	2,701	273
121	1,479	250	2,242	187	2,036	233	2,262	284
122	1,485	227	1,612	241	1,984	332	2,632	303
123	1,887	251	2,069	239	2,299	279	2,510	286
124	2,028	233	2,073	267	2,767	291	3,608	265
125	2,568	246	1,729	215	1,819	244	3,593	261
126	1,564	208	2,676	268	1,906	301	2,493	253
127	1,725	210	2,410	206	2,806	259	2,513	253
128	2,892	236	1,879	241	1,747	345	2,581	303
129	2,053	226	2,581	219	1,815	234	2,505	252
130	1,893	190	2,101	260	2,655	216	3,161	279
131	1,656	230	2,010	213	3,264	290	4,399	282
132	2,072	177	2,005	240	2,518	357	2,382	274
133	1,628	198	1,981	268	1,823	300	2,464	291
134	1,496	266	3,000	242	2,271	261	2,214	271
135	1,630	194	1,621	250	2,856	221	2,733	285
136	1,600	233	1,840	255	2,590	280	2,462	272
137	4,003	192	1,884	247	2,098	238	2,267	260
138	1,773	239	2,180	233	1,929	249	2,793	273
139	1,546	201	1,867	297	2,658	325	2,617	274
140	1,917	202	2,139	277	1,984	235	2,501	265
141	2,677	205	2,263	223	2,381	239	2,556	256
142	2,042	234	5,340	295	1,963	286	2,329	403
143	1,791	209	1,771	247	2,451	277	2,636	334
144	1,448	255	1,592	208	3,309	245	2,927	305
145	1,551	203	2,261	240	2,300	383	2,328	310
146	1,548	208	1,535	236	1,946	300	3,188	338

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
147	1,887	234	2,040	231	2,338	263	3,488	260
148	2,601	202	1,866	221	2,818	258	2,643	305
149	2,112	209	1,886	243	2,297	262	2,655	267
150	1,900	239	2,205	208	1,974	239	2,456	242
151	1,661	224	2,527	305	1,905	219	3,326	286
152	1,505	212	1,712	272	5,961	298	2,360	336
153	2,373	208	1,953	243	1,874	233	2,664	254
154	2,303	203	1,704	250	1,975	264	2,630	268
155	2,856	213	2,143	287	2,172	228	2,489	295
156	1,534	209	2,356	195	2,368	272	2,850	260
157	2,193	224	2,267	243	2,072	304	2,513	256
158	4,016	218	2,220	221	2,000	234	3,222	281
159	1,396	249	1,856	207	2,604	250	3,057	294
160	1,632	228	1,851	233	2,257	244	2,843	282
161	1,787	203	2,244	238	2,266	251	2,416	251
162	1,638	231	2,095	241	2,305	257	2,432	358
163	2,758	193	2,092	222	2,065	236	6,098	281
164	2,237	233	2,917	268	2,232	290	2,702	263
165	1,417	232	1,671	266	2,284	236	2,448	353
166	1,829	331	2,188	243	2,050	268	2,564	272
167	1,879	195	2,916	253	2,092	237	4,260	277
168	1,945	186	1,575	251	1,918	220	3,152	288
169	1,829	191	2,083	252	2,287	263	2,415	318
170	1,615	200	2,602	232	1,940	248	2,518	321
171	1,833	240	2,280	216	2,204	251	2,702	300
172	2,424	192	1,529	303	1,815	264	2,257	275
173	1,637	180	2,488	225	1,764	253	2,300	354
174	1,349	186	2,125	254	1,977	281	2,479	323
175	1,673	207	1,889	255	2,982	280	2,816	262
176	1,876	222	2,443	217	2,229	258	2,294	241
177	1,540	203	2,834	238	1,765	239	2,531	258
178	1,708	262	1,761	212	2,955	241	3,001	269
179	2,879	212	2,235	228	2,732	276	2,752	308
180	4,023	254	2,026	264	4,774	243	2,506	275
181	1,623	234	2,540	284	3,007	261	2,693	270
182	1,732	180	2,187	207	2,657	292	2,857	288
183	1,583	258	2,586	228	2,013	285	2,457	314

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
184	1,468	238	2,569	222	2,462	305	2,410	267
185	1,921	209	1,834	255	2,096	222	2,423	282
186	1,598	268	1,690	255	1,864	236	2,307	276
187	1,537	202	2,105	382	2,221	298	2,608	273
188	1,829	197	2,801	266	2,204	242	2,451	237
189	1,432	230	3,111	222	1,955	325	2,941	373
190	1,762	242	1,786	234	2,166	226	2,303	263
191	1,999	199	1,743	236	2,897	254	3,174	388
192	2,304	210	1,865	225	2,470	282	3,757	273
193	2,162	227	1,777	333	2,325	401	2,384	314
194	2,356	245	2,449	267	1,906	227	2,492	269
195	1,515	296	2,003	247	1,912	247	2,424	256
196	1,510	251	2,421	217	4,417	250	2,747	297
197	3,140	218	1,967	243	1,995	240	2,706	318
198	1,898	214	2,335	279	1,851	235	2,653	241
199	1,472	239	2,207	241	2,292	232	2,573	291
200	1,835	221	2,102	258	2,127	240	2,442	277
201	1,791	217	2,229	215	4,686	264	4,105	275
202	1,907	214	1,694	249	4,134	268	2,195	257
203	1,327	282	1,688	218	1,770	310	4,887	271
204	1,781	193	2,376	238	2,015	284	2,393	316
205	1,527	210	3,125	291	2,417	220	2,517	314
206	1,413	188	1,855	232	3,039	244	2,431	353
207	1,537	203	1,967	227	2,163	282	2,371	257
208	2,418	238	3,685	247	2,168	219	2,389	303
209	1,750	198	1,642	234	2,610	261	2,460	358
210	1,809	231	2,536	333	2,024	225	2,459	292
211	1,509	250	2,025	263	2,206	239	2,630	279
212	2,596	233	1,875	221	2,281	270	2,073	345
213	1,554	219	1,823	288	2,195	273	2,300	265
214	1,559	256	1,850	220	2,958	374	2,428	303
215	1,519	238	1,766	350	1,876	293	2,473	275
216	1,658	208	1,401	242	1,892	203	2,663	283
217	1,504	231	1,847	243	2,706	246	2,693	273
218	1,972	183	1,721	254	1,966	252	2,864	289
219	2,747	225	2,408	228	2,187	220	2,398	337
220	1,756	236	1,776	237	2,838	279	2,193	286

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
221	1,456	215	2,491	283	2,050	331	3,159	258
222	1,664	210	2,872	215	2,168	258	3,248	275
223	1,323	244	1,950	254	2,417	236	2,317	331
224	1,739	217	1,998	211	2,728	271	2,755	276
225	1,993	202	1,727	229	2,022	231	2,455	278
226	1,637	218	2,011	245	1,963	264	2,849	267
227	3,536	227	1,752	239	3,566	272	2,616	263
228	1,499	198	1,703	227	1,961	268	5,103	299
229	1,427	247	2,763	212	2,214	256	2,614	311
230	2,371	199	1,746	232	2,260	262	3,408	236
231	1,302	254	1,811	243	2,248	253	2,388	253
232	1,777	241	2,518	363	2,019	274	2,311	290
233	1,521	216	2,009	211	2,531	251	2,908	314
234	2,147	220	2,163	226	1,985	233	2,436	322
235	1,593	200	1,952	360	2,084	259	3,377	252
236	1,886	220	1,746	258	2,191	262	2,381	307
237	1,557	235	2,044	219	2,176	287	2,973	272
238	3,836	184	2,005	286	2,043	293	2,368	285
239	1,639	230	1,784	244	2,572	287	2,550	285
240	1,757	212	2,708	285	2,251	241	2,451	261
241	3,846	268	2,164	231	2,397	236	3,275	293
242	1,592	210	1,590	248	2,586	272	2,671	250
243	1,393	208	2,380	223	1,981	252	2,422	288
244	2,717	248	2,284	259	1,851	243	2,237	275
245	1,571	213	1,771	250	2,035	321	2,172	265
246	1,755	238	2,384	250	1,924	598	2,441	265
247	1,576	200	2,133	216	2,308	238	2,240	291
248	1,506	197	1,763	253	3,790	258	2,751	274
249	7,791	216	2,524	244	2,069	239	2,326	270
250	1,836	208	1,955	246	2,395	283	2,290	372
251	2,004	222	1,769	201	2,681	246	2,364	281
252	1,986	206	2,133	220	1,808	236	4,251	280
253	1,848	205	1,550	254	2,091	234	2,784	308
254	2,138	250	3,150	253	2,044	260	2,817	275
255	1,606	245	1,664	211	2,260	233	2,784	266
256	1,718	253	1,962	233	2,148	291	3,732	284
257	1,880	264	1,661	235	2,042	228	2,495	347

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
258	2,477	222	2,159	231	1,984	231	2,391	288
259	2,189	212	1,973	271	2,121	240	2,584	298
260	1,683	193	4,970	255	2,336	243	2,348	321
261	2,559	229	1,954	257	6,453	247	2,657	280
262	3,811	199	1,959	220	2,207	267	2,305	287
263	1,717	242	2,749	241	4,380	239	2,251	309
264	1,407	184	1,897	412	2,217	264	2,880	264
265	1,522	250	2,094	234	2,524	246	3,056	309
266	1,820	242	1,922	272	2,396	246	2,783	283
267	1,743	244	3,808	316	2,377	223	2,319	287
268	1,714	235	2,523	227	1,899	245	3,657	295
269	1,675	283	1,782	243	2,099	237	2,652	277
270	1,742	231	1,826	232	2,228	323	2,637	269
271	1,462	197	2,111	259	2,607	221	2,818	278
272	2,536	212	1,922	209	2,192	306	2,393	269
273	1,806	300	1,798	235	2,031	254	2,909	302
274	1,612	310	1,595	215	2,116	280	2,809	326
275	2,140	221	1,836	248	2,706	259	2,712	301
276	2,562	222	2,248	275	1,986	244	2,610	265
277	2,611	265	2,443	219	2,388	234	2,826	371
278	2,294	262	1,650	236	2,901	260	3,863	295
279	1,510	323	1,581	223	2,512	322	2,597	274
280	1,571	212	2,072	235	1,879	276	2,524	290
281	2,155	234	2,533	230	2,203	259	2,613	282
282	1,499	220	1,993	270	2,099	253	3,973	324
283	1,574	222	1,970	239	2,500	234	2,416	291
284	1,923	195	3,261	220	2,199	391	2,593	298
285	2,307	224	2,104	226	2,162	274	3,434	248
286	1,433	322	1,969	255	2,045	224	2,548	297
287	1,708	216	2,155	233	6,684	219	2,445	290
288	4,063	201	2,454	209	2,252	269	2,288	266
289	2,479	215	1,773	232	2,421	287	3,089	282
290	1,899	250	2,874	228	2,096	278	2,427	275
291	1,860	264	2,677	209	2,871	255	2,548	244
292	1,838	212	1,591	197	1,947	224	2,805	293
293	2,113	333	2,178	212	1,994	264	3,331	302
294	1,534	215	1,844	268	3,578	292	2,937	284

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
295	1,457	221	1,878	271	2,275	249	2,252	303
296	1,448	217	2,101	254	1,822	283	3,606	246
297	2,290	232	4,676	197	2,125	233	2,333	297
298	1,962	262	2,175	244	2,648	221	2,889	396
299	2,050	237	2,117	211	2,695	269	2,563	282
300	1,916	204	1,892	240	4,082	280	3,510	273
301	1,971	239	2,016	221	1,870	230	2,538	251
302	1,624	280	1,846	221	2,424	254	2,453	257
303	1,739	239	2,802	259	1,987	240	2,917	269
304	1,674	779	2,038	209	2,582	306	2,773	317
305	1,538	222	2,155	199	2,384	238	3,187	352
306	1,963	198	1,911	305	2,260	268	2,468	280
307	1,661	216	1,677	226	1,936	256	3,620	309
308	2,220	225	2,325	240	2,485	218	2,377	239
309	2,417	231	1,917	241	2,137	248	2,463	280
310	1,525	225	1,693	237	2,232	246	3,446	247
311	1,641	292	2,939	343	2,259	253	2,466	274
312	1,167	271	1,745	236	2,017	256	2,269	275
313	1,711	238	2,239	230	3,447	282	2,472	281
314	1,710	214	1,742	233	2,642	300	3,262	292
315	1,508	213	1,867	238	2,469	251	3,101	287
316	1,975	220	2,121	259	3,197	221	2,520	254
317	1,796	267	2,147	244	2,827	223	2,434	317
318	2,203	235	3,757	299	3,109	234	3,586	287
319	3,732	206	1,978	212	2,154	278	2,347	277
320	2,007	265	1,958	251	2,204	220	2,706	289
321	2,457	196	1,645	251	2,245	260	3,593	290
322	1,938	258	1,863	256	2,289	229	3,766	286
323	1,777	225	1,890	238	2,390	238	2,731	254
324	1,397	256	1,635	232	2,195	290	2,638	312
325	2,311	203	2,603	253	1,838	246	2,574	297
326	1,800	226	2,026	241	1,824	322	2,724	243
327	1,810	272	2,792	186	2,889	258	2,399	327
328	1,959	229	2,001	274	2,180	213	2,434	288
329	2,197	219	1,531	230	2,543	292	3,096	276
330	2,799	239	2,488	248	1,995	253	2,519	266
331	2,120	194	1,618	273	1,928	233	4,061	306

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
332	1,552	230	2,686	288	2,845	237	2,190	288
333	1,830	256	2,201	220	1,969	276	2,569	271
334	1,447	236	3,932	237	1,821	235	2,544	261
335	1,700	215	2,020	221	2,069	252	2,274	268
336	1,626	579	2,654	248	1,892	288	2,992	276
337	2,513	218	1,974	264	2,455	270	2,719	301
338	1,628	226	1,903	251	1,955	262	2,691	277
339	1,585	220	1,716	251	1,966	346	2,631	482
340	2,506	193	2,607	256	1,956	237	2,412	271
341	1,687	273	4,740	235	1,980	329	2,233	273
342	2,500	215	1,668	222	2,756	236	2,283	258
343	2,288	196	1,814	229	2,586	285	2,598	284
344	1,442	229	1,705	209	2,130	267	2,527	287
345	1,771	224	2,610	257	2,050	240	2,325	271
346	1,799	172	1,955	289	1,947	301	2,430	330
347	1,757	217	1,780	293	2,687	336	2,694	293
348	1,348	202	1,450	277	2,137	286	2,806	304
349	2,665	203	1,665	257	2,355	258	2,450	316
350	1,627	206	1,937	250	1,913	303	2,827	280
351	1,906	229	1,803	226	2,178	234	3,128	280
352	1,496	243	1,745	222	1,939	274	2,463	292
353	1,676	302	2,130	260	2,045	287	2,418	261
354	1,967	230	1,957	218	3,517	248	3,103	292
355	1,545	244	1,948	242	3,246	247	2,467	279
356	1,226	213	2,081	278	2,042	244	3,914	278
357	1,770	243	1,824	233	2,395	225	2,795	309
358	2,878	276	2,253	234	1,830	266	5,242	287
359	1,477	245	2,231	251	1,961	244	2,797	286
360	2,742	221	1,901	242	1,992	225	2,641	272
361	1,873	209	1,826	213	2,129	329	4,100	302
362	1,469	257	1,745	218	1,899	261	2,349	320
363	1,755	214	3,217	267	2,063	246	2,657	280
364	1,996	246	1,956	220	1,747	249	2,532	337
365	1,800	258	1,817	215	1,649	288	2,412	311
366	1,516	221	1,921	246	2,690	241	2,176	285
367	1,736	201	2,033	277	2,069	276	2,520	275
368	1,868	325	1,995	320	1,787	265	2,398	257

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
369	2,741	242	2,295	201	1,940	250	2,749	286
370	1,882	230	1,987	227	3,823	254	5,331	289
371	1,603	224	2,188	249	1,739	273	2,676	360
372	1,529	208	2,619	274	2,008	241	2,672	253
373	1,981	229	1,657	226	1,941	255	2,834	284
374	2,254	257	2,247	254	2,473	270	2,390	280
375	1,939	224	2,933	246	2,379	260	2,504	279
376	2,037	186	1,949	226	4,417	223	2,542	281
377	3,975	268	1,867	277	2,119	261	2,475	243
378	1,339	186	2,353	213	2,024	271	3,462	320
379	2,587	247	2,366	236	2,572	253	2,507	252
380	1,536	232	2,227	240	3,024	494	2,945	299
381	1,298	230	1,570	242	2,218	220	2,185	289
382	2,112	201	1,853	285	1,946	247	2,528	284
383	2,145	220	2,154	218	2,557	234	3,264	297
384	1,695	197	2,162	226	2,321	242	2,430	297
385	1,487	229	2,078	307	1,943	239	2,675	278
386	1,681	353	2,077	236	1,930	262	2,574	294
387	3,549	243	1,700	261	1,943	277	2,457	341
388	1,556	238	2,803	247	2,114	321	2,718	374
389	1,863	214	1,402	387	2,878	291	2,325	355
390	2,411	224	6,102	244	2,416	283	2,884	275
391	1,362	283	2,468	217	1,973	281	2,762	298
392	2,611	270	2,519	231	1,974	243	2,395	511
393	1,894	219	1,818	286	1,915	227	5,065	343
394	1,561	215	2,008	230	1,775	228	2,430	357
395	1,659	188	1,682	238	2,496	284	2,904	312
396	1,940	288	1,798	239	3,277	228	2,424	289
397	1,461	209	1,766	234	2,055	286	2,622	320
398	1,804	223	1,661	269	2,743	260	2,471	290
399	1,360	212	1,892	203	2,133	335	2,958	242
400	1,859	210	2,020	261	1,838	255	2,487	259
401	1,819	230	1,809	228	3,209	277	2,382	273
402	1,577	245	2,387	222	2,071	251	2,376	465
403	1,612	197	1,839	267	2,277	237	2,159	261
404	2,013	213	2,397	248	2,451	270	2,458	359
405	1,606	208	1,824	256	1,633	219	2,316	289

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
406	1,753	231	1,653	246	2,501	256	3,029	275
407	1,632	245	1,953	222	2,019	251	2,904	291
408	1,435	266	1,576	280	1,932	274	2,643	305
409	3,428	216	2,006	220	1,931	253	2,700	300
410	1,670	190	1,808	225	2,036	248	2,554	262
411	1,873	196	1,887	244	2,456	258	2,753	277
412	1,496	187	2,139	216	3,661	290	2,852	262
413	1,457	202	2,178	331	2,885	323	2,594	243
414	1,576	201	1,784	251	2,856	282	2,195	301
415	2,005	247	1,829	223	2,692	282	3,179	295
416	2,021	212	2,154	234	1,777	229	3,852	289
417	1,673	226	2,378	232	1,915	236	2,930	277
418	2,592	198	1,966	248	2,329	266	3,166	285
419	1,726	261	3,657	222	2,354	229	2,599	260
420	1,820	219	2,675	220	2,254	218	2,205	334
421	1,951	201	2,924	229	1,994	249	2,436	256
422	1,678	210	1,926	210	1,783	289	2,165	265
423	2,383	207	1,846	235	2,386	287	2,565	275
424	1,624	252	2,806	230	2,274	298	2,665	284
425	1,781	350	1,618	244	2,492	323	2,379	270
426	1,578	238	1,619	239	2,968	264	2,482	333
427	1,650	184	1,895	260	3,010	248	2,499	292
428	2,132	286	2,292	265	1,918	257	2,965	311
429	1,641	225	1,670	239	1,926	246	2,811	301
430	1,825	220	1,500	216	1,999	254	2,505	319
431	1,908	295	2,080	233	2,262	266	2,946	251
432	2,074	235	2,279	215	2,071	297	2,375	244
433	1,551	193	2,092	280	2,244	261	2,799	233
434	1,779	220	2,041	219	2,056	235	2,588	273
435	1,786	212	1,769	262	1,956	262	4,409	313
436	2,435	231	2,088	287	2,469	264	2,653	293
437	1,657	245	2,630	240	1,776	251	2,453	296
438	2,536	229	2,114	222	2,502	226	2,413	289
439	1,607	219	1,825	234	3,099	209	2,446	296
440	1,584	246	3,330	223	2,611	235	2,085	288
441	1,489	190	2,113	313	2,063	263	3,844	287
442	1,662	212	1,495	261	2,296	283	2,269	306

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
443	2,457	239	1,979	261	2,169	288	2,782	284
444	1,421	226	2,338	222	2,087	275	3,305	242
445	1,942	222	1,664	239	2,427	278	2,899	303
446	1,466	256	1,783	271	1,792	251	2,270	300
447	1,987	209	1,765	245	1,802	256	2,571	286
448	1,839	234	2,431	234	2,394	261	2,976	264
449	1,561	207	2,068	261	2,392	207	2,970	281
450	1,672	296	2,387	258	2,006	233	2,454	324
451	1,720	234	1,683	262	1,922	226	2,416	271
452	1,879	246	1,790	247	2,157	290	2,898	339
453	2,385	208	2,878	247	2,027	244	2,362	373
454	4,554	222	1,649	207	2,337	240	2,540	270
455	1,940	223	1,912	255	1,985	249	2,233	257
456	1,312	232	2,056	228	2,049	221	2,234	298
457	2,137	226	2,195	199	1,827	252	2,610	289
458	1,770	256	1,902	254	2,600	222	2,845	316
459	1,460	283	1,755	230	2,056	263	2,736	244
460	1,517	231	2,077	322	2,620	267	2,275	250
461	1,851	196	1,854	209	1,928	259	2,744	346
462	1,877	251	1,825	246	2,710	249	2,996	278
463	1,964	257	2,096	253	2,300	226	2,195	299
464	1,992	235	1,774	231	2,303	299	2,318	268
465	1,794	254	1,698	219	2,375	277	2,684	291
466	1,760	221	2,631	262	2,343	263	3,177	270
467	1,522	223	2,361	229	2,187	251	2,389	327
468	2,508	198	1,716	255	2,783	222	2,250	316
469	2,552	236	1,867	222	2,702	232	2,412	283
470	1,892	241	1,488	233	2,105	279	2,567	283
471	1,415	209	2,967	281	2,720	244	2,629	286
472	1,664	220	1,722	259	2,518	261	2,328	287
473	1,396	238	1,803	292	2,191	276	3,054	277
474	1,881	228	2,297	217	2,133	220	2,303	282
475	1,907	231	1,794	211	2,455	251	2,188	260
476	1,694	248	2,012	213	2,659	258	2,317	309
477	1,689	254	1,527	235	1,839	235	2,686	280
478	1,744	234	1,950	220	2,794	269	2,704	288
479	2,204	204	1,592	251	2,100	257	2,058	273

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
480	2,023	215	2,210	222	2,293	240	2,319	317
481	1,716	200	2,306	224	1,971	224	4,041	308
482	1,297	210	2,251	254	2,247	251	3,314	322
483	1,641	265	2,353	260	2,263	305	2,825	360
484	1,717	271	1,801	271	2,359	245	2,261	295
485	1,618	232	2,170	208	3,239	230	2,800	275
486	2,104	226	1,818	250	2,216	260	2,761	286
487	1,523	245	1,840	239	1,805	236	2,456	311
488	1,838	220	2,043	346	2,219	251	2,329	269
489	1,696	233	2,086	214	2,094	261	2,362	254
490	1,654	219	2,202	285	2,475	220	6,985	316
491	1,936	194	1,512	210	2,153	238	2,347	273
492	2,377	182	2,430	291	3,243	262	2,583	277
493	2,605	190	1,885	222	2,907	226	2,741	347
494	1,832	247	1,865	247	1,972	232	2,659	288
495	2,480	238	1,824	253	1,933	307	2,435	290
496	1,639	201	2,422	269	2,520	224	2,556	290
497	2,650	263	3,004	251	1,997	274	2,152	280
498	1,744	234	1,978	241	2,298	250	2,435	238
499	1,541	198	1,657	254	2,077	346	2,400	368
500	2,777	214	3,150	244	2,561	316	2,629	287
501	1,688	243	2,485	246	2,719	256	2,698	340
502	1,798	204	2,761	224	2,219	256	2,901	323
503	1,723	216	1,943	216	2,780	267	2,740	286
504	1,397	236	1,809	241	1,980	283	2,915	337
505	1,809	232	1,914	227	2,084	250	2,333	280
506	2,024	233	1,800	230	2,172	235	3,193	347
507	1,587	245	2,087	226	2,013	242	3,661	258
508	1,403	283	1,929	270	1,901	256	2,967	294
509	2,428	259	1,647	254	2,404	262	2,550	278
510	4,587	207	2,663	236	1,863	252	2,304	254
511	1,516	208	3,152	272	1,859	262	2,530	283
512	1,569	197	4,259	236	2,507	259	2,540	273
513	1,599	223	2,070	249	1,856	256	3,099	287
514	1,887	232	1,747	245	1,979	289	2,772	295
515	1,605	214	1,990	218	1,980	285	2,562	296
516	1,501	185	2,993	253	1,955	249	2,641	265

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
517	1,960	237	2,175	242	2,277	309	2,649	358
518	1,473	223	4,408	263	1,936	298	5,026	253
519	1,648	247	1,723	288	2,921	234	2,463	295
520	3,674	387	1,603	199	2,323	283	2,780	273
521	5,731	220	1,885	202	2,106	271	3,657	292
522	1,301	231	2,159	255	2,602	259	2,449	273
523	3,653	345	1,915	264	1,914	262	2,508	276
524	2,027	221	2,213	252	2,026	357	3,227	316
525	1,684	281	1,959	264	2,112	292	2,432	283
526	1,670	218	1,832	296	2,306	235	2,671	297
527	2,014	223	2,381	243	1,923	254	2,361	328
528	1,655	243	2,318	258	2,690	258	2,775	336
529	1,399	184	1,839	253	2,291	224	2,783	351
530	1,749	232	2,206	254	2,116	243	2,739	292
531	1,494	190	2,533	196	2,219	236	2,717	292
532	1,927	218	1,921	241	2,443	277	2,420	310
533	1,439	222	2,110	224	1,904	235	2,811	260
534	1,963	226	2,782	215	2,786	264	2,724	282
535	1,528	250	1,759	292	2,101	236	3,368	322
536	2,243	216	1,762	224	1,864	251	2,689	296
537	1,389	215	2,379	224	2,000	274	2,350	271
538	1,847	286	2,264	211	1,938	259	2,415	284
539	2,237	215	2,250	232	1,964	238	3,463	292
540	2,710	205	1,722	226	2,398	322	2,373	242
541	1,765	227	2,444	226	2,063	253	4,206	563
542	2,130	230	3,254	258	2,022	278	3,304	264
543	2,271	207	1,634	238	1,887	296	2,704	285
544	1,576	213	2,246	244	1,976	265	2,890	275
545	1,716	269	1,788	222	2,462	241	2,543	296
546	1,480	316	2,181	217	2,868	298	3,050	269
547	1,757	217	2,282	244	1,757	255	2,904	282
548	8,372	228	1,794	234	2,059	234	2,440	313
549	2,369	189	1,764	295	2,148	259	2,756	327
550	1,862	180	1,824	302	2,088	250	2,303	259
551	1,417	234	1,636	225	2,030	348	2,921	264
552	2,239	211	2,188	223	2,701	254	2,508	334
553	2,085	240	1,829	455	1,800	239	2,390	283

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
554	1,667	295	1,872	221	2,235	290	2,406	256
555	2,071	212	2,332	230	1,809	253	3,783	266
556	2,051	278	1,786	243	1,888	280	2,280	280
557	2,029	256	1,790	226	2,484	236	2,516	273
558	2,238	256	2,407	269	4,172	246	2,420	254
559	1,968	211	1,601	247	3,033	292	2,362	317
560	1,783	254	1,873	225	2,177	259	2,480	274
561	1,832	205	1,996	228	2,047	232	2,641	289
562	2,029	235	3,145	220	2,285	264	2,334	345
563	1,485	227	2,008	318	2,333	249	2,984	278
564	1,400	291	1,848	266	1,994	231	2,197	279
565	2,062	195	1,905	315	2,650	305	2,768	311
566	3,036	236	1,959	233	2,326	216	2,457	272
567	1,981	212	2,760	260	1,879	389	2,484	259
568	1,917	223	2,768	249	2,002	288	2,052	361
569	1,681	255	2,892	219	1,851	243	2,848	306
570	2,085	209	2,038	197	1,996	276	2,589	277
571	1,563	217	2,500	217	1,922	269	2,367	320
572	1,502	219	2,458	225	2,776	243	2,540	257
573	2,469	213	1,644	229	1,751	246	3,469	280
574	2,354	239	1,627	206	2,032	226	2,549	296
575	1,357	194	2,659	245	2,291	263	2,748	249
576	2,466	199	1,958	287	2,130	235	2,753	259
577	1,787	237	1,920	226	2,076	251	2,577	261
578	1,957	230	1,951	216	2,163	428	2,227	310
579	1,377	229	2,006	263	2,539	254	2,699	280
580	1,886	210	2,131	276	1,842	258	3,732	277
581	1,860	223	2,757	231	1,805	231	2,335	296
582	1,677	189	2,376	254	2,175	244	2,313	254
583	1,483	201	1,977	247	2,035	234	3,559	318
584	3,256	218	2,994	264	2,253	261	2,192	355
585	1,542	206	2,034	254	2,161	216	2,920	287
586	1,512	220	3,346	232	1,950	252	2,742	255
587	1,649	206	1,789	238	2,221	231	2,473	335
588	1,596	214	1,941	245	2,011	247	2,641	338
589	1,838	212	2,166	273	1,809	215	2,941	264
590	1,664	201	1,800	232	3,749	251	2,990	295

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
591	2,077	236	2,273	283	2,329	263	2,363	328
592	1,594	212	1,958	277	2,201	290	2,634	284
593	1,496	209	2,083	255	1,927	290	2,823	286
594	1,848	335	1,853	262	4,898	311	2,534	315
595	1,892	221	1,835	233	2,109	361	2,358	272
596	2,009	207	1,958	219	2,471	251	3,091	239
597	1,942	283	1,989	204	1,997	271	2,166	322
598	1,504	214	1,963	211	2,293	295	2,188	284
599	1,792	315	1,494	256	1,961	247	2,763	355
600	1,596	203	1,700	227	1,740	232	2,371	262
601	1,684	224	1,800	224	2,084	252	2,240	305
602	1,392	276	1,703	283	1,812	209	3,742	260
603	1,726	192	3,047	259	2,187	260	2,270	306
604	1,602	252	2,459	247	2,155	221	2,690	267
605	1,500	257	1,705	231	2,174	242	2,321	267
606	2,076	266	1,529	239	4,770	254	2,832	273
607	1,684	206	1,759	219	2,165	263	2,342	298
608	1,607	253	1,617	313	2,266	241	2,616	306
609	1,581	207	2,581	266	2,034	256	2,618	319
610	1,745	206	1,963	256	2,267	252	4,359	376
611	1,600	234	2,050	239	2,256	262	2,578	314
612	1,836	228	1,725	248	2,239	269	2,680	375
613	1,579	257	1,661	251	3,756	235	2,582	279
614	2,036	196	1,927	251	2,289	256	2,725	260
615	1,966	220	2,004	232	3,145	245	2,161	264
616	1,638	222	1,471	270	4,346	246	2,709	296
617	2,029	205	1,771	239	1,922	251	2,980	281
618	2,314	196	2,269	278	2,927	239	2,489	290
619	1,961	224	1,787	304	2,314	249	2,216	265
620	2,373	229	1,716	257	2,313	267	2,621	299
621	1,823	302	1,824	218	2,162	296	2,445	327
622	2,372	217	1,825	233	2,023	246	3,418	311
623	1,387	224	1,779	256	2,252	239	2,811	275
624	1,841	249	1,667	269	1,959	243	2,559	306
625	1,926	198	2,614	225	1,962	253	3,142	237
626	1,467	274	1,900	216	2,440	211	2,557	276
627	1,485	244	2,152	210	1,994	302	2,384	282

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
628	1,518	307	2,157	225	2,311	227	2,490	292
629	2,224	228	1,902	226	3,269	255	2,515	278
630	1,492	255	1,671	232	2,064	278	2,808	249
631	1,840	254	2,452	568	2,291	230	4,072	293
632	2,096	301	3,166	217	2,599	265	2,277	258
633	3,065	205	1,744	238	2,670	259	2,450	302
634	1,670	240	3,188	234	1,811	246	2,457	244
635	1,806	229	3,216	229	2,942	244	2,746	274
636	1,682	218	1,753	258	4,322	275	2,185	290
637	1,458	224	1,688	210	2,733	253	2,429	288
638	1,603	194	1,765	252	2,028	345	2,225	300
639	1,748	193	1,979	235	2,320	254	2,874	288
640	1,407	239	3,217	249	2,937	228	3,694	280
641	2,088	207	2,622	255	2,152	291	2,476	287
642	2,144	213	2,265	251	2,185	353	2,218	329
643	2,155	239	1,655	221	3,818	216	2,422	292
644	1,779	259	1,858	309	2,713	253	2,871	343
645	1,780	215	2,427	278	3,925	282	2,292	295
646	1,792	243	2,288	193	2,032	247	2,262	256
647	2,260	243	1,918	239	2,261	255	2,479	315
648	1,723	227	1,798	253	1,687	249	2,788	246
649	1,998	310	1,912	200	1,988	254	2,690	335
650	1,582	232	2,853	234	2,176	286	2,315	248
651	2,282	229	1,595	220	2,057	290	2,812	315
652	1,685	234	1,622	286	1,997	264	2,539	419
653	1,412	263	2,128	262	2,628	245	2,452	278
654	2,582	329	1,899	253	2,563	225	2,470	299
655	1,684	203	1,810	328	2,252	198	2,600	292
656	2,111	218	2,500	233	2,031	223	2,631	299
657	1,816	256	1,872	220	2,057	280	2,664	241
658	2,469	204	2,812	259	2,252	397	2,346	283
659	1,451	235	2,510	209	2,290	265	2,617	291
660	4,320	211	1,876	212	1,889	282	3,069	325
661	2,990	236	1,996	253	1,824	229	2,359	276
662	1,894	243	1,828	204	1,985	282	2,485	281
663	2,900	211	1,526	244	2,138	240	3,162	326
664	1,805	254	1,719	265	2,191	227	2,301	273

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
665	2,275	203	2,101	273	1,912	311	2,387	306
666	1,649	275	2,083	303	2,249	251	2,935	508
667	1,780	241	2,123	218	2,433	256	2,590	257
668	2,156	235	2,029	190	1,902	269	2,202	280
669	2,336	221	2,142	215	3,299	248	4,028	274
670	1,680	250	2,433	230	3,561	341	2,299	321
671	1,587	236	1,917	234	2,146	247	2,916	303
672	1,773	206	1,906	327	2,125	300	2,976	304
673	1,845	204	1,855	274	2,293	258	2,219	254
674	1,605	226	1,993	294	3,022	242	2,943	257
675	2,471	237	1,801	230	1,968	312	2,642	331
676	1,767	205	1,785	229	2,142	236	2,970	291
677	1,504	245	1,836	307	2,174	227	2,135	288
678	1,664	185	2,831	239	1,891	241	7,079	295
679	1,834	343	3,143	202	2,052	253	3,887	300
680	2,257	268	2,090	221	3,392	243	2,319	286
681	2,589	229	2,039	250	1,915	259	2,518	278
682	1,682	228	1,902	254	2,479	254	2,880	289
683	1,358	218	2,248	273	2,292	216	2,653	277
684	1,901	215	2,018	283	2,873	253	2,537	346
685	3,395	246	8,082	243	2,606	242	2,136	257
686	1,808	273	1,616	204	3,304	310	2,249	317
687	1,995	215	1,522	238	2,396	252	2,362	295
688	1,690	211	1,782	290	1,930	270	4,036	295
689	2,266	208	1,842	241	2,004	279	2,362	237
690	1,648	227	1,744	266	2,282	277	2,528	283
691	2,015	254	1,684	210	2,388	261	3,332	300
692	1,552	249	1,957	226	1,993	254	2,698	287
693	1,586	207	1,974	270	4,929	217	2,409	291
694	1,554	187	6,543	234	2,221	258	2,540	276
695	1,673	214	2,198	259	1,795	233	2,849	321
696	1,793	273	2,063	256	1,922	259	2,474	285
697	1,880	257	2,718	255	2,404	295	2,472	285
698	1,714	247	1,757	232	2,414	303	3,212	390
699	1,562	204	1,598	289	1,687	249	2,263	285
700	1,477	206	1,828	240	1,803	306	2,695	278
701	2,591	238	1,985	208	1,976	294	2,729	286

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
702	2,407	191	2,139	236	1,674	289	2,076	352
703	2,332	207	2,156	245	2,240	274	3,762	266
704	1,786	221	2,283	245	1,824	238	2,360	315
705	1,626	235	1,860	217	2,090	338	2,483	316
706	2,798	203	1,959	267	2,021	238	3,054	287
707	1,548	239	2,426	267	1,895	237	4,032	310
708	1,671	309	1,956	260	2,945	280	2,293	273
709	1,960	216	1,670	243	2,679	274	2,332	269
710	2,008	210	1,621	236	2,257	239	2,865	267
711	1,666	233	1,769	228	1,967	265	2,646	250
712	1,689	258	1,710	209	1,780	255	2,227	295
713	1,720	267	2,145	240	2,350	234	2,238	381
714	2,828	238	1,980	215	2,354	234	2,358	287
715	1,653	212	1,874	241	2,359	265	2,221	257
716	1,618	218	1,999	236	1,687	211	2,102	297
717	1,477	224	1,463	217	2,431	254	3,633	344
718	1,973	232	2,147	297	2,069	249	2,523	278
719	1,885	222	1,612	251	1,720	251	2,324	304
720	2,100	234	1,876	221	2,170	235	2,052	346
721	1,907	202	1,714	240	1,914	229	2,689	311
722	1,742	214	2,581	217	2,151	282	3,356	294
723	1,456	189	1,576	253	2,110	258	2,032	305
724	2,015	269	1,793	266	2,035	266	2,460	275
725	2,030	237	1,807	252	2,128	285	2,333	261
726	1,876	308	1,983	248	1,842	238	2,430	303
727	1,881	253	1,860	220	1,950	288	2,165	265
728	1,456	229	1,694	233	2,608	271	2,173	276
729	1,625	270	1,987	295	2,099	250	2,507	301
730	2,092	281	2,189	224	2,150	311	2,894	262
731	2,105	240	2,324	208	2,126	235	2,224	281
732	2,263	289	1,879	406	2,193	254	2,398	298
733	2,320	258	1,829	210	1,792	248	2,766	286
734	1,443	282	2,115	234	2,641	278	3,207	245
735	1,510	247	1,967	210	2,136	245	2,566	356
736	1,922	209	1,797	395	2,091	251	2,583	299
737	1,471	216	1,570	652	2,031	252	2,697	294
738	1,883	224	3,309	216	2,018	233	2,535	281

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
739	1,516	251	1,745	246	5,845	273	2,417	281
740	1,683	235	2,045	230	2,805	278	2,385	356
741	1,677	211	2,525	248	1,961	226	2,565	258
742	1,501	246	1,950	255	2,382	262	3,087	255
743	1,506	220	2,689	256	2,073	249	2,714	289
744	1,558	215	3,069	230	2,350	270	4,487	297
745	2,682	219	1,846	232	1,887	222	2,681	278
746	1,671	235	2,038	243	1,999	207	2,348	271
747	1,415	268	2,059	187	1,991	231	2,643	268
748	2,193	173	2,061	253	2,036	259	2,466	327
749	1,438	202	1,970	292	4,080	268	2,612	308
750	2,201	214	1,780	233	2,295	269	3,357	276
751	5,138	249	2,065	217	2,136	280	2,482	290
752	1,413	204	1,409	244	1,926	270	2,868	266
753	1,570	256	2,398	291	1,953	217	2,743	298
754	1,561	243	1,714	353	2,178	242	2,993	272
755	1,495	203	2,055	209	2,185	242	2,669	273
756	1,631	223	1,768	261	2,004	270	2,499	299
757	1,660	215	1,897	212	2,059	274	2,860	303
758	2,002	316	2,578	236	2,931	377	2,273	268
759	1,853	229	1,865	257	2,490	230	2,735	321
760	2,343	191	2,137	255	2,096	263	2,752	293
761	1,951	235	1,451	260	2,010	231	2,613	262
762	1,732	236	2,341	242	2,142	245	2,655	275
763	1,987	229	1,642	441	2,231	238	2,476	287
764	2,647	203	1,893	245	1,847	259	2,423	269
765	1,522	376	2,056	294	2,943	322	2,201	279
766	1,409	229	2,101	261	2,213	251	2,589	262
767	1,786	211	2,002	243	2,808	288	3,080	287
768	2,584	220	1,827	230	2,131	235	3,843	274
769	1,636	200	1,628	248	1,803	220	2,301	283
770	1,565	216	1,759	240	2,652	272	2,660	253
771	2,622	196	2,210	241	2,260	283	2,661	281
772	1,774	233	2,130	237	1,951	247	2,818	378
773	1,232	251	2,036	253	2,386	270	2,563	281
774	1,370	204	1,789	229	2,280	259	2,296	287
775	2,265	236	1,649	223	2,126	266	2,464	271

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
776	1,568	202	2,238	238	2,344	346	3,015	255
777	1,317	240	1,634	266	1,813	266	2,566	265
778	1,466	258	1,589	252	2,254	238	2,833	271
779	1,871	216	1,994	249	2,281	257	2,485	277
780	3,060	229	2,627	251	3,196	223	2,712	344
781	1,601	220	1,578	250	2,607	306	15,289	288
782	1,467	207	2,685	202	2,154	236	2,944	297
783	2,223	191	2,133	216	2,155	289	5,241	269
784	1,825	199	1,925	280	2,471	222	2,503	250
785	2,557	200	2,223	261	2,850	277	2,688	293
786	1,804	207	1,716	250	1,999	259	3,528	294
787	1,622	224	1,641	217	3,670	240	2,674	265
788	2,703	236	2,147	223	1,891	258	2,684	275
789	1,904	222	1,860	221	2,287	236	2,431	273
790	1,231	266	2,690	256	2,032	334	2,946	338
791	1,656	254	1,901	216	2,077	310	2,504	305
792	2,728	205	2,086	277	2,366	304	2,556	260
793	1,812	207	1,699	209	6,346	232	2,420	321
794	1,968	223	2,349	254	2,185	265	3,301	263
795	1,597	208	3,151	266	1,966	226	2,685	301
796	1,835	214	2,049	226	2,364	215	3,635	344
797	3,162	228	1,816	237	1,774	355	2,419	307
798	1,354	255	2,450	226	2,007	235	2,576	226
799	2,341	227	2,117	234	1,643	451	2,715	285
800	1,537	202	1,943	225	2,213	292	2,582	267
801	1,762	246	2,585	219	2,352	260	3,219	285
802	2,175	270	1,521	252	1,808	255	2,900	314
803	2,878	206	2,021	340	1,833	306	2,923	297
804	3,892	211	2,047	290	3,846	246	2,149	307
805	1,831	171	2,460	269	2,902	229	3,025	283
806	1,785	222	1,925	192	2,174	308	2,381	278
807	1,637	203	1,834	233	2,602	285	2,575	291
808	1,670	230	2,029	247	1,866	269	2,376	302
809	2,768	209	2,117	267	2,362	233	4,630	288
810	1,893	253	1,631	204	2,000	249	2,412	273
811	1,523	204	1,532	202	1,994	278	2,441	259
812	1,938	258	1,970	322	2,303	244	2,473	346

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
813	1,603	270	1,713	227	2,293	281	6,916	295
814	1,891	303	1,855	239	2,402	226	2,799	288
815	2,017	215	2,112	247	2,165	248	2,632	257
816	1,668	273	1,870	271	2,087	229	2,588	285
817	1,756	197	1,701	220	2,516	248	2,338	279
818	1,714	242	2,376	243	2,021	227	2,628	303
819	1,463	243	1,877	221	1,916	237	2,331	254
820	1,462	224	2,265	270	2,656	258	2,639	240
821	1,491	219	1,617	224	2,178	277	2,495	295
822	4,091	221	2,344	243	2,406	233	2,822	287
823	3,330	237	3,903	239	2,190	244	2,884	312
824	2,040	258	1,816	245	1,977	305	2,527	288
825	1,714	174	1,580	282	2,026	256	2,552	260
826	1,606	270	2,157	205	1,938	219	2,554	297
827	1,572	213	1,733	242	2,685	260	2,664	270
828	1,958	231	1,793	300	1,969	273	2,823	298
829	1,669	212	2,133	237	2,217	243	2,712	517
830	2,882	229	1,943	220	2,434	291	2,463	328
831	1,433	221	2,383	186	2,263	246	2,386	270
832	1,634	215	2,121	333	2,073	231	2,675	280
833	2,478	208	1,801	285	2,212	220	2,567	292
834	1,552	232	1,902	233	1,733	223	2,320	266
835	1,707	214	2,087	251	1,782	278	2,473	273
836	1,818	266	1,621	361	1,762	218	2,707	297
837	1,776	238	1,774	230	1,986	229	2,749	257
838	1,781	205	2,633	238	2,070	257	2,852	348
839	1,919	224	1,747	239	2,134	247	2,217	287
840	2,007	233	1,914	208	2,070	251	2,642	288
841	2,304	236	2,706	269	4,452	254	2,952	291
842	1,516	189	1,590	205	2,025	243	2,733	311
843	2,155	227	2,692	244	2,061	261	2,971	295
844	1,994	241	1,872	256	2,224	319	2,382	257
845	1,672	229	1,951	202	1,992	301	2,352	312
846	2,142	196	1,938	234	2,004	199	3,338	307
847	1,442	235	1,867	268	4,435	248	2,804	280
848	1,906	189	2,975	220	2,004	259	2,336	302
849	1,651	208	1,549	234	2,282	242	2,621	285

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
850	1,550	199	1,720	240	2,703	239	2,412	281
851	1,925	231	1,992	315	5,840	262	4,322	313
852	1,396	285	2,365	220	2,262	248	2,628	284
853	1,888	228	2,267	228	2,420	321	2,721	271
854	1,570	215	4,504	231	2,701	303	3,034	316
855	3,238	314	2,828	254	2,197	242	3,074	269
856	2,822	230	2,028	211	1,853	253	2,368	273
857	1,562	243	2,141	229	2,768	226	2,984	376
858	1,400	219	1,644	219	1,630	268	2,634	259
859	2,164	209	2,548	241	3,234	239	2,357	331
860	1,839	209	1,804	401	1,838	251	2,713	326
861	1,974	237	2,055	223	2,042	229	2,528	263
862	2,243	196	1,631	282	1,933	253	2,154	322
863	1,442	184	2,200	212	1,804	243	2,486	269
864	1,703	216	2,729	277	1,749	252	2,454	285
865	1,945	229	3,147	279	3,498	218	3,127	251
866	1,523	219	2,304	215	1,905	285	3,565	340
867	1,994	210	1,835	267	2,508	256	2,646	279
868	1,632	223	1,985	253	2,451	227	2,169	273
869	1,611	245	2,695	220	2,520	291	2,121	291
870	2,183	325	1,884	228	3,319	266	2,549	518
871	2,612	183	2,516	268	3,001	234	4,718	267
872	1,994	208	2,079	267	1,880	255	2,406	284
873	2,525	188	1,792	195	2,287	256	2,589	280
874	1,949	204	1,787	223	2,614	254	2,322	285
875	1,458	229	1,789	209	3,214	263	2,531	321
876	1,563	202	2,097	204	1,934	238	2,696	284
877	1,920	207	2,956	275	1,878	290	3,090	289
878	2,453	260	1,755	240	1,997	258	2,549	260
879	1,962	211	2,781	243	2,214	222	2,312	267
880	2,828	249	1,741	234	4,147	232	2,477	300
881	1,436	202	1,522	223	1,544	279	2,444	296
882	1,943	215	1,859	252	2,804	252	2,901	265
883	1,720	222	2,932	224	1,897	282	2,280	305
884	1,688	218	1,769	237	2,269	278	2,394	280
885	1,952	242	2,712	211	2,853	300	2,944	273
886	1,539	216	1,807	258	2,008	238	2,538	250

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
887	1,610	243	1,722	239	2,562	251	2,822	258
888	1,447	222	2,458	250	1,974	253	2,650	280
889	1,542	327	2,742	242	2,183	291	2,489	317
890	1,698	222	2,661	232	2,354	236	2,985	326
891	1,780	210	2,687	239	2,133	267	3,484	282
892	1,851	228	1,621	257	1,889	238	2,796	296
893	1,534	221	2,153	204	1,870	231	2,582	269
894	1,664	236	2,958	240	1,840	278	2,395	346
895	2,417	225	1,632	262	2,409	244	2,689	295
896	1,923	208	1,704	256	1,881	255	2,838	285
897	1,647	210	3,071	243	1,752	243	2,621	261
898	2,132	213	1,723	207	1,965	261	2,859	287
899	1,670	206	2,237	241	2,180	253	3,065	290
900	1,617	286	1,703	248	2,093	267	2,489	277
901	3,562	301	1,650	228	1,855	254	2,744	252
902	1,553	224	1,770	360	2,201	240	2,413	274
903	1,848	263	1,720	249	2,797	233	2,296	247
904	2,288	250	1,984	281	1,895	239	2,394	264
905	1,435	234	2,159	258	2,786	243	2,542	316
906	1,971	211	1,854	227	1,913	237	3,216	255
907	1,922	224	1,789	370	2,652	283	3,113	301
908	1,825	206	2,036	260	1,922	274	2,493	282
909	1,798	194	2,761	245	2,192	262	4,803	343
910	1,740	231	3,590	230	2,056	261	2,221	271
911	1,792	194	1,437	205	1,786	242	5,444	281
912	1,860	216	2,954	310	2,048	251	2,128	300
913	1,981	214	1,954	250	2,219	270	2,424	295
914	1,472	259	1,999	260	2,187	236	2,420	284
915	1,797	217	2,438	234	1,871	283	2,583	349
916	1,757	219	1,837	227	2,429	286	3,964	364
917	2,688	243	1,989	257	2,854	280	3,630	287
918	1,749	222	2,380	220	2,620	252	2,953	255
919	1,840	302	1,798	218	2,773	267	2,832	290
920	2,008	174	2,237	226	1,964	292	4,869	271
921	2,027	206	1,582	209	2,052	226	2,660	271
922	1,694	211	2,019	232	1,737	263	2,855	278
923	1,706	222	2,768	297	1,977	284	2,744	308

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
924	1,501	232	1,967	231	1,979	252	2,538	288
925	1,745	217	1,729	246	2,521	271	2,438	288
926	1,789	194	1,807	207	2,054	240	2,491	275
927	1,793	206	2,322	240	2,015	238	2,198	297
928	1,406	242	2,002	235	1,560	309	3,074	280
929	1,564	226	3,269	213	1,796	220	3,210	264
930	1,603	242	1,944	249	1,919	274	2,601	274
931	1,674	209	1,995	234	1,962	218	2,573	277
932	2,909	206	2,444	281	2,689	364	2,290	270
933	2,750	550	1,920	282	1,988	239	3,145	289
934	1,915	266	1,850	237	2,567	237	2,346	299
935	1,659	226	2,128	257	2,529	252	2,856	271
936	2,143	266	1,758	294	1,817	251	2,317	390
937	3,703	205	2,002	207	2,257	210	2,453	248
938	2,004	233	2,085	277	2,217	325	2,729	281
939	2,563	200	1,808	226	1,953	305	2,800	351
940	1,683	216	2,072	262	1,960	227	2,327	265
941	2,051	209	2,264	242	1,973	271	2,822	272
942	1,747	208	2,064	244	2,142	248	3,367	302
943	2,540	224	1,964	223	1,901	262	1,999	269
944	1,463	209	2,177	256	2,065	308	2,237	271
945	1,865	231	1,737	435	2,165	267	2,153	318
946	1,951	222	2,285	219	2,407	300	2,515	270
947	2,396	225	1,800	233	1,969	232	3,300	269
948	1,838	246	2,141	249	2,681	238	2,407	296
949	1,950	219	1,871	245	2,200	246	2,494	284
950	2,109	215	1,682	201	1,960	263	2,466	274
951	1,621	206	1,618	259	2,187	249	2,583	281
952	2,732	250	1,674	283	1,986	293	2,759	288
953	2,012	241	1,849	272	2,007	287	2,570	260
954	3,145	216	1,742	210	2,931	332	2,792	269
955	2,525	201	1,859	304	2,704	308	2,511	340
956	1,458	239	1,936	205	1,868	233	2,619	317
957	1,664	241	2,313	240	2,405	273	3,272	278
958	1,627	200	2,214	242	1,897	263	2,843	295
959	1,346	263	2,002	219	2,703	261	2,496	284
960	1,560	259	1,723	261	1,899	269	2,079	287

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
961	1,865	221	2,349	253	2,077	235	3,027	322
962	1,635	254	2,034	228	2,735	398	2,453	284
963	1,564	287	1,685	255	2,350	240	2,310	357
964	1,705	228	1,639	276	2,270	252	2,395	272
965	1,810	259	2,223	196	2,084	255	2,321	325
966	1,723	297	1,706	247	2,794	354	2,412	292
967	2,048	246	3,408	228	2,665	211	2,917	275
968	2,489	214	2,044	236	2,422	245	2,523	258
969	1,454	236	1,702	235	2,220	225	2,033	274
970	1,583	203	1,758	240	2,728	242	3,300	293
971	1,771	202	1,604	243	1,975	329	3,294	335
972	1,959	224	2,705	237	1,859	261	2,773	262
973	2,408	208	1,911	216	1,909	274	2,172	293
974	1,834	196	1,608	216	2,299	196	2,832	288
975	1,409	217	1,757	231	2,214	267	3,054	339
976	1,513	217	1,601	234	4,061	246	2,244	384
977	1,538	229	1,430	250	2,282	272	2,645	254
978	1,569	259	2,290	253	2,000	253	3,694	291
979	1,592	243	2,323	238	2,463	244	2,990	298
980	2,564	259	2,234	235	2,324	244	2,534	279
981	1,624	204	2,240	193	2,290	250	2,244	300
982	1,584	218	2,844	224	2,336	518	2,317	351
983	1,946	251	2,652	245	2,263	287	3,010	318
984	1,546	233	1,863	226	1,965	258	2,529	313
985	2,098	235	2,733	204	3,693	355	2,818	380
986	2,183	211	1,808	225	2,413	248	2,855	329
987	1,903	235	2,057	245	2,138	235	2,518	307
988	1,657	235	1,717	218	2,124	306	2,811	294
989	1,825	294	1,915	270	2,511	255	2,372	265
990	1,621	195	2,429	231	1,980	315	3,031	268
991	1,629	240	2,229	218	2,099	252	2,305	296
992	1,885	209	2,139	287	5,756	249	2,404	300
993	2,059	230	2,135	237	2,243	233	2,427	281
994	1,657	306	3,248	325	2,282	290	2,367	262
995	1,894	223	1,821	242	1,932	245	2,441	244
996	2,212	204	1,861	240	2,170	288	2,874	303
997	1,520	205	2,542	283	2,840	206	2,463	297

Calculation No.	Supplier Distance 8 km		Supplier Distance 25 km		Supplier Distance 42 km		Supplier Distance 77 km	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
998	1,564	220	2,811	254	2,375	250	2,340	279
999	1,871	247	1,981	264	2,778	280	2,334	268
1000	1,668	293	2,334	247	2,479	256	2,932	249

Q.2 LPV 111 HAUL DISTANCE ANALYSIS

For the analysis of the influence of material haul distance on the total embodied energy and CO_2 emissions associated with Deep Soil Mixing (DSM) at LPV 111, the method described in Ch. 7 was followed to determine total embodied energy and CO_2 emissions with increasing haul distance. Construction details and quantities for the project are described in Chs. 4 – 5 and Appendix F.

Table Q.5 presents the results from the SEEAM analyses with material haul distances defined by different distance multiples, *M* of the actual material haul distances. The resulting total embodied energy and CO_2 emissions values presented here are actually the analytically computed mean values generated by the SEEAM Spreadsheet Calculator. The standard deviations are not reported here. The tabulated information in Table Q.5 corresponds to Figure 7.3. Actual distances used in the SEEAM analysis are shown in Table 7.2.

Table Q.5 Results from SEEAM analysis of Deep Soil Mixing at LPV 111 with different material haul distances.

Distance Multiple, *M*	Embodied Energy (GJ)	% Increase over Minimum Distance Embodied Energy	CO_2 Emissions (tonnes)	% Increase over Minimum Distance CO_2 Emissions
1.0	1,174,000	0%	147,000	0%
2.0	1,228,000	5%	151,000	3%
3.0	1,281,000	9%	155,000	5%
4.0	1,334,000	14%	159,000	8%

Tables Q.6 and Q.7 show the proportion of total embodied energy and CO_2 emissions associated with materials, materials transportation, site operations and waste transportation with increasing distance multiple, *M* for DSM at LPV 111. The tabulated information corresponds to Figure 7.4. Actual distances from the SEEAM analysis are shown in Table 7.2.

Table Q.6 Proportion of total embodied energy for Deep Soil Mixing at LPV 111 due to materials, materials transportation, site operations and waste transportation by distance multiple, *M*.

Distance Multiple, *M*	Materials	Materials Transport	Site Operations	Waste Transport
1.0	65%	13%	22%	0%
2.0	62%	17%	21%	0%
3.0	60%	20%	20%	0%
4.0	57%	23%	20%	0%

Table Q.7 Proportion of total CO_2 emissions for Deep Soil Mixing at LPV 111 due to materials, materials transportation, site operations and waste transportation by distance multiple, *M*.

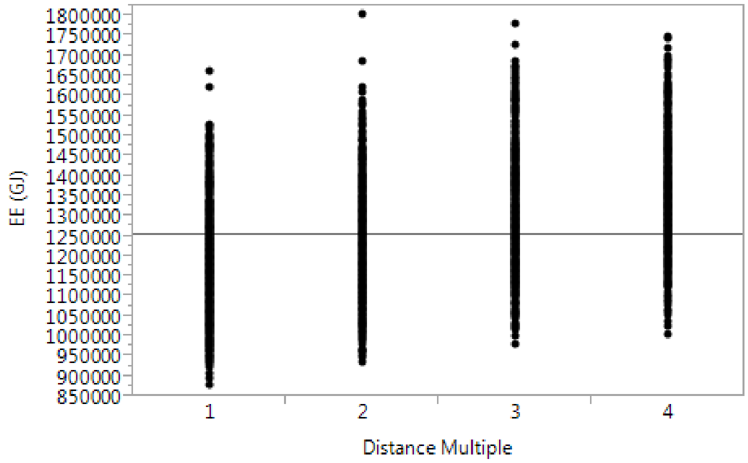
Distance Multiple, *M*	Materials	Materials Transport	Site Operations	Waste Transport
1.0	71%	15%	13%	0%
2.0	70%	17%	13%	0%
3.0	68%	19%	13%	0%
4.0	66%	22%	12%	0%

In addition to the analysis presented in Ch. 7 and in the preceding tables, the SEEAM Spreadsheet Calculator was used to conduct a Monte Carlo simulation for total embodied energy and CO_2 emissions for each multiple of the as-built material haul distances. Nonparametric statistical hypothesis tests were then conducted on the simulated data sets to determine whether or not all distance multiples (M) resulted in significantly different total embodied energy and CO_2 emissions for the DSM at LPV 111. To begin, the Kruskal-Wallis test (Kruskal and Wallis 1952) was used to check for differences with a significance level, $\alpha = 0.05$.

The Kruskal-Wallis test yielded $p < 0.0001$, indicating differences exist. Therefore, the Steel-Dwass method of multiple comparisons was used to check for differences between the embodied energy and CO_2 emissions assessment results for each different set of haul distances, defined by the distance multiple, M. The Steel-Dwass method was originally proposed independently by Steel (1960) and Dwass (1960), and was further elaborated on by Critchlow and Fligner (1991). The Steel-Dwass comparisons revealed that all distances result in significantly different total embodied energy and CO_2 emissions for the DSM at LPV 111, with the base distances resulting in the least total embodied energy and CO_2 emissions and a distance multiple, $M = 4$ resulting in the most embodied energy and CO_2 emissions. All statistical testing was performed using JMP Pro (SAS Institute 2013). The JMP output is shown in Figures Q.3 and Q.4. The levels correspond to the distance multiple, M.

Fit Group

Oneway Analysis of EE (GJ) By Distance Multiple



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
1	1000	1325100	2000500	1325.10	-21.355
2	1000	1774276	2000500	1774.28	-7.153
3	1000	2223367	2000500	2223.37	7.047
4	1000	2679258	2000500	2679.26	21.462

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
763.1027	3	<.0001*

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*	Alpha
2.56903	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
4	1	644.0410	25.82634	24.93737	<.0001*	159222.0	144977.0	173498.0
3	1	464.4850	25.82634	17.98493	<.0001*	104597.0	90627.0	118478.0
4	2	459.2060	25.82634	17.78053	<.0001*	105721.5	91458.0	120156.0
4	3	254.2660	25.82634	9.84522	<.0001*	54822.5	40790.0	68729.0
2	1	242.2710	25.82634	9.38077	<.0001*	53490.0	39142.0	67887.0
3	2	235.5130	25.82634	9.11910	<.0001*	51150.5	36996.0	65354.0

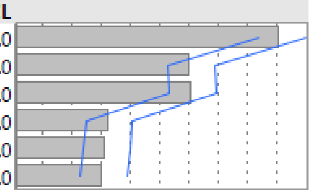
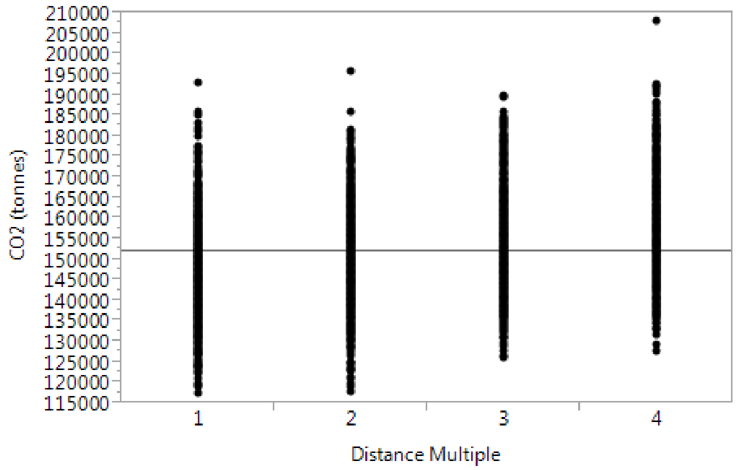


Figure Q.3 Statistical comparison of *n* = 1,000 Monte Carlo simulated data sets of total embodied energy for Deep Soil Mixing at LPV 111 with different material haul distances.

Oneway Analysis of CO2 (tonnes) By Distance Multiple



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
1	1000	1463490	2000500	1463.49	-16.980
2	1000	1777514	2000500	1777.51	-7.051
3	1000	2167186	2000500	2167.19	5.270
4	1000	2593811	2000500	2593.81	18.760

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
538.2945	3	<.0001*

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*	Alpha
2.56903	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
4	1	548.1180	25.82634	21.22321	<.0001*	12266.00	10907.00	13620.00
4	2	411.9260	25.82634	15.94984	<.0001*	8908.00	7540.00	10262.00
3	1	358.8940	25.82634	13.89643	<.0001*	7498.00	6162.00	8834.00
4	3	226.5750	25.82634	8.77302	<.0001*	4758.00	3380.00	6136.00
3	2	201.0520	25.82634	7.78476	<.0001*	4124.00	2773.00	5479.00
2	1	167.0060	25.82634	6.46650	<.0001*	3364.00	2030.00	4693.00

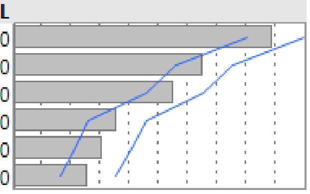


Figure Q.4 Statistical comparison of *n* = 1,000 Monte Carlo simulated data sets of total CO_2 emissions for Deep Soil Mixing at LPV 111 with different material haul distances.

The raw data from the Monte Carlo simulations for different material haul distances for DSM at LPV 111 is included in Table Q.8. The table extends for 28 pages to present all 1,000 simulated data values.

Table Q.8 Monte Carlo simulated data for different material haul distances for Deep Soil Mixing at LPV 111.

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
1	1,239,180	159,665	1,213,755	139,962	1,413,112	150,472	1,401,599	163,574
2	1,103,995	135,429	1,177,033	140,080	1,597,277	170,653	1,317,390	161,827
3	1,310,942	141,065	1,089,916	161,823	1,457,290	159,396	1,358,547	140,545
4	1,193,894	165,336	1,235,347	158,241	1,149,414	164,348	1,370,399	168,851
5	1,358,512	146,390	1,127,028	146,200	1,444,821	141,057	1,288,416	167,141
6	1,062,624	156,666	1,272,944	153,536	1,161,859	142,572	1,267,764	171,729
7	1,164,404	144,625	1,220,174	139,572	1,303,817	165,786	1,518,805	153,842
8	1,194,402	131,816	1,082,833	139,309	1,228,283	143,431	1,311,661	161,223
9	1,084,145	147,188	1,179,475	143,133	1,135,765	141,821	1,371,148	180,344
10	1,401,909	136,905	1,196,346	141,590	1,321,328	153,265	1,453,967	157,527
11	1,173,090	143,542	944,648	143,208	1,274,428	153,158	1,364,581	167,861
12	1,137,499	152,223	1,136,760	152,830	1,314,902	161,857	1,479,592	164,470
13	1,029,237	138,762	1,290,937	132,063	1,290,070	151,108	1,184,769	135,076
14	1,176,744	147,205	1,070,841	157,303	1,208,606	150,725	1,405,301	167,143
15	1,188,253	145,681	1,197,284	149,181	1,126,642	159,471	1,290,453	156,588
16	1,119,772	147,112	1,253,407	144,323	1,245,005	153,233	1,229,927	156,723
17	1,252,824	167,214	1,050,729	119,947	1,422,048	161,260	1,422,528	163,996
18	1,229,775	154,974	1,172,271	151,201	1,379,700	155,216	1,176,962	173,577
19	1,313,235	153,700	981,578	156,766	1,134,575	136,982	1,434,702	153,344
20	985,405	139,295	1,189,580	152,903	1,276,600	157,744	1,419,826	161,296
21	1,032,196	142,120	1,119,599	147,193	1,388,208	151,145	1,297,077	140,868
22	1,238,254	137,230	1,251,991	149,946	1,282,723	139,717	1,272,665	157,827
23	1,240,569	143,790	1,212,603	141,388	1,204,240	151,561	1,303,052	187,179
24	1,236,216	120,823	1,058,953	159,496	1,256,184	146,780	1,166,747	174,430
25	981,718	144,162	1,290,854	161,631	1,077,297	178,796	1,300,657	161,294
26	1,080,663	131,430	1,232,373	128,897	1,295,780	165,722	1,162,946	170,917
27	1,380,526	145,463	1,386,216	174,638	1,201,433	138,653	1,243,125	163,625
28	1,154,873	127,152	1,267,042	163,542	1,416,866	145,504	1,294,575	169,558
29	1,119,649	142,262	1,257,728	171,903	1,298,698	160,091	1,403,943	167,413
30	1,328,422	142,719	1,173,463	134,260	1,343,069	166,146	1,307,064	158,030
31	1,138,996	152,276	1,288,883	142,894	1,418,969	161,489	1,430,029	157,265
32	1,181,468	156,900	1,274,910	161,484	1,192,930	146,299	1,183,337	169,377
33	1,211,922	146,734	1,152,068	154,644	1,351,232	162,519	1,342,640	162,337
34	988,883	155,179	1,290,445	161,862	1,345,043	165,628	1,507,046	152,940
35	1,091,672	148,188	1,127,918	168,337	1,379,402	141,965	1,316,282	162,472

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
36	1,274,904	141,371	1,407,843	136,320	1,490,731	155,496	1,343,766	166,877
37	1,445,650	139,598	1,198,707	161,101	1,252,180	151,554	1,603,745	179,970
38	1,157,946	147,735	1,081,868	142,103	1,265,725	162,614	1,391,777	143,274
39	1,348,022	152,781	1,195,756	155,669	1,222,076	155,161	1,268,449	147,647
40	1,213,219	147,562	1,065,774	172,188	1,662,612	164,890	1,456,689	148,293
41	950,121	159,932	1,183,675	134,433	1,307,550	158,039	1,348,589	166,688
42	1,391,753	141,781	1,168,413	164,348	1,185,581	149,044	1,565,588	156,832
43	1,118,029	148,649	1,061,884	143,976	1,140,504	157,917	1,286,786	153,689
44	1,404,671	146,349	1,116,742	155,904	1,351,284	150,795	1,220,409	146,391
45	988,139	141,675	1,172,596	149,745	1,396,475	145,835	1,275,102	166,692
46	1,106,137	148,588	1,312,864	132,182	1,246,643	157,960	1,158,642	141,435
47	1,209,466	137,882	1,343,825	148,702	1,227,868	168,175	1,256,332	149,563
48	1,103,403	140,416	1,028,955	174,176	1,254,941	167,313	1,182,214	151,901
49	1,284,786	157,315	1,318,699	146,987	1,641,916	141,745	1,197,181	168,046
50	1,095,706	144,810	1,143,609	151,040	1,503,222	161,440	1,077,618	170,574
51	1,290,965	156,870	1,195,025	148,221	1,280,467	182,378	1,355,255	156,494
52	1,299,643	147,271	982,026	151,686	1,304,620	138,426	1,423,262	150,479
53	1,061,898	122,804	1,024,604	136,457	1,375,407	134,858	1,157,863	157,418
54	1,012,299	146,645	1,166,388	144,068	1,670,455	145,530	1,264,815	160,608
55	1,173,955	146,981	1,259,494	176,670	1,266,377	143,716	1,201,166	151,771
56	1,165,483	144,952	1,321,339	148,513	1,521,885	149,068	1,384,719	149,694
57	1,369,870	138,768	1,282,283	156,610	1,300,429	141,938	1,261,916	147,302
58	1,146,597	138,191	1,315,116	139,708	1,298,231	160,852	1,385,330	180,649
59	1,090,317	139,203	1,370,116	151,035	1,231,483	137,895	1,403,259	159,753
60	1,057,164	137,774	1,354,883	179,141	1,409,927	175,535	1,474,993	145,365
61	1,331,788	133,106	1,444,989	168,336	1,117,632	163,885	1,463,388	164,405
62	1,172,801	139,968	1,389,743	174,565	1,232,757	143,144	1,383,093	146,775
63	1,104,937	140,507	1,353,064	131,045	1,511,124	161,899	1,267,739	192,395
64	1,294,266	127,940	1,288,697	175,495	1,311,371	163,264	1,322,540	139,341
65	1,050,540	140,897	1,212,328	146,905	1,194,299	148,540	1,335,669	162,663
66	1,034,209	150,681	1,316,176	176,575	1,348,809	146,538	1,351,984	159,506
67	1,255,431	154,430	1,000,560	148,937	1,297,697	160,188	1,450,204	147,930
68	981,598	130,532	1,382,897	159,159	1,284,117	151,219	1,312,956	152,483
69	1,273,291	177,051	1,111,342	151,370	1,463,369	147,523	1,420,791	155,702
70	1,221,181	117,238	1,399,040	149,343	1,274,568	152,438	1,219,401	172,888
71	1,116,612	166,847	1,270,238	131,634	1,083,831	166,092	1,263,971	149,106
72	1,004,850	152,590	1,030,437	180,967	1,228,924	154,286	1,459,436	171,122

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
73	1,141,944	131,593	965,474	141,195	1,217,272	133,690	1,652,936	129,175
74	1,013,607	143,700	1,288,913	175,785	1,438,581	143,978	1,125,782	165,349
75	1,140,673	155,341	1,210,378	144,884	1,298,502	145,242	1,386,363	132,991
76	1,009,841	167,103	1,476,003	141,533	1,588,340	170,295	1,323,894	180,249
77	1,623,517	146,764	1,175,060	140,679	1,191,162	161,115	1,370,769	160,068
78	1,037,967	136,251	1,125,145	154,893	1,488,017	166,233	1,362,391	168,526
79	894,267	173,699	1,336,280	141,166	1,266,605	170,610	1,128,441	155,165
80	1,079,008	142,692	1,320,225	157,700	1,272,409	163,422	1,504,703	145,012
81	1,257,497	142,754	1,244,612	141,147	1,388,849	138,262	1,352,661	148,762
82	1,301,371	154,764	1,184,900	152,088	1,450,916	143,871	1,476,723	164,670
83	1,281,252	146,507	1,253,074	142,400	1,266,528	163,773	1,331,186	143,172
84	1,290,434	137,706	1,116,661	135,480	1,196,340	152,835	1,400,374	190,287
85	1,082,596	146,435	1,310,689	146,737	1,252,201	174,226	1,242,587	207,867
86	950,495	158,638	1,188,618	128,071	1,250,658	145,962	1,434,135	163,698
87	1,133,364	160,936	1,247,810	162,651	1,202,146	155,101	1,433,319	167,004
88	963,037	135,843	1,318,257	150,209	1,361,437	142,430	1,341,433	169,352
89	1,148,039	137,860	1,355,737	140,688	1,464,620	154,951	1,173,844	171,719
90	1,263,345	143,594	1,094,110	145,162	1,269,542	163,182	1,384,045	146,593
91	1,162,510	150,646	1,140,665	153,636	1,313,816	131,027	1,550,757	142,644
92	1,154,944	155,559	1,260,489	139,271	1,458,833	168,609	1,243,387	163,608
93	1,426,148	150,657	1,338,805	151,925	1,326,935	148,788	1,357,721	169,543
94	1,095,208	140,831	1,164,274	134,789	1,244,647	158,222	1,242,920	162,503
95	1,102,516	123,550	1,582,780	147,732	1,350,992	162,549	1,409,863	145,082
96	994,188	152,647	1,206,687	137,025	1,318,049	161,102	1,308,725	153,375
97	1,166,461	145,675	1,223,565	148,458	1,510,044	178,359	1,026,415	160,795
98	932,601	162,005	1,062,070	171,488	1,321,042	148,108	1,310,770	134,503
99	1,059,086	157,052	1,349,434	137,554	1,306,409	162,190	1,076,571	163,386
100	1,348,492	140,705	1,274,816	138,800	1,181,293	149,914	1,286,707	149,577
101	1,038,836	157,172	1,105,503	143,216	1,172,282	163,934	1,273,493	156,697
102	1,217,193	141,111	1,154,483	133,656	1,288,013	149,454	1,240,733	185,738
103	1,165,018	143,026	1,685,541	146,577	1,219,410	165,214	1,206,523	181,496
104	1,058,254	136,812	1,165,126	158,648	1,644,277	153,297	1,194,398	153,999
105	1,047,467	164,111	1,300,832	147,345	1,347,898	162,383	1,239,283	163,917
106	1,022,000	146,984	1,244,139	166,267	1,486,268	177,197	1,201,602	167,271
107	1,661,061	129,447	1,231,312	160,019	1,328,355	145,134	1,489,199	167,652
108	1,248,091	155,547	1,107,419	145,763	1,234,583	135,745	1,486,112	131,273
109	1,087,667	158,564	1,475,423	129,645	1,259,334	140,583	1,353,125	182,001

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
110	1,074,681	153,366	1,398,837	163,171	1,124,099	129,517	1,382,535	157,045
111	1,166,737	131,641	1,109,512	144,471	1,196,554	142,649	1,251,079	162,317
112	1,175,373	139,752	1,155,351	178,263	1,026,659	167,574	1,454,635	139,192
113	1,023,717	137,239	1,138,280	155,333	1,463,670	157,317	1,239,627	167,898
114	1,211,637	151,042	1,146,617	166,001	1,155,424	145,574	1,309,215	172,941
115	1,166,613	132,065	1,155,882	141,406	1,237,470	138,561	1,408,553	138,460
116	1,081,668	153,694	1,240,036	156,824	1,280,464	161,024	1,224,826	150,832
117	1,292,305	144,804	1,191,265	155,544	1,346,520	175,787	1,364,333	160,196
118	1,318,616	151,652	1,138,650	145,373	1,122,167	156,759	1,360,215	127,642
119	1,218,342	153,483	1,169,383	135,625	1,253,158	184,465	1,580,300	169,040
120	1,067,326	144,701	1,034,078	134,469	1,387,338	150,741	1,458,333	148,696
121	1,012,435	146,175	1,333,848	170,986	1,218,364	146,739	1,139,198	151,367
122	1,239,733	124,991	1,420,553	173,942	1,365,577	151,194	1,420,177	184,928
123	1,394,610	140,921	1,339,607	137,468	1,207,035	126,517	1,300,131	143,874
124	963,299	144,795	1,363,363	136,587	1,528,662	165,218	1,543,305	166,021
125	1,483,898	145,401	1,219,222	144,284	1,355,328	149,102	1,356,880	150,166
126	1,433,186	124,629	1,075,736	159,562	1,354,556	156,521	1,312,437	151,907
127	1,059,999	155,118	1,071,370	169,740	1,415,164	153,676	1,338,185	165,360
128	1,166,930	150,883	1,012,373	147,502	1,534,637	145,076	1,262,819	139,735
129	1,109,021	136,631	1,267,264	134,117	1,032,202	153,928	1,260,864	158,235
130	1,382,972	151,202	1,345,209	147,390	1,213,324	163,713	1,303,714	134,479
131	1,496,393	152,198	1,085,884	149,711	1,326,401	142,865	1,359,255	157,580
132	1,090,963	144,223	1,125,690	151,455	1,224,993	160,593	1,332,041	172,799
133	1,314,594	151,833	996,276	152,277	1,281,721	149,794	1,279,523	164,209
134	1,277,035	132,223	1,249,461	168,946	1,160,605	159,548	1,450,189	163,179
135	1,106,151	147,793	1,243,806	136,592	1,396,872	160,198	1,413,348	156,249
136	1,005,091	154,943	1,074,376	147,267	1,106,398	180,075	1,264,279	149,065
137	1,131,868	130,895	1,084,246	133,858	1,390,223	152,644	1,318,053	156,795
138	1,202,299	168,182	1,320,301	165,040	1,110,439	147,649	1,289,935	156,067
139	1,232,972	146,801	1,353,174	153,162	1,205,369	135,742	1,411,406	173,853
140	1,138,701	141,699	1,243,564	143,196	1,248,099	138,827	1,577,727	166,029
141	1,141,673	135,037	1,292,902	158,592	1,199,439	141,406	1,517,774	153,055
142	1,265,811	167,427	1,088,395	152,321	1,192,553	148,666	1,433,080	160,973
143	1,053,432	140,271	1,384,567	195,692	1,384,971	139,598	1,258,057	162,263
144	1,242,603	152,612	1,159,756	147,225	1,620,284	155,847	1,253,626	172,638
145	1,246,310	149,868	1,229,879	139,901	1,304,160	145,186	1,368,462	180,129
146	1,224,384	157,980	1,150,451	146,343	1,336,751	135,407	1,368,289	153,633

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
147	1,232,304	131,287	1,019,258	167,689	1,107,994	152,525	1,483,107	146,147
148	1,039,409	143,808	1,215,496	148,258	1,359,948	155,723	1,460,520	159,782
149	1,241,057	155,693	1,100,306	145,093	1,380,481	156,356	1,360,228	150,715
150	1,374,858	146,488	1,088,000	160,668	1,258,073	140,039	1,261,842	155,063
151	1,167,511	153,448	1,128,805	181,637	1,230,002	148,171	1,288,603	161,294
152	961,728	165,068	1,259,091	142,155	1,157,600	169,719	1,222,433	157,308
153	1,129,939	149,614	1,138,609	142,527	1,226,775	149,402	1,442,853	150,328
154	1,010,998	131,362	1,010,905	164,274	1,272,552	162,100	1,208,583	154,859
155	1,243,403	127,332	1,249,089	157,277	1,272,272	165,346	1,345,068	149,447
156	1,220,138	152,107	1,301,218	166,152	1,299,321	138,365	1,387,107	167,622
157	1,231,768	144,317	1,157,253	161,434	1,237,518	164,951	1,322,007	149,483
158	1,019,487	127,875	1,246,087	145,177	1,416,781	146,544	1,261,670	152,769
159	1,205,930	149,482	962,101	120,961	1,290,903	147,567	1,351,481	165,631
160	1,072,065	154,314	1,338,377	162,575	1,319,581	143,997	1,240,242	176,929
161	1,217,149	132,271	1,137,016	153,218	1,161,430	184,738	1,421,072	159,552
162	1,281,397	141,592	1,163,417	144,415	1,560,688	168,327	1,630,387	151,446
163	1,131,098	144,383	1,073,206	148,884	1,226,649	179,132	1,261,248	156,597
164	1,157,085	129,115	1,187,782	143,875	1,251,815	153,858	1,237,070	161,581
165	1,112,288	147,910	1,184,576	136,001	1,372,043	163,334	1,609,974	168,776
166	1,059,797	151,403	1,528,045	144,871	1,395,813	165,807	1,611,055	192,013
167	1,201,728	142,871	1,493,009	161,402	1,235,334	163,990	1,271,029	157,727
168	1,124,422	141,351	1,034,112	148,010	1,159,915	189,582	1,269,816	151,560
169	1,525,128	167,580	1,284,337	137,348	1,212,767	149,008	1,284,659	155,984
170	1,277,609	144,297	1,222,816	141,954	1,218,938	149,054	1,389,514	155,328
171	1,272,551	158,530	1,273,995	154,396	1,263,197	158,707	1,127,855	152,646
172	1,358,040	149,232	1,116,592	158,474	1,193,442	144,244	1,476,918	139,662
173	1,203,298	161,440	1,161,376	150,953	1,452,387	166,138	1,355,016	174,963
174	1,155,670	143,650	1,113,915	147,909	1,346,524	164,264	1,328,628	157,817
175	1,158,871	154,249	1,262,932	146,102	1,245,021	163,413	1,157,868	171,228
176	1,278,064	136,371	1,321,106	157,155	1,358,635	131,339	1,379,102	151,867
177	1,000,317	127,461	1,362,448	149,074	1,412,519	169,299	1,150,068	151,240
178	1,020,037	137,577	1,319,743	159,546	1,523,866	142,393	1,356,617	157,628
179	1,233,839	166,174	1,053,833	130,630	1,220,262	143,990	1,265,767	139,797
180	1,047,644	152,481	1,106,000	141,287	1,200,494	148,390	1,239,510	147,913
181	1,058,069	156,630	1,524,857	157,914	1,470,473	162,157	1,416,720	186,297
182	1,238,718	130,959	1,345,538	155,341	1,212,639	140,717	1,548,620	144,757
183	1,056,445	133,466	1,222,262	144,334	1,219,068	141,481	1,413,557	143,861

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
184	1,390,478	134,730	1,048,904	160,170	1,338,900	158,693	1,373,166	188,185
185	1,264,609	165,420	1,195,907	179,601	1,218,508	165,887	1,373,521	154,344
186	1,189,501	143,096	1,232,395	156,949	1,361,710	138,845	1,644,759	165,046
187	1,243,567	155,552	1,093,456	163,311	1,159,406	152,135	1,088,385	149,779
188	1,071,087	159,562	1,004,267	168,223	1,185,683	152,687	1,177,254	168,900
189	1,271,651	153,125	1,155,610	158,774	1,537,121	151,049	1,217,927	171,837
190	1,249,015	133,213	1,193,231	168,351	1,181,595	173,032	1,417,149	156,824
191	1,190,574	137,813	1,111,294	139,073	1,176,287	158,939	1,215,201	150,656
192	1,134,565	151,921	1,146,076	135,917	1,136,824	144,349	1,353,679	145,993
193	1,207,727	152,088	1,139,134	144,161	1,195,681	156,744	1,171,059	145,158
194	1,053,588	155,261	1,146,413	155,183	1,299,449	140,119	1,083,145	142,385
195	1,170,400	151,683	1,183,828	150,503	1,216,108	164,735	1,200,441	158,556
196	957,928	148,596	1,203,073	162,936	1,294,839	146,858	1,207,373	176,051
197	1,182,275	131,790	1,109,412	155,506	1,209,026	148,507	1,089,315	164,846
198	1,184,039	136,314	1,321,554	146,923	1,289,287	143,920	1,213,937	178,444
199	1,147,291	138,623	1,209,273	155,178	1,271,591	171,618	1,172,250	163,437
200	1,219,333	133,367	1,164,148	155,733	1,248,631	148,641	1,592,729	174,002
201	1,186,582	152,514	1,274,515	156,411	1,312,716	152,489	1,356,661	175,682
202	1,199,368	153,495	1,271,558	181,632	1,329,264	141,074	1,385,873	158,462
203	1,176,757	141,836	1,188,721	163,719	1,174,061	142,239	1,154,869	168,308
204	979,898	128,849	1,291,438	166,808	1,235,702	153,380	1,369,523	179,783
205	1,060,237	129,911	1,205,254	164,124	1,299,996	168,723	1,495,807	161,909
206	1,200,326	149,695	1,206,123	135,556	1,227,266	171,876	1,380,783	176,404
207	1,280,352	148,647	1,140,054	169,408	1,222,998	166,764	1,317,006	153,719
208	1,246,107	151,887	1,123,477	180,387	1,136,930	147,226	1,428,192	163,088
209	1,088,026	152,190	1,179,264	146,590	1,301,632	161,070	1,509,482	156,339
210	1,197,173	147,050	1,109,554	159,083	1,204,886	143,794	1,236,417	176,432
211	1,144,365	132,797	1,306,189	158,573	1,084,481	134,295	1,307,124	183,904
212	1,131,469	138,241	1,240,665	135,840	1,288,182	153,364	1,601,529	147,099
213	1,121,085	151,648	1,057,058	135,949	1,483,907	148,186	1,230,000	138,494
214	1,110,642	124,117	1,219,968	154,942	1,316,681	146,210	1,367,177	146,483
215	1,167,031	150,668	1,267,446	151,444	1,440,489	151,303	1,252,109	150,116
216	1,054,550	146,027	1,311,931	166,145	1,192,887	151,870	1,356,345	171,269
217	1,246,343	160,404	1,341,253	149,330	1,243,416	136,004	1,260,887	167,792
218	1,132,661	135,779	1,225,598	140,136	1,284,226	181,167	1,122,357	157,503
219	1,152,924	148,214	1,021,916	164,475	1,273,381	147,093	1,603,012	153,515
220	1,331,299	147,182	1,052,432	160,928	1,220,590	138,848	1,524,744	169,853

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
221	1,146,923	149,959	1,038,182	148,738	1,486,786	144,727	1,372,557	152,536
222	1,456,851	161,785	1,346,313	149,377	1,326,924	163,718	1,199,911	162,635
223	1,371,751	141,394	1,253,319	135,920	1,336,963	138,235	1,137,818	158,677
224	1,146,245	157,415	945,705	135,257	1,613,632	144,887	1,204,619	147,460
225	1,107,233	129,288	1,391,597	140,511	1,245,203	155,091	1,318,501	177,263
226	1,197,588	123,872	1,142,109	146,753	1,285,618	151,809	1,389,875	162,947
227	1,194,268	167,244	1,166,296	149,887	1,185,528	154,245	1,541,356	165,416
228	1,329,695	156,811	1,099,250	150,262	1,492,128	147,187	1,524,219	157,344
229	1,023,931	148,682	1,256,410	168,799	1,262,872	136,082	1,230,883	157,728
230	1,282,715	149,014	1,339,018	133,271	1,459,216	150,036	1,275,343	159,829
231	1,042,561	142,497	1,254,872	160,246	1,114,027	158,013	1,132,550	156,441
232	1,210,760	143,129	1,083,899	141,609	1,393,035	144,706	1,414,935	147,412
233	1,075,735	146,245	1,157,872	144,844	1,333,560	149,142	1,609,986	157,403
234	1,263,820	162,507	1,111,110	135,701	1,210,065	153,045	1,265,073	156,011
235	1,188,073	151,308	1,408,825	145,522	1,349,353	141,665	1,274,672	143,450
236	1,303,056	164,972	1,242,599	157,350	1,148,325	173,915	1,319,441	147,109
237	1,134,542	136,681	1,362,110	144,641	1,157,262	155,076	1,333,872	147,723
238	1,077,924	152,368	1,018,102	140,891	1,184,889	145,602	1,054,511	159,756
239	1,017,581	144,397	1,198,565	165,111	1,139,099	152,302	1,169,533	166,889
240	1,189,253	144,136	1,245,455	148,464	1,228,798	155,331	1,107,579	153,988
241	1,302,230	153,548	1,137,176	144,678	1,266,339	130,535	1,175,204	137,359
242	1,040,083	123,635	1,267,525	147,694	1,158,568	143,317	1,327,317	152,748
243	1,159,617	140,492	1,124,951	151,794	1,274,941	147,585	1,446,414	172,046
244	1,240,245	153,064	1,215,373	149,835	1,304,514	163,290	1,339,417	150,750
245	1,036,186	137,650	969,303	145,897	1,304,859	156,936	1,487,366	167,258
246	1,290,466	162,181	1,225,062	150,791	1,269,612	164,250	1,477,418	154,590
247	1,268,488	149,882	1,325,373	167,987	1,263,235	160,786	1,407,542	163,085
248	1,077,296	166,218	1,217,636	137,667	1,234,252	175,856	1,322,922	181,373
249	1,258,769	142,669	1,308,646	139,415	1,268,820	145,022	1,301,695	140,730
250	1,108,759	153,229	1,167,555	166,463	1,296,812	150,554	1,461,713	152,616
251	1,170,823	154,899	1,111,871	151,466	1,249,503	162,286	1,335,207	168,198
252	1,060,072	127,255	1,312,214	148,207	1,359,734	129,626	1,222,275	172,069
253	1,030,599	140,686	1,221,139	153,619	1,253,960	138,789	1,263,144	157,219
254	1,095,997	168,205	1,083,033	162,339	1,336,569	160,128	1,455,083	171,991
255	1,222,601	138,440	1,409,969	149,616	1,373,084	142,058	1,288,113	147,863
256	1,411,964	159,596	1,184,857	149,553	1,438,918	165,034	1,467,412	155,119
257	1,115,761	137,535	1,334,127	151,219	1,185,219	154,982	1,386,642	153,062

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
258	1,371,376	158,665	1,219,093	128,978	1,249,504	141,911	1,284,901	138,171
259	1,432,938	140,981	1,334,774	148,697	1,429,181	168,307	1,263,603	160,706
260	1,090,288	127,516	1,256,709	149,825	1,240,265	140,335	1,198,553	144,789
261	1,107,770	164,739	1,052,295	147,156	1,200,781	148,630	1,397,423	150,103
262	1,094,114	131,512	1,216,958	129,894	1,395,319	138,741	1,315,550	150,129
263	1,163,051	139,835	1,112,394	166,840	1,395,771	155,048	1,155,133	164,512
264	1,163,357	141,297	1,260,270	156,440	1,176,011	154,546	1,339,087	173,078
265	1,228,566	138,064	1,117,802	139,972	1,368,587	147,753	1,300,054	166,320
266	1,236,932	145,287	1,053,549	162,040	1,295,532	157,464	1,324,389	151,348
267	1,266,493	127,970	1,318,461	146,939	1,331,180	146,716	1,259,464	155,293
268	1,147,648	154,699	1,256,498	139,665	1,250,522	182,769	1,252,574	154,706
269	1,320,970	132,671	1,259,954	148,360	1,058,719	148,535	1,485,432	152,280
270	1,142,716	147,666	1,181,265	147,915	1,361,982	169,360	1,351,218	150,254
271	1,173,035	149,758	1,252,838	144,384	1,370,406	160,994	1,406,465	154,087
272	1,145,577	122,165	1,281,375	154,101	1,155,578	145,091	1,264,511	152,377
273	1,084,948	150,193	1,462,079	133,511	1,109,265	154,959	1,144,106	161,534
274	1,422,396	160,295	1,282,312	146,203	1,461,193	140,228	1,456,556	163,412
275	1,162,206	167,408	1,283,257	162,270	1,524,323	150,607	1,309,705	158,454
276	1,050,898	129,331	1,307,417	166,001	1,320,234	145,298	1,371,902	151,634
277	933,183	152,413	1,292,309	142,023	1,173,443	165,261	1,355,680	162,378
278	1,305,968	157,679	1,524,844	162,576	1,562,635	153,566	1,339,997	161,128
279	1,180,176	160,932	1,174,381	148,384	1,405,099	160,096	1,480,986	150,515
280	1,141,437	168,388	1,420,001	154,358	1,256,406	173,815	1,291,424	168,636
281	1,278,238	147,010	1,378,107	139,695	1,157,656	168,172	1,344,970	176,234
282	1,084,536	136,662	1,118,472	148,667	1,512,835	177,858	1,415,011	146,523
283	1,210,314	133,601	1,135,290	147,358	1,254,087	140,750	1,583,355	167,077
284	1,076,867	163,393	1,191,036	149,414	1,169,645	158,866	1,095,934	168,269
285	1,219,777	140,040	1,088,289	160,184	1,475,976	154,161	1,129,686	149,633
286	1,467,805	155,011	1,079,664	148,006	1,120,439	143,043	1,121,902	154,467
287	972,328	158,383	1,028,341	147,329	1,028,619	151,171	1,627,881	155,616
288	1,140,658	147,653	1,269,388	141,614	1,208,385	152,298	1,240,334	152,363
289	1,159,099	155,850	1,228,239	150,936	1,164,902	144,191	1,284,715	175,663
290	1,044,549	138,313	1,166,246	151,791	1,372,833	162,632	1,367,066	136,180
291	1,144,535	161,847	1,513,516	135,308	1,129,180	156,807	1,307,408	165,696
292	1,051,144	137,643	1,251,372	134,122	1,253,292	141,767	1,283,803	158,140
293	1,220,193	143,298	1,310,444	145,852	1,253,926	166,712	1,270,251	151,422
294	1,133,011	135,152	1,323,301	161,980	1,258,619	143,170	1,302,930	176,377

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
295	989,502	137,938	1,489,951	158,225	1,097,007	151,080	1,421,970	167,841
296	1,134,768	135,705	1,168,545	132,647	1,468,770	144,784	1,479,231	165,481
297	1,387,789	165,972	1,406,110	156,302	1,416,775	158,531	1,462,136	160,667
298	1,022,604	150,307	1,076,426	166,043	1,188,908	136,924	1,235,486	179,503
299	1,118,096	139,481	1,152,186	157,875	1,152,432	175,642	1,198,663	145,320
300	1,316,704	145,857	1,109,501	134,068	1,188,473	155,711	1,320,157	157,687
301	1,060,994	141,335	1,465,569	146,810	1,356,834	166,799	1,280,882	153,964
302	1,444,319	133,330	1,121,562	170,166	1,258,788	148,717	1,362,474	165,243
303	1,437,837	141,118	988,100	151,657	1,237,733	158,890	1,552,647	146,533
304	1,153,953	144,606	1,041,493	142,302	1,179,227	164,309	1,171,492	157,172
305	1,252,689	158,926	1,095,662	135,948	1,243,763	150,607	1,142,883	153,876
306	957,259	143,369	1,225,350	176,496	1,312,149	172,945	1,372,600	161,563
307	1,334,037	151,964	1,196,897	152,479	1,478,015	172,556	1,156,030	142,917
308	1,208,332	164,021	1,253,959	158,339	1,292,886	147,619	1,457,712	151,766
309	1,358,786	140,447	1,175,483	153,229	1,117,717	145,061	1,507,892	133,324
310	1,169,169	152,397	1,198,869	137,363	1,349,059	164,453	1,450,346	157,155
311	1,333,700	127,692	1,013,464	139,444	1,192,176	164,407	1,190,297	162,208
312	1,189,809	162,733	1,171,509	152,481	1,217,490	135,935	1,364,671	155,881
313	1,062,083	125,569	1,138,800	154,798	1,587,584	154,029	1,262,571	152,968
314	1,153,931	133,323	1,426,431	136,163	1,090,432	160,008	1,198,364	174,803
315	1,360,948	126,820	1,067,506	145,624	1,282,165	141,637	1,257,931	167,941
316	1,158,122	149,729	1,078,408	157,104	1,237,690	141,025	1,419,915	159,991
317	1,164,096	145,169	1,041,803	153,763	1,453,498	189,803	1,517,430	153,523
318	1,048,451	146,064	1,006,525	131,450	1,277,463	151,192	1,389,365	142,404
319	1,129,021	140,205	1,309,284	164,990	1,152,045	148,096	1,481,053	169,921
320	1,384,625	165,308	1,020,353	150,037	1,397,383	151,770	1,251,705	173,061
321	1,146,026	141,879	965,617	142,637	1,589,825	163,371	1,517,684	153,452
322	1,393,775	131,883	1,293,490	156,106	1,107,155	142,788	1,391,765	155,276
323	1,067,834	143,885	1,119,559	146,835	1,412,396	161,778	1,372,724	156,796
324	1,134,339	146,476	1,211,060	158,046	1,286,665	133,940	1,197,937	149,495
325	1,165,710	148,362	1,022,062	161,835	1,323,399	155,455	1,166,177	147,932
326	999,956	148,486	1,187,154	131,209	1,131,949	155,091	1,395,918	159,336
327	1,187,857	143,501	1,164,338	141,906	1,225,993	160,387	1,166,170	145,880
328	1,193,836	147,511	1,174,077	132,271	1,464,430	145,484	1,697,885	144,262
329	1,146,513	138,767	1,101,280	165,735	1,197,000	147,450	1,153,941	133,133
330	1,147,260	155,405	1,148,010	163,033	1,171,652	159,853	1,380,577	167,990
331	1,027,351	130,684	1,119,226	131,829	1,331,690	158,584	1,441,270	147,409

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
332	1,061,429	129,475	1,398,397	144,176	1,367,836	139,483	1,312,743	157,251
333	1,179,328	157,062	1,350,378	142,828	1,311,888	155,793	1,377,884	160,615
334	1,011,920	140,952	1,092,885	153,273	1,383,617	140,125	1,227,099	173,934
335	1,274,152	136,605	1,145,074	155,123	1,302,801	162,338	1,364,330	153,867
336	1,238,112	161,258	1,196,233	174,398	1,219,690	160,111	1,321,537	144,122
337	1,167,948	154,357	1,222,910	175,213	1,245,253	160,402	1,377,428	166,463
338	1,011,115	141,278	1,317,670	137,062	1,238,061	162,461	1,293,148	151,110
339	1,095,795	164,901	1,212,674	149,637	1,310,312	162,015	1,417,991	180,682
340	1,156,621	160,893	1,305,207	146,377	1,263,359	146,250	1,388,668	160,625
341	1,498,616	154,897	1,283,527	164,151	1,349,513	152,109	1,181,991	149,872
342	1,343,397	119,666	1,252,050	143,729	1,509,067	164,565	1,282,580	150,746
343	1,166,787	158,211	1,331,447	145,349	1,504,027	133,244	1,688,491	154,824
344	1,027,400	181,745	1,369,933	148,486	1,351,953	128,947	1,398,455	164,895
345	1,154,113	142,735	1,239,943	138,717	1,282,460	152,833	1,263,758	177,009
346	1,150,677	143,206	1,156,036	142,119	1,299,898	166,549	1,291,931	176,585
347	1,119,352	141,910	1,172,008	167,629	1,149,270	145,313	1,263,867	174,784
348	1,093,366	147,334	1,283,378	143,900	1,232,585	141,698	1,303,818	171,642
349	1,161,568	151,317	1,253,497	138,870	1,102,933	139,451	1,334,548	146,389
350	1,301,481	146,587	1,300,266	133,109	1,425,377	156,731	1,569,201	169,789
351	1,184,060	145,964	1,189,548	152,145	1,237,531	155,620	1,285,846	150,203
352	1,120,334	164,260	1,256,373	165,652	1,300,585	163,804	1,133,072	167,516
353	1,338,779	140,101	1,211,438	146,839	1,210,514	135,154	1,332,073	140,612
354	1,160,379	165,260	1,145,833	134,524	1,340,583	160,841	1,577,277	162,172
355	1,054,015	128,838	1,300,434	140,171	1,217,860	167,482	1,309,657	145,434
356	1,059,741	160,941	1,093,596	153,012	1,100,132	156,659	1,221,984	154,696
357	1,236,835	128,871	1,239,928	157,390	1,190,700	151,553	1,246,812	171,495
358	1,105,909	140,715	1,255,166	160,259	1,379,182	150,132	1,338,778	151,429
359	1,264,462	155,447	1,420,558	133,592	1,248,903	157,703	1,429,084	154,329
360	1,146,647	149,671	1,124,312	144,905	1,209,760	155,761	1,357,676	149,025
361	1,159,211	124,084	1,140,274	137,412	1,239,649	153,246	1,343,493	163,389
362	1,314,515	135,473	1,188,159	123,298	1,304,699	179,596	1,332,305	162,970
363	1,188,074	157,653	1,076,268	172,069	1,137,651	165,000	1,469,974	146,267
364	996,033	132,958	1,137,939	135,427	1,149,433	154,889	1,158,708	165,695
365	1,379,162	141,309	1,204,046	135,706	1,548,035	159,056	1,426,432	160,899
366	1,154,514	135,572	1,344,607	144,108	1,248,324	149,869	1,257,137	161,601
367	1,202,180	138,187	1,393,613	163,026	1,271,865	149,358	1,475,199	178,905
368	1,148,977	149,499	1,187,214	138,345	1,466,099	136,845	1,440,896	163,206

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
369	1,296,467	145,801	1,180,147	164,627	1,286,451	161,082	1,453,983	159,733
370	1,201,256	131,486	1,258,412	139,849	1,255,061	171,611	1,328,965	169,833
371	1,088,662	176,472	1,559,385	140,617	1,307,966	143,050	1,159,266	159,139
372	1,142,727	166,652	1,150,336	167,437	1,110,579	153,499	1,362,045	154,709
373	1,029,946	148,250	1,218,927	153,844	1,271,296	153,001	1,267,510	157,475
374	1,179,919	158,966	1,445,436	143,668	1,337,200	150,476	1,381,297	161,435
375	1,119,789	152,680	1,341,072	152,435	1,241,192	155,459	1,297,660	167,182
376	1,293,700	142,027	1,347,518	126,386	1,205,909	168,316	1,607,910	134,203
377	1,195,660	146,921	1,485,278	160,358	1,126,932	168,778	1,232,389	157,812
378	1,076,526	119,836	1,401,521	142,688	1,634,080	185,875	1,278,953	143,963
379	1,090,344	158,647	1,143,080	160,629	1,448,513	157,620	1,242,550	150,938
380	1,415,449	162,482	1,177,901	136,997	1,379,131	140,639	1,263,141	168,120
381	1,380,286	144,533	1,271,082	171,048	1,290,527	159,612	1,135,376	158,605
382	1,461,526	142,132	1,233,899	162,018	1,224,844	152,408	1,181,792	168,340
383	1,100,384	143,482	1,141,373	156,031	1,342,023	156,853	1,147,856	151,645
384	1,333,267	146,925	1,110,725	151,902	1,183,928	160,391	1,469,780	155,369
385	1,111,836	159,348	1,447,029	136,827	1,194,163	133,593	1,231,364	151,628
386	1,082,507	143,287	1,395,801	154,148	1,212,617	169,256	1,166,704	157,002
387	1,077,781	155,532	1,247,439	153,022	1,230,697	169,286	1,263,363	160,183
388	1,373,067	150,164	1,089,997	161,932	1,045,691	142,784	1,263,960	181,575
389	1,110,625	146,225	1,143,518	147,402	1,382,293	156,098	1,392,598	160,219
390	1,192,058	161,342	1,233,261	133,854	1,282,178	155,683	1,277,089	160,744
391	1,226,191	139,696	1,310,813	152,780	1,144,493	179,937	1,446,797	171,601
392	1,325,250	144,969	1,357,080	154,740	1,342,089	157,080	1,257,104	166,656
393	1,162,273	154,302	1,232,654	150,951	1,380,898	142,394	1,374,723	150,602
394	1,055,162	135,796	1,250,832	142,506	1,175,202	154,505	1,353,257	169,068
395	1,262,628	144,903	1,141,079	128,642	1,529,159	166,825	1,455,540	136,605
396	1,385,061	148,483	1,124,182	161,105	1,254,923	143,680	1,222,590	177,195
397	1,028,703	171,399	1,115,383	156,760	1,279,275	148,560	1,413,692	160,607
398	934,699	147,703	1,327,085	155,071	1,148,124	175,936	1,403,417	170,893
399	1,051,015	144,625	1,140,441	139,328	1,161,648	152,842	1,125,195	179,761
400	1,155,512	127,523	1,039,340	142,105	1,606,236	144,805	1,315,277	142,889
401	1,243,637	141,009	1,623,004	136,163	1,024,261	160,075	1,178,379	158,355
402	1,148,012	134,636	1,140,282	140,073	1,398,548	166,627	1,676,566	163,941
403	1,189,563	158,713	1,301,346	151,077	1,082,705	151,233	1,249,476	162,479
404	1,011,388	133,535	1,395,999	141,659	1,290,595	152,538	1,388,540	156,624
405	1,167,809	145,649	1,544,468	155,886	1,158,891	177,715	1,335,764	173,070

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
406	1,157,148	143,198	1,315,384	141,203	1,084,002	156,197	1,534,004	140,595
407	1,184,363	138,842	1,036,891	138,631	1,392,298	138,671	1,322,285	171,942
408	1,021,693	162,900	1,193,868	155,188	1,206,565	173,481	1,395,627	169,243
409	1,086,593	124,513	1,090,517	149,451	1,346,358	156,605	1,384,849	158,085
410	1,092,561	128,587	1,455,742	170,631	1,166,761	140,574	1,298,965	157,066
411	1,087,882	129,384	1,300,129	138,573	1,183,881	144,714	1,463,910	150,007
412	1,233,450	147,612	1,232,319	148,322	1,209,493	154,090	1,491,508	148,805
413	1,280,821	143,526	1,144,380	148,380	1,104,336	152,206	1,175,504	165,580
414	1,478,670	157,550	1,419,990	164,165	1,359,991	154,975	1,232,413	172,381
415	1,061,613	139,992	1,534,256	141,592	1,367,716	162,184	1,404,949	178,574
416	1,077,728	137,559	1,051,737	141,475	1,091,145	142,451	1,243,652	156,069
417	1,196,262	158,872	1,185,142	148,833	1,309,834	167,909	1,360,641	148,195
418	1,112,053	182,942	1,099,878	169,496	1,448,023	143,353	1,183,448	160,347
419	964,779	147,798	1,170,184	152,792	1,103,430	139,705	1,379,289	150,564
420	1,189,556	151,673	1,204,437	140,883	1,222,406	155,146	1,265,017	162,793
421	1,473,971	141,694	1,365,362	150,174	1,296,437	162,961	1,153,621	183,278
422	1,151,365	151,985	1,225,563	167,444	1,273,744	164,595	1,350,283	159,620
423	1,075,310	146,502	1,284,570	156,363	1,673,910	159,795	1,194,088	169,356
424	1,146,362	159,293	1,080,979	156,977	1,340,296	164,779	1,274,997	160,723
425	1,288,323	165,816	1,422,533	133,144	1,340,901	167,537	1,286,660	152,581
426	1,009,390	161,897	1,576,096	135,514	1,143,194	156,285	1,291,065	159,697
427	1,332,591	160,400	1,174,614	147,967	1,327,198	140,310	1,208,974	158,917
428	1,289,176	142,962	1,456,104	147,755	1,277,903	158,212	1,563,967	161,128
429	1,100,225	147,460	1,170,846	147,404	1,266,795	167,256	1,335,012	137,560
430	1,054,487	146,995	1,135,975	148,311	1,115,806	145,726	1,267,081	146,935
431	1,351,311	141,718	1,452,965	154,619	1,105,826	167,036	1,229,728	165,613
432	1,434,638	138,551	1,188,695	147,948	1,194,417	140,983	1,362,207	156,764
433	1,022,943	161,205	1,298,356	142,130	1,192,619	154,704	1,294,652	149,049
434	1,312,519	152,697	1,185,986	149,672	1,221,596	137,216	1,037,295	143,129
435	1,490,079	150,701	1,176,651	146,339	1,261,013	149,910	1,395,393	157,167
436	1,264,920	132,508	1,247,585	151,684	1,186,138	158,870	1,262,750	145,352
437	1,351,286	163,221	1,117,868	150,888	1,151,101	155,903	1,344,545	167,069
438	1,081,418	155,614	1,202,674	128,768	1,163,768	157,317	1,223,088	171,002
439	1,276,634	148,229	1,236,031	144,107	1,314,209	160,890	1,293,668	157,783
440	1,289,147	141,967	1,113,311	138,197	1,407,627	172,855	1,249,595	180,451
441	1,381,798	137,563	1,332,857	133,667	1,185,033	165,112	1,371,731	160,516
442	1,174,001	127,842	1,286,853	137,729	1,101,192	161,517	1,296,766	156,577

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
443	1,218,072	134,864	1,465,516	146,612	1,297,538	152,136	1,340,833	152,499
444	1,039,801	143,962	1,140,023	142,091	1,247,787	178,481	1,164,559	165,172
445	1,197,508	147,293	1,277,253	150,622	1,091,494	173,053	1,251,803	166,941
446	1,096,121	146,649	1,087,549	157,635	1,060,734	162,332	1,318,437	136,504
447	1,029,792	155,265	1,226,239	150,963	1,265,079	180,216	1,433,356	162,675
448	985,468	145,484	1,142,114	152,927	1,438,076	152,831	1,342,208	156,399
449	1,130,428	156,483	1,280,632	169,293	1,148,613	142,681	1,384,346	147,185
450	1,133,253	142,194	1,255,588	166,970	1,340,654	161,478	1,406,336	165,804
451	1,006,828	141,059	1,246,001	168,300	1,274,177	158,003	1,299,162	153,835
452	1,117,037	147,830	1,205,719	159,191	1,466,647	149,816	1,275,995	138,686
453	1,032,216	133,964	1,387,278	145,436	1,055,241	143,241	1,292,738	173,646
454	1,063,678	127,919	1,104,300	138,969	1,367,781	177,104	1,063,865	145,731
455	1,176,708	128,783	1,312,891	145,122	1,305,629	145,936	1,250,031	147,697
456	1,153,984	137,051	1,192,298	154,052	1,228,284	144,800	1,413,508	137,200
457	1,087,219	155,454	1,313,881	177,139	1,273,210	136,191	1,439,632	161,030
458	1,049,666	153,108	1,351,634	155,657	1,213,617	164,733	1,295,924	152,096
459	1,193,260	155,356	1,206,749	164,348	1,271,320	171,586	1,414,248	144,838
460	1,074,428	158,044	1,165,054	185,949	1,206,706	136,914	1,299,225	157,877
461	1,160,082	157,100	1,334,518	123,789	1,411,925	156,164	1,251,905	187,883
462	1,220,105	168,360	1,247,263	153,701	1,285,841	159,291	1,224,022	137,390
463	1,174,645	144,866	1,182,694	150,793	1,126,947	147,053	1,282,318	167,880
464	1,054,713	164,948	1,153,323	157,867	1,157,015	182,974	1,220,505	174,929
465	1,099,644	157,968	1,290,396	148,103	1,052,846	148,355	1,413,837	150,839
466	1,472,225	156,404	1,451,751	147,755	1,362,092	150,707	1,200,902	169,411
467	1,118,445	153,779	1,362,006	128,091	1,083,728	140,270	1,224,950	166,967
468	1,079,571	132,560	1,306,802	141,406	1,236,619	178,821	1,334,559	154,936
469	1,265,790	144,514	1,256,977	161,377	1,195,367	153,846	1,404,486	153,105
470	1,219,069	151,674	1,182,227	150,030	1,181,072	159,051	1,158,561	138,970
471	1,117,623	146,255	1,178,454	143,328	1,484,098	157,761	1,458,890	172,195
472	877,906	158,068	1,029,763	135,383	1,170,557	145,167	1,345,269	159,730
473	1,293,859	154,407	1,215,770	162,874	1,438,910	153,862	1,541,450	155,479
474	931,046	131,077	1,241,932	147,541	1,101,587	167,936	1,181,240	152,768
475	1,093,386	146,417	1,176,175	161,610	1,189,711	152,468	1,244,834	157,594
476	1,336,610	161,110	1,157,570	147,431	1,181,756	162,123	1,291,613	164,209
477	1,322,207	136,205	1,151,622	148,296	1,305,786	156,315	1,366,456	163,688
478	1,199,190	138,264	1,403,216	162,500	1,194,909	153,982	1,354,751	158,397
479	1,236,505	119,375	1,490,630	161,981	1,456,111	152,880	1,522,048	144,685

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
480	1,160,294	149,395	1,046,414	150,797	1,309,063	154,660	1,618,141	135,998
481	1,066,177	136,961	1,380,329	148,870	1,225,742	148,885	1,437,855	159,571
482	1,112,425	133,059	1,203,866	156,601	1,234,324	135,450	1,549,253	171,356
483	1,318,388	156,456	1,177,140	139,561	1,260,448	175,393	1,351,667	183,782
484	1,197,480	154,063	1,164,459	142,871	1,142,452	148,496	1,295,847	165,975
485	1,053,522	153,633	1,372,502	170,153	1,410,377	145,029	1,182,861	178,795
486	1,178,951	140,819	1,028,441	158,432	1,482,471	151,865	1,166,911	151,401
487	1,210,094	170,816	1,121,772	162,798	1,370,123	157,324	1,263,054	142,657
488	1,266,203	137,756	1,116,546	157,510	1,244,297	160,285	1,379,575	166,278
489	1,182,417	193,068	1,035,431	162,820	1,410,585	174,581	1,415,784	157,875
490	1,253,054	150,430	1,444,848	172,196	1,270,544	168,269	1,370,142	139,738
491	1,005,021	139,317	1,316,084	139,873	1,185,627	148,924	1,591,789	137,915
492	1,165,911	148,134	1,125,613	140,241	1,687,932	152,750	1,477,531	163,574
493	1,294,784	139,646	1,106,815	138,889	1,186,672	162,476	1,169,781	166,501
494	1,198,418	137,842	1,438,905	145,028	1,385,236	154,054	1,377,013	137,469
495	1,240,589	136,035	1,242,875	150,380	1,181,131	160,293	1,207,403	171,258
496	1,338,064	141,772	1,488,467	151,606	1,183,394	149,727	1,308,875	140,059
497	1,159,354	158,262	1,356,663	153,460	1,252,372	166,628	1,245,923	173,490
498	1,124,523	164,055	1,316,112	143,950	1,349,209	145,813	1,454,396	156,091
499	1,205,408	149,505	1,094,250	173,483	1,129,186	155,739	1,341,706	162,710
500	1,414,323	143,585	1,361,495	139,642	1,170,015	164,117	1,271,647	160,490
501	1,056,199	133,418	1,160,474	166,185	1,369,903	138,885	1,291,718	151,703
502	1,024,001	124,284	957,793	147,814	1,168,831	175,054	1,173,448	164,815
503	952,398	146,229	1,044,683	144,980	1,322,815	151,709	1,503,909	146,711
504	977,462	155,092	1,317,383	152,583	1,403,607	145,666	1,205,768	148,958
505	1,125,723	153,932	1,337,992	145,945	1,241,953	167,239	1,411,121	176,586
506	1,325,701	140,283	1,330,650	147,302	1,277,329	147,547	1,195,476	156,008
507	1,171,067	139,885	1,296,658	154,878	1,296,188	147,135	1,462,975	149,707
508	1,192,945	146,516	1,215,021	147,380	1,298,576	148,641	1,374,250	177,163
509	968,345	137,538	1,190,142	167,017	1,178,646	136,971	1,419,626	157,828
510	1,261,565	152,076	1,440,839	161,680	1,288,885	148,602	1,307,759	176,760
511	1,128,057	152,338	1,243,796	155,185	1,405,836	140,107	1,306,085	158,022
512	1,115,544	152,080	1,286,600	160,050	1,108,619	159,638	1,156,306	151,889
513	1,108,138	159,929	1,175,671	140,470	1,251,940	154,891	1,249,722	138,403
514	1,271,507	149,694	1,334,858	161,655	1,202,199	157,836	1,173,015	147,768
515	1,046,590	144,934	1,240,799	147,531	1,524,021	155,875	1,486,216	156,922
516	992,289	143,864	1,140,422	126,303	1,208,113	152,699	1,718,126	155,200

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
517	1,377,426	127,737	1,373,650	159,625	1,210,701	169,130	1,281,668	157,734
518	1,470,725	142,147	1,304,172	155,109	1,346,969	169,158	1,326,596	162,113
519	1,328,918	137,901	1,287,325	164,935	1,320,898	136,320	1,279,731	156,985
520	1,287,707	143,355	1,358,839	155,203	1,196,280	156,316	1,396,015	160,048
521	1,064,312	128,845	1,140,301	145,203	1,529,650	140,065	1,195,606	137,959
522	997,864	157,499	1,321,506	141,776	1,363,995	143,036	1,394,355	152,607
523	1,035,952	140,705	1,413,797	149,660	1,295,594	157,594	1,396,567	161,511
524	1,066,887	135,712	1,204,165	140,709	1,279,292	167,004	1,412,520	146,285
525	1,074,214	127,836	1,183,917	142,346	1,209,031	149,991	1,237,469	154,741
526	946,264	131,140	1,237,473	136,490	1,207,703	146,667	1,216,373	139,475
527	1,041,512	133,875	1,441,547	160,007	1,299,755	151,670	1,188,548	161,811
528	1,137,653	141,112	1,299,330	159,652	1,160,601	177,217	1,328,962	164,588
529	1,458,709	135,045	1,115,161	144,717	1,435,697	162,554	1,419,803	166,957
530	1,170,687	152,849	1,257,217	134,472	1,441,844	178,318	1,274,162	183,980
531	1,314,480	154,308	1,186,670	147,158	1,241,843	153,916	1,508,726	147,140
532	1,127,278	142,854	1,148,497	137,055	1,247,023	155,048	1,433,237	170,296
533	1,139,550	122,523	1,083,965	144,496	1,304,031	143,065	1,465,337	160,814
534	1,118,172	129,405	1,295,812	162,011	1,199,907	153,367	1,305,632	140,552
535	1,264,732	154,083	1,222,072	168,378	1,291,626	154,934	1,350,442	154,539
536	1,186,748	139,276	1,134,719	123,021	1,415,337	152,462	1,257,293	144,728
537	1,005,857	165,891	1,211,635	135,522	1,376,093	154,590	1,327,413	158,636
538	1,025,713	151,085	1,078,837	159,979	1,106,732	160,965	1,364,273	168,910
539	1,142,418	153,770	1,285,071	146,344	1,376,629	169,482	1,440,347	178,478
540	1,025,508	158,996	1,245,224	162,564	1,298,512	154,617	1,222,289	147,651
541	1,133,366	152,593	1,398,288	160,125	1,333,332	150,003	1,253,679	180,265
542	1,105,838	133,302	1,367,914	148,966	1,285,265	142,060	1,170,768	159,845
543	908,581	135,111	1,065,325	153,399	1,475,723	164,323	1,676,788	162,828
544	1,023,713	145,325	1,121,382	157,268	1,600,009	141,342	1,270,627	147,196
545	999,830	134,663	1,068,757	132,628	1,273,119	155,093	1,124,318	150,581
546	1,113,146	142,167	1,456,271	150,218	1,279,618	165,971	1,157,540	143,343
547	1,011,380	143,629	1,133,470	134,865	1,022,364	173,984	1,387,036	158,324
548	1,057,369	143,343	1,553,581	138,719	1,145,219	163,080	1,379,784	157,485
549	1,432,468	162,943	1,279,890	153,947	1,154,459	172,575	1,386,778	169,407
550	934,187	144,171	1,159,960	150,971	1,309,031	151,533	1,379,480	160,852
551	1,083,139	131,158	1,276,370	156,136	1,102,190	150,731	1,360,313	144,110
552	1,047,691	149,623	1,429,338	134,884	1,162,144	156,928	1,343,003	143,250
553	1,303,114	164,499	1,069,478	143,465	1,782,119	164,652	1,089,121	155,527

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
554	1,134,736	148,202	1,268,151	149,107	1,278,602	169,420	1,457,608	157,231
555	1,216,442	147,751	1,034,521	144,597	1,264,161	157,649	1,213,386	147,836
556	1,261,675	142,555	1,264,176	149,104	1,468,460	151,337	1,274,422	151,227
557	1,145,983	137,582	1,164,069	130,420	1,364,058	148,277	1,341,237	160,126
558	1,151,088	135,649	1,366,766	138,334	1,396,717	158,061	1,415,539	162,988
559	1,267,201	143,486	1,161,432	143,964	1,325,568	154,457	1,187,940	167,535
560	1,267,818	149,148	1,350,379	143,622	1,301,942	153,906	1,243,620	153,471
561	1,367,468	166,086	1,140,383	140,620	1,236,014	152,635	1,384,612	157,551
562	1,276,400	139,501	1,233,119	145,177	1,585,072	141,217	1,634,767	155,007
563	921,908	154,640	1,068,996	147,604	1,477,048	177,287	1,422,161	172,428
564	1,186,761	150,142	1,267,134	170,141	1,389,252	171,895	1,344,960	181,330
565	1,360,565	137,054	1,266,148	139,652	1,273,821	183,961	1,439,008	165,363
566	1,146,267	170,537	1,029,590	156,193	1,219,177	143,480	1,243,369	167,758
567	1,060,933	122,780	1,173,011	155,669	1,535,783	139,448	1,177,791	166,564
568	1,083,424	145,521	1,230,248	154,486	1,138,004	148,147	1,197,183	155,798
569	1,073,658	162,769	1,280,530	152,152	1,099,542	142,686	1,223,416	154,289
570	1,466,581	157,720	1,059,446	159,351	1,278,244	151,760	1,304,577	139,278
571	1,138,686	134,841	1,509,538	142,199	1,338,979	155,253	1,312,689	166,179
572	1,111,348	151,857	1,089,954	149,169	1,291,082	160,696	1,348,177	172,597
573	1,031,825	163,973	1,270,987	147,751	1,462,244	144,712	1,236,608	136,544
574	1,242,566	143,642	1,172,484	136,330	1,260,582	169,261	1,173,418	165,980
575	1,239,535	142,888	1,134,801	140,802	1,295,706	132,690	1,134,867	160,998
576	1,182,694	139,948	1,249,707	138,575	1,266,966	164,272	1,552,629	142,747
577	1,208,675	133,157	1,220,896	149,440	1,424,200	158,843	1,384,987	154,129
578	1,208,098	153,463	1,296,767	148,350	1,293,408	152,198	1,427,099	156,255
579	1,184,613	144,842	1,542,116	146,088	1,014,470	128,820	1,103,250	151,832
580	1,128,395	147,235	1,437,090	138,801	1,338,872	174,940	1,339,483	167,348
581	1,182,729	147,871	1,394,892	151,828	1,296,196	157,940	1,132,679	159,309
582	1,080,208	145,601	1,190,741	151,539	1,426,044	140,783	1,392,927	169,253
583	1,007,011	133,340	1,367,126	142,893	1,297,970	156,767	1,377,937	169,809
584	1,098,544	138,658	1,446,104	137,644	1,116,382	156,916	1,457,648	139,560
585	1,335,479	145,202	1,183,423	145,130	1,301,351	163,937	1,143,728	163,114
586	1,144,560	134,597	1,255,704	150,197	1,592,771	167,044	1,445,149	182,728
587	987,923	158,221	1,105,520	142,362	1,340,393	167,301	1,234,244	164,918
588	1,300,107	137,988	1,247,425	143,256	1,442,531	137,848	1,518,408	160,781
589	1,099,459	146,168	1,309,878	139,200	1,324,170	154,114	1,252,565	153,822
590	1,346,783	160,195	1,339,119	142,675	1,191,033	158,356	1,193,043	161,061

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
591	1,328,973	161,892	1,231,647	160,142	1,102,682	162,737	1,248,447	159,818
592	1,372,697	156,697	1,126,450	143,893	1,451,024	143,691	1,165,086	150,231
593	1,155,250	141,699	1,175,503	153,299	1,409,101	161,365	1,335,270	181,352
594	1,133,165	140,784	1,403,932	134,118	1,429,008	132,563	1,178,986	179,987
595	1,180,878	155,279	1,080,911	148,173	1,410,709	133,564	1,223,250	160,592
596	1,184,742	141,415	1,450,386	157,057	1,569,518	145,256	1,236,274	152,652
597	1,094,097	153,020	1,148,673	167,078	1,421,582	156,580	1,326,391	147,216
598	1,251,203	163,582	1,140,066	143,174	1,206,708	139,791	1,415,869	151,755
599	1,183,074	165,647	1,329,796	171,203	1,238,436	150,764	1,292,363	147,419
600	1,228,054	144,960	1,125,579	153,392	1,373,151	163,975	1,382,396	157,442
601	1,257,144	156,452	1,183,633	151,404	1,182,628	160,147	1,324,537	155,340
602	1,070,351	140,120	1,255,345	157,190	1,122,619	156,306	1,464,061	132,711
603	974,100	126,525	1,190,585	148,300	1,313,967	164,513	1,424,545	154,699
604	1,228,021	161,806	1,355,572	142,505	1,332,631	146,693	1,301,471	146,132
605	1,070,456	149,079	1,351,006	139,531	1,138,842	166,557	1,454,386	172,105
606	1,275,260	172,403	1,182,445	139,187	1,197,696	140,370	1,318,356	153,233
607	1,376,753	157,059	1,213,814	146,357	1,191,361	149,009	1,300,042	150,418
608	1,191,155	160,876	1,306,421	144,203	1,441,072	134,152	1,260,677	179,372
609	1,181,547	139,990	1,364,210	142,524	1,255,704	150,240	1,293,897	163,072
610	1,124,027	137,376	1,095,576	157,221	1,325,094	170,498	1,213,225	141,515
611	1,297,097	144,556	1,167,340	168,797	1,277,647	175,503	1,261,789	140,750
612	1,313,743	139,266	1,237,450	158,753	1,533,336	163,001	1,313,307	158,434
613	1,084,768	157,621	1,278,923	154,812	1,117,183	169,739	1,298,108	153,658
614	1,030,076	161,209	1,152,229	147,625	1,071,353	133,821	1,164,386	152,328
615	1,144,212	150,271	1,287,455	169,510	1,158,296	145,979	1,436,770	161,518
616	1,224,431	153,171	1,310,267	158,574	1,269,542	164,044	1,219,213	163,311
617	1,293,639	146,083	1,328,761	150,188	1,426,401	160,872	1,143,155	146,934
618	1,126,501	144,777	1,124,534	151,727	1,319,764	155,180	1,494,851	174,018
619	1,083,952	154,334	1,066,084	150,434	1,325,528	151,763	1,404,402	164,805
620	1,088,742	137,402	1,166,636	146,585	1,335,531	147,876	1,281,636	151,082
621	1,184,961	140,674	1,229,929	132,749	1,258,806	143,921	1,278,501	157,461
622	1,213,891	151,405	1,237,323	151,256	1,209,223	162,624	1,189,933	160,634
623	1,152,549	137,066	1,325,100	151,783	1,284,587	137,313	1,394,435	154,283
624	1,276,916	147,336	1,110,047	138,174	1,476,253	135,028	1,271,580	165,019
625	1,293,816	140,345	1,264,230	148,290	1,304,593	151,794	1,489,548	147,643
626	1,080,878	135,953	1,202,550	159,133	1,236,522	150,023	1,317,440	166,700
627	1,190,153	144,968	1,136,110	142,762	1,066,013	147,364	1,212,627	170,872

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**	**Embodied Energy (GJ)**	**CO_2 Emissions (tonnes)**
628	1,529,581	155,965	1,285,276	161,597	1,400,895	149,530	1,510,252	142,373
629	1,223,001	146,635	1,228,738	149,864	1,226,795	166,640	1,541,823	169,118
630	1,215,252	144,975	1,255,225	145,998	1,169,786	163,299	1,164,500	142,691
631	1,066,998	140,648	1,108,524	139,761	1,227,369	168,675	1,439,743	182,483
632	1,368,386	150,386	1,501,604	159,538	1,265,560	151,219	1,157,666	145,333
633	1,466,238	155,343	1,291,980	125,040	1,184,857	127,858	1,376,516	161,528
634	1,200,180	140,399	1,159,019	136,208	1,210,875	145,409	1,533,927	159,739
635	1,196,975	159,034	1,314,435	165,150	1,726,606	150,163	1,607,888	158,024
636	1,298,032	156,909	1,121,650	153,390	1,343,139	154,067	1,349,562	163,388
637	1,186,164	140,886	1,282,651	136,087	1,386,199	149,704	1,215,420	165,021
638	1,205,293	148,669	1,207,348	156,972	1,276,896	162,973	1,247,925	154,768
639	1,094,959	134,833	1,344,305	135,414	1,117,592	147,172	1,248,781	163,355
640	976,440	137,359	1,361,054	146,377	1,252,098	145,191	1,327,876	149,589
641	1,296,263	136,731	1,020,542	136,377	1,461,488	159,565	1,352,530	152,855
642	1,179,600	156,384	1,244,590	143,791	1,131,646	136,976	1,498,927	173,860
643	1,478,010	150,610	1,139,440	166,530	1,230,417	158,668	1,273,399	146,610
644	1,104,148	129,787	1,091,262	155,454	1,262,560	157,070	1,293,851	147,210
645	1,241,156	154,348	968,640	148,459	1,251,126	150,072	1,301,767	178,752
646	1,276,905	137,332	1,121,978	164,793	1,135,994	158,427	1,236,401	159,490
647	1,064,552	150,032	1,249,004	148,854	1,228,251	156,902	1,178,228	152,036
648	1,228,711	145,437	1,158,244	162,378	1,125,657	161,455	1,366,369	171,400
649	996,662	145,752	1,258,137	160,530	1,236,019	147,682	1,294,628	162,230
650	1,115,702	151,674	1,485,962	148,380	1,412,554	153,576	1,411,409	157,552
651	1,387,310	132,287	1,335,955	131,712	1,373,949	139,817	1,354,119	156,291
652	1,393,128	132,674	1,261,173	169,391	1,349,522	153,709	1,413,823	166,445
653	1,412,003	138,838	1,379,320	146,564	1,413,013	145,573	1,314,134	164,848
654	1,010,836	139,664	1,339,150	146,968	1,305,043	142,158	1,219,439	158,034
655	1,199,517	153,691	1,180,962	158,059	1,298,361	168,766	1,314,237	153,519
656	1,262,824	145,279	1,259,236	139,903	1,523,682	150,983	1,420,163	155,209
657	1,313,066	127,706	1,396,999	136,990	1,653,513	167,708	1,234,397	162,838
658	1,158,394	146,983	1,074,500	118,919	1,478,062	173,774	1,107,183	138,794
659	1,190,667	133,760	1,264,239	150,989	1,288,348	145,865	1,171,785	149,082
660	1,152,503	136,111	1,406,196	154,290	1,459,128	158,842	1,462,911	174,581
661	1,003,309	157,551	1,406,230	140,519	1,240,132	167,101	1,396,713	149,302
662	1,217,496	149,593	1,123,591	127,114	1,437,556	126,179	1,319,614	140,103
663	1,189,998	169,860	1,364,225	162,876	1,295,531	139,317	1,253,763	166,388
664	1,051,087	161,566	1,063,740	147,496	1,172,403	129,446	1,123,548	144,049

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
665	1,376,259	143,175	1,089,870	173,152	1,520,575	145,060	1,530,995	160,398
666	1,187,096	141,289	1,264,574	165,838	1,050,242	169,819	1,300,521	172,094
667	1,123,343	139,141	1,052,916	155,274	1,299,763	148,617	1,084,817	153,844
668	1,042,732	148,750	1,215,968	132,803	1,284,665	158,125	1,353,466	168,283
669	1,263,371	153,785	1,232,759	149,474	1,309,741	161,240	1,347,389	161,367
670	1,252,824	134,484	1,331,718	143,145	1,191,533	148,542	1,371,601	153,472
671	1,201,103	128,130	1,431,828	142,885	1,172,265	153,768	1,290,743	136,996
672	1,302,543	144,674	1,408,726	165,602	1,232,048	152,957	1,296,136	163,286
673	1,403,561	140,549	1,114,127	154,455	1,082,133	138,636	1,473,788	146,647
674	1,207,316	142,655	1,208,820	150,811	1,238,605	147,273	1,318,324	145,215
675	1,162,621	158,342	1,380,162	138,420	1,228,678	135,962	1,511,096	172,950
676	1,289,097	126,435	1,346,224	137,353	1,294,066	147,487	1,447,130	149,990
677	1,282,681	144,355	1,168,028	139,209	1,140,539	165,973	1,341,532	184,967
678	1,055,535	138,134	1,040,860	151,236	1,123,599	156,387	1,309,912	156,377
679	1,357,022	147,429	1,242,275	163,019	1,246,864	147,466	1,210,912	157,376
680	1,303,363	133,710	1,209,892	143,879	1,372,365	137,461	1,502,648	151,546
681	1,051,473	150,672	1,221,835	156,279	1,367,013	149,546	1,287,511	168,358
682	1,293,620	137,677	1,206,788	133,234	1,154,304	147,724	1,299,206	170,870
683	1,094,230	141,551	1,098,135	138,027	1,100,378	157,236	1,742,250	175,567
684	1,129,376	145,821	1,368,384	122,719	1,152,027	163,658	1,245,407	171,149
685	1,431,714	131,738	1,250,187	163,480	1,059,999	149,486	1,339,435	173,437
686	1,271,021	129,133	1,129,974	133,949	1,436,073	138,223	1,360,203	155,153
687	1,262,354	157,092	980,610	150,764	1,331,686	163,569	1,406,189	167,044
688	1,181,015	158,463	1,279,588	131,208	1,275,503	140,160	1,053,498	152,825
689	1,016,484	126,396	1,210,941	159,930	1,409,051	160,123	1,454,511	149,928
690	971,175	180,067	1,254,666	153,511	1,357,143	149,501	1,237,195	150,238
691	1,321,581	150,938	1,403,190	143,667	1,302,308	148,785	1,281,984	156,487
692	1,171,787	124,848	1,173,936	133,746	1,313,547	164,336	1,236,934	136,711
693	1,406,295	155,189	1,109,438	161,882	1,031,854	162,572	1,409,277	161,336
694	1,283,614	150,014	1,251,570	145,155	1,245,484	163,493	1,452,734	138,989
695	1,209,644	143,691	1,375,321	164,372	1,201,740	144,129	1,263,647	154,335
696	1,194,099	146,616	1,080,092	159,040	1,301,455	156,487	1,503,896	174,083
697	1,268,554	150,334	1,195,203	161,989	1,270,107	179,960	1,485,982	158,373
698	1,063,357	137,652	1,165,086	128,233	1,310,595	163,462	1,181,418	143,867
699	1,343,211	177,617	1,226,626	138,132	1,321,802	161,436	1,352,077	135,820
700	1,313,372	152,461	1,472,598	154,289	1,266,424	164,665	1,281,569	168,416
701	1,183,164	158,178	1,109,298	139,756	1,171,793	144,378	1,460,034	174,115

Calculation No.	As-Built Trucking Distance (*M* = 1)		*M* = 2 Trucking Distances		*M* = 3 Trucking Distances		*M* = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
702	1,400,066	132,419	1,324,522	148,473	1,609,656	163,947	1,408,952	191,632
703	1,374,525	156,931	1,159,923	157,783	1,279,607	180,426	1,437,007	157,445
704	981,208	157,344	1,220,448	172,310	1,276,045	147,048	1,268,363	173,494
705	996,319	148,974	1,326,452	134,791	1,395,593	160,538	1,201,763	152,911
706	1,238,633	164,628	1,422,874	144,323	1,261,565	144,024	1,003,719	139,194
707	1,174,082	185,824	1,195,382	136,516	1,123,617	174,137	1,195,940	165,409
708	1,248,869	151,718	1,422,007	139,375	1,153,704	133,682	1,262,936	166,550
709	1,127,722	157,353	1,245,201	154,512	1,414,795	144,629	1,170,447	169,841
710	1,096,084	134,052	1,346,781	151,227	1,379,049	149,723	1,395,658	160,320
711	1,136,074	143,515	1,144,243	132,659	1,321,937	154,765	1,475,788	145,039
712	1,187,744	135,902	1,133,935	146,862	1,161,857	151,256	1,222,563	163,919
713	1,320,231	175,666	1,169,882	143,066	1,192,513	160,163	1,108,765	143,617
714	1,182,652	136,731	1,343,231	156,536	1,180,068	148,077	1,227,735	142,204
715	1,180,855	139,981	1,105,922	156,213	1,214,772	148,715	1,258,589	141,882
716	1,432,175	149,751	1,138,416	149,362	1,263,606	142,761	1,326,771	138,710
717	1,124,347	158,764	1,189,472	167,570	1,173,299	150,451	1,408,047	159,508
718	1,173,005	151,558	1,335,275	142,912	1,366,118	143,343	1,350,766	180,713
719	1,000,447	135,758	1,318,590	127,157	1,399,172	166,082	1,306,241	150,393
720	1,198,138	154,343	1,441,158	153,987	980,439	145,130	1,446,311	160,881
721	1,299,435	158,200	1,289,019	157,086	1,347,705	173,490	1,341,968	179,020
722	1,043,999	167,909	1,022,128	150,356	1,226,159	144,097	1,330,694	181,458
723	1,118,620	163,230	1,249,611	117,763	1,474,863	152,649	1,313,263	173,997
724	1,164,549	130,582	1,109,294	131,822	1,303,073	150,843	1,232,059	157,792
725	1,301,912	149,659	1,149,815	147,267	1,246,102	133,670	1,353,993	182,252
726	1,324,669	157,670	1,315,135	166,320	1,194,353	185,730	1,371,523	179,675
727	1,352,262	129,714	1,229,754	162,317	1,349,181	147,775	1,276,552	149,470
728	1,156,669	142,208	1,375,055	142,188	1,229,442	169,436	1,215,604	160,662
729	1,241,696	140,284	1,153,157	149,219	1,330,010	144,149	1,195,244	160,413
730	977,352	151,071	1,256,814	145,356	1,495,565	138,607	1,262,944	160,360
731	1,090,334	140,108	1,140,992	164,697	1,001,516	150,671	1,270,048	137,047
732	1,204,219	146,653	1,279,282	132,873	1,262,107	166,067	1,339,673	171,114
733	1,216,735	141,692	1,243,831	145,655	1,218,821	162,109	1,283,556	143,087
734	1,083,821	145,393	1,179,215	158,548	1,079,684	143,122	1,437,966	160,788
735	1,380,507	160,391	1,332,398	142,418	1,249,047	153,465	1,169,808	164,091
736	1,202,262	156,428	1,316,786	153,190	1,096,787	153,773	1,474,023	167,395
737	939,051	158,192	1,166,024	143,572	1,370,691	155,043	1,500,933	150,213
738	1,171,839	155,242	1,164,867	128,912	1,246,853	164,123	1,375,616	179,637

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
739	1,265,515	152,479	1,184,317	140,515	1,227,612	138,745	1,433,901	173,549
740	1,129,900	138,517	1,205,399	145,774	1,161,947	141,047	1,184,310	161,179
741	1,021,483	145,060	1,323,807	122,626	1,133,455	149,482	1,409,095	170,639
742	1,184,173	140,013	1,269,790	144,961	1,213,913	158,758	1,371,369	148,180
743	1,060,001	131,774	1,321,605	143,366	1,239,022	138,811	1,558,244	157,536
744	1,259,143	139,780	1,176,162	160,806	1,558,008	152,232	1,324,511	152,697
745	1,139,665	160,381	1,091,375	142,593	1,120,911	175,650	1,541,076	146,975
746	1,275,363	156,486	1,037,390	140,832	1,327,196	163,854	1,234,774	185,159
747	1,053,458	126,712	1,335,386	153,340	1,342,752	147,911	1,302,172	158,759
748	973,457	144,424	1,097,556	154,351	1,391,321	145,208	1,401,384	167,897
749	1,011,399	135,968	1,084,059	163,937	1,269,747	126,556	1,242,100	166,319
750	1,134,286	134,574	1,031,993	165,401	1,384,288	136,602	1,348,525	149,006
751	1,068,302	145,423	1,286,345	132,636	1,402,283	145,232	1,621,866	143,303
752	1,003,347	147,810	1,439,476	147,035	1,321,335	142,244	1,307,846	151,395
753	1,284,306	145,195	1,256,140	156,454	1,149,168	169,421	1,280,653	171,993
754	1,043,557	143,018	1,305,960	148,018	1,175,529	155,048	1,307,465	164,558
755	1,054,179	139,918	1,306,413	141,301	1,242,043	137,803	1,384,894	154,639
756	1,258,487	132,459	1,332,864	145,229	1,329,629	166,100	1,194,562	180,814
757	1,182,695	150,889	1,080,764	163,373	1,193,842	183,312	1,210,881	156,892
758	1,243,550	158,067	1,093,624	150,049	1,195,724	170,619	1,235,015	153,004
759	1,124,959	147,045	1,326,465	164,831	1,229,565	176,426	1,645,222	174,426
760	1,213,843	136,882	1,259,187	161,334	1,148,988	152,879	1,146,541	158,127
761	1,192,097	134,179	1,085,194	142,801	1,154,887	148,266	1,446,682	164,927
762	994,203	151,920	1,295,518	150,003	1,117,740	145,318	1,182,551	137,349
763	1,452,824	141,255	1,086,974	145,869	1,164,176	146,278	1,461,530	160,043
764	1,223,062	148,815	1,315,707	154,207	1,275,324	166,561	1,426,133	161,934
765	1,163,695	143,570	1,446,498	151,730	1,212,846	137,098	1,383,542	160,397
766	1,479,306	156,912	1,174,178	141,650	1,167,735	165,478	1,356,161	169,459
767	1,138,471	150,530	1,010,787	154,379	1,479,044	165,178	1,414,154	156,610
768	1,100,379	144,092	1,085,936	165,735	1,185,729	161,277	1,466,852	171,624
769	1,236,774	143,616	1,294,300	159,401	1,322,277	145,601	1,295,325	175,216
770	1,244,927	137,602	1,260,451	163,920	1,243,285	146,091	1,355,716	147,048
771	1,094,237	133,072	1,395,891	137,148	1,329,200	159,821	1,242,208	142,063
772	1,210,571	158,661	1,335,458	152,514	1,146,551	159,511	1,540,576	145,255
773	1,213,294	135,662	1,056,850	169,837	1,212,975	154,041	1,444,596	166,300
774	1,179,474	133,613	1,372,913	131,892	1,116,503	135,185	1,243,704	156,345
775	1,235,626	135,806	1,235,869	176,300	1,573,205	162,290	1,328,549	136,989

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
776	1,093,295	165,729	1,181,290	141,391	1,163,964	171,991	1,245,753	148,674
777	1,352,450	145,465	1,227,478	161,397	1,139,711	156,355	1,252,227	159,169
778	1,203,010	136,299	1,272,059	136,734	1,222,735	141,895	1,294,281	157,225
779	1,106,446	129,224	1,243,399	148,630	1,460,087	136,188	1,243,889	180,279
780	1,181,595	137,688	1,239,648	145,204	1,175,503	153,131	1,503,443	158,663
781	1,069,313	167,431	1,142,651	153,017	1,337,124	157,877	1,227,610	180,066
782	1,260,795	134,149	1,253,512	155,473	1,166,179	173,466	1,351,479	175,863
783	1,268,655	160,527	1,182,059	156,480	1,236,894	133,141	1,300,286	160,076
784	1,088,407	163,978	1,243,477	137,922	1,436,270	151,120	1,330,370	184,051
785	1,505,336	149,267	1,109,787	151,590	1,227,946	157,327	1,340,191	149,673
786	1,203,648	129,973	1,361,337	138,214	1,239,937	138,075	1,396,468	173,425
787	1,085,904	156,248	1,271,704	158,367	1,295,291	174,612	1,345,374	165,706
788	1,263,698	150,441	1,261,941	137,550	1,090,955	169,037	1,387,477	155,555
789	1,223,982	145,996	1,238,943	124,551	1,299,760	137,075	1,263,420	185,162
790	1,296,780	129,160	1,291,632	144,934	1,349,362	159,469	1,455,883	155,601
791	1,034,194	137,412	1,289,584	167,506	1,144,109	155,766	1,337,244	154,783
792	1,225,648	146,222	1,031,472	159,572	1,328,591	159,329	1,416,637	146,366
793	1,134,197	138,992	1,232,117	153,250	1,222,635	164,971	1,358,905	159,467
794	1,032,064	136,640	933,750	158,430	1,085,737	145,944	1,357,352	154,050
795	1,124,683	160,534	1,298,614	136,925	1,260,793	150,522	1,400,127	175,856
796	1,268,681	154,293	1,112,266	144,446	1,331,252	155,337	1,270,444	172,760
797	1,155,491	133,700	1,100,524	167,922	1,161,424	169,495	1,240,269	158,880
798	1,095,439	149,945	1,223,911	149,425	1,232,019	179,503	1,347,730	180,859
799	1,462,244	146,756	1,101,283	141,769	1,192,496	160,986	1,229,456	151,799
800	1,166,012	142,462	1,161,609	145,158	1,179,287	132,751	1,302,850	153,916
801	1,059,333	143,720	1,188,406	158,895	1,282,690	152,177	1,310,552	164,377
802	1,306,813	149,446	1,145,379	146,444	1,316,399	154,915	1,128,388	159,364
803	1,050,859	144,368	1,159,615	163,256	1,376,622	130,650	1,269,145	173,125
804	1,215,110	134,845	1,307,401	152,813	1,393,173	164,504	1,180,929	170,756
805	1,316,005	148,291	1,168,725	168,146	1,351,626	162,239	1,394,636	131,444
806	1,131,380	181,024	1,486,346	126,494	1,355,467	145,021	1,473,395	146,164
807	1,384,949	142,277	1,106,617	158,602	1,245,126	155,138	1,226,801	187,159
808	1,132,911	142,204	1,187,893	164,995	1,227,760	157,926	1,429,412	162,427
809	1,465,898	161,200	1,046,485	139,037	1,231,116	159,255	1,283,145	143,601
810	1,250,176	156,452	1,160,352	144,930	1,245,296	140,035	1,250,813	142,087
811	1,101,158	159,062	1,109,259	157,504	1,171,785	146,126	1,484,943	147,382
812	1,209,080	146,138	1,157,227	143,945	1,313,487	136,560	1,336,281	174,310

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
813	1,178,428	155,694	1,403,235	153,023	1,269,338	140,976	1,303,399	171,393
814	1,244,885	139,094	1,301,740	150,288	1,147,205	136,781	1,508,644	163,381
815	1,138,048	118,902	1,350,519	139,023	1,146,094	165,110	1,377,124	176,442
816	999,672	133,988	1,027,204	152,049	1,266,973	148,562	1,537,159	140,177
817	1,267,248	145,396	1,142,144	160,786	1,102,454	181,749	1,315,629	150,112
818	1,124,448	132,721	981,165	155,413	1,362,527	147,944	1,437,608	156,591
819	1,326,937	152,351	1,127,783	151,589	1,253,118	160,823	1,275,388	190,803
820	1,039,409	152,717	1,245,545	144,620	1,106,627	153,237	1,586,411	144,865
821	1,048,534	162,344	1,410,638	128,403	1,371,276	176,774	1,332,224	161,088
822	1,001,683	146,478	1,222,912	145,594	1,628,427	161,039	1,412,264	148,318
823	1,126,969	150,805	1,305,520	132,987	1,453,400	138,591	1,568,504	157,412
824	1,052,291	154,995	1,332,053	144,074	1,425,555	144,210	1,239,094	153,040
825	1,232,507	146,876	1,128,618	152,078	1,177,099	165,482	1,271,266	136,136
826	1,279,916	156,256	1,329,805	142,116	1,179,730	143,161	1,274,336	141,305
827	1,046,993	158,170	1,194,928	138,825	1,561,857	157,075	1,237,989	156,678
828	991,614	161,629	1,224,761	145,048	1,414,160	154,493	1,245,291	161,245
829	1,038,184	125,040	1,337,460	139,415	1,381,459	151,939	1,166,861	153,735
830	1,157,555	156,994	1,361,283	131,607	1,022,074	154,560	1,263,061	149,982
831	1,175,818	174,675	1,282,995	150,744	1,212,353	146,092	1,173,384	153,267
832	1,134,178	133,440	1,163,403	148,351	1,347,002	160,423	1,252,643	155,603
833	1,172,586	130,281	1,218,242	141,375	1,298,202	153,025	1,160,259	145,254
834	1,284,603	169,703	1,079,371	150,498	1,149,906	148,520	1,334,610	165,345
835	1,100,767	149,189	1,509,578	132,256	1,278,352	155,917	1,389,765	167,271
836	1,114,079	141,924	1,201,574	162,802	1,412,154	158,408	1,296,773	161,380
837	1,123,688	137,762	1,029,708	124,777	1,299,881	146,365	1,362,094	154,561
838	1,050,134	138,840	1,255,120	147,090	1,130,183	160,475	1,416,609	152,127
839	1,156,208	137,049	1,138,080	174,917	1,247,865	168,277	1,575,453	158,044
840	1,171,517	146,813	1,309,882	133,933	1,180,471	150,574	1,468,896	145,630
841	1,018,288	142,018	1,053,227	150,101	1,320,228	154,605	1,321,380	168,425
842	1,079,512	152,291	1,096,601	153,792	1,132,987	153,446	1,309,199	158,881
843	1,121,582	158,338	1,147,993	145,867	1,388,955	151,427	1,497,420	160,649
844	1,302,737	147,878	1,339,715	153,284	1,263,656	148,119	1,254,601	166,762
845	1,138,257	137,174	1,141,387	168,978	1,283,612	145,292	1,400,699	151,849
846	1,384,964	153,755	1,386,231	142,295	1,407,922	147,501	1,352,570	175,196
847	1,314,973	127,885	993,451	149,223	1,426,560	171,295	1,471,098	174,744
848	1,033,470	140,569	1,189,660	157,879	1,201,315	144,094	1,350,356	177,302
849	1,138,157	136,773	1,132,132	153,316	1,298,910	143,738	1,327,953	158,068

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
850	1,000,471	149,625	1,264,433	159,867	1,164,014	153,242	1,227,036	145,654
851	1,050,427	126,337	1,291,889	143,318	1,159,038	148,989	1,419,740	135,507
852	1,110,644	148,656	1,310,638	152,857	1,402,098	134,293	1,242,272	159,518
853	1,174,065	125,324	1,180,053	141,913	1,424,311	145,451	1,372,532	160,164
854	1,261,924	144,699	1,588,666	151,022	1,171,694	155,394	1,568,875	135,487
855	1,104,865	144,007	1,084,686	166,153	1,320,635	156,087	1,520,120	177,158
856	1,306,066	141,381	1,390,636	160,756	1,179,672	165,002	1,292,125	167,034
857	1,122,850	145,661	1,364,908	148,484	1,312,699	163,028	1,394,078	151,101
858	1,002,940	157,641	1,309,709	151,219	1,245,461	152,203	1,339,413	176,765
859	1,069,206	152,245	1,144,271	150,161	1,160,661	155,003	1,360,453	149,906
860	1,255,565	139,997	1,280,121	152,913	1,472,144	150,371	1,252,413	143,972
861	947,337	138,022	1,237,744	134,208	1,161,967	149,675	1,271,437	168,579
862	1,109,039	143,043	1,362,942	145,749	1,191,269	165,265	1,439,583	168,347
863	1,035,934	168,488	1,259,385	158,711	1,134,980	159,049	1,436,061	162,367
864	987,595	141,001	1,046,547	149,729	1,418,219	148,475	1,350,791	156,509
865	1,146,706	136,677	1,226,217	152,484	1,448,024	163,531	1,210,417	157,208
866	1,392,505	167,014	1,029,644	140,524	1,385,756	160,838	1,216,443	176,392
867	1,284,432	146,594	949,865	151,369	1,292,291	156,107	1,367,731	166,182
868	1,183,686	147,676	1,400,963	144,797	1,268,507	178,566	1,251,786	151,559
869	1,032,164	158,753	1,230,800	146,835	1,238,110	157,259	1,248,816	163,576
870	1,351,489	158,801	1,287,168	169,649	1,317,025	153,103	1,745,896	146,957
871	1,130,456	151,985	1,401,443	165,371	1,487,081	161,554	1,354,652	147,197
872	983,002	138,917	1,151,974	153,814	1,200,153	144,118	1,363,618	156,521
873	1,270,950	130,093	1,110,451	165,600	1,179,377	172,637	1,436,634	140,048
874	1,211,648	150,659	1,002,381	148,432	1,393,137	161,481	1,577,310	162,014
875	1,192,714	147,354	1,319,893	146,370	1,242,295	135,276	1,315,803	151,013
876	1,181,467	143,381	1,229,783	144,912	1,286,921	139,822	1,232,112	164,979
877	1,280,977	139,016	1,301,357	158,789	1,178,087	149,196	1,270,856	171,102
878	1,240,945	129,657	1,271,215	146,592	1,098,322	139,921	1,460,903	142,403
879	1,136,451	150,155	1,160,165	141,776	1,169,609	145,859	1,239,679	162,583
880	1,047,660	150,460	1,356,654	152,325	1,292,042	148,342	1,420,659	177,591
881	1,174,767	142,032	1,110,708	151,297	1,233,076	147,418	1,245,121	171,997
882	1,197,461	168,580	1,338,426	158,809	1,285,296	184,855	1,147,590	152,216
883	1,134,916	141,699	1,256,126	136,757	1,204,511	153,175	1,282,050	144,604
884	1,127,676	146,312	1,803,280	144,779	1,269,004	145,049	1,437,467	156,492
885	1,136,817	124,663	1,279,672	147,267	1,194,243	158,174	1,474,569	161,681
886	1,106,874	137,639	1,359,352	165,596	1,157,833	152,375	1,452,746	148,245

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
887	1,130,907	154,651	1,415,688	132,727	1,275,981	139,228	1,263,139	160,065
888	1,029,474	164,148	1,577,489	140,792	1,223,926	161,155	1,607,979	157,314
889	1,236,081	139,694	1,449,591	158,055	1,251,605	147,742	1,188,438	175,532
890	1,160,212	154,980	1,420,487	171,727	1,171,874	156,798	1,521,616	171,440
891	1,023,559	140,403	1,048,583	166,682	1,141,784	146,736	1,321,845	154,792
892	1,207,283	135,789	1,316,314	138,230	1,411,951	148,098	1,060,860	166,109
893	1,025,294	148,744	1,026,402	177,308	1,342,274	155,025	1,143,810	177,873
894	1,055,054	150,210	1,086,059	143,460	1,287,587	154,081	1,406,971	171,433
895	976,771	140,513	1,113,624	147,359	1,368,938	136,191	1,523,700	155,703
896	1,014,587	130,993	1,180,983	150,914	1,233,455	169,636	1,505,050	158,794
897	1,105,918	151,295	1,158,560	139,667	1,242,200	165,004	1,444,047	167,488
898	1,157,241	145,552	1,151,179	161,541	1,248,698	161,097	1,456,870	151,798
899	1,059,821	174,747	1,096,845	159,674	1,371,800	147,484	1,457,889	186,356
900	1,262,113	161,730	1,140,774	134,395	1,379,294	156,863	1,330,123	163,997
901	941,608	150,567	1,199,274	154,677	1,280,335	164,540	1,671,649	139,533
902	1,352,855	143,515	1,178,155	149,085	1,443,048	156,038	1,500,876	158,476
903	1,239,977	150,047	1,128,629	155,746	1,058,411	149,914	1,419,311	144,342
904	1,485,344	145,970	1,338,934	135,892	1,329,206	157,900	1,218,291	156,926
905	1,198,397	163,124	1,208,513	155,856	1,425,032	168,268	1,391,309	162,462
906	1,036,409	134,420	1,471,360	138,332	1,374,235	146,789	1,213,584	162,075
907	1,117,921	154,458	1,218,846	146,006	1,120,148	151,125	1,613,089	168,177
908	1,050,037	141,308	1,403,140	145,780	1,322,793	130,554	1,385,178	144,663
909	1,063,677	145,128	1,154,296	142,921	1,358,971	157,325	1,383,694	165,693
910	1,323,945	138,451	1,379,131	139,318	1,254,801	157,404	1,236,149	173,519
911	1,214,601	126,622	1,044,729	121,394	1,329,723	144,894	1,487,020	151,861
912	1,239,906	145,942	1,432,172	148,233	1,171,182	159,009	1,267,307	148,953
913	1,116,220	158,052	1,225,494	163,328	1,287,942	143,887	1,363,166	168,979
914	1,127,303	142,307	1,259,318	156,669	1,248,388	137,620	1,363,541	163,717
915	1,174,560	168,468	1,177,133	145,367	1,389,872	135,841	1,395,615	150,954
916	1,283,949	136,506	1,187,880	152,150	1,187,953	153,925	1,538,000	138,793
917	1,082,905	175,955	1,098,952	156,561	1,170,363	160,046	1,345,990	154,241
918	1,300,089	146,440	1,178,093	153,088	1,210,307	150,684	1,321,511	165,754
919	1,179,880	160,618	1,292,626	157,957	1,280,284	165,090	1,413,617	167,768
920	1,155,885	142,988	1,205,957	155,375	1,177,626	171,109	1,156,057	165,909
921	1,177,600	148,210	1,298,745	147,650	1,241,989	139,768	1,315,073	148,754
922	1,109,443	139,316	1,227,027	143,412	1,266,715	161,656	1,390,393	166,935
923	1,191,734	136,506	1,212,148	140,354	1,421,420	158,843	1,445,679	153,171

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
924	1,155,345	152,187	1,201,183	132,210	1,384,101	151,079	1,271,063	153,628
925	1,301,655	147,093	1,442,919	139,462	1,246,298	168,302	1,366,353	161,171
926	1,231,700	138,675	1,184,103	160,892	1,392,956	164,823	1,237,647	161,162
927	1,309,365	156,446	1,240,716	155,964	1,375,348	165,623	1,297,821	162,149
928	1,163,318	145,959	1,611,718	158,801	1,223,310	166,805	1,351,745	152,540
929	1,141,444	142,839	1,372,830	151,737	1,302,836	159,274	1,307,058	161,052
930	1,318,853	143,867	1,100,970	154,201	1,175,005	131,847	1,229,226	154,949
931	1,169,017	134,956	1,054,911	164,516	1,481,045	137,691	1,485,666	145,824
932	1,213,105	137,264	1,487,834	150,395	1,014,830	143,111	1,528,583	158,213
933	1,224,834	158,299	1,236,967	138,708	1,241,056	169,668	1,193,923	152,623
934	1,269,525	164,451	1,559,728	146,036	1,377,047	161,039	1,292,232	155,257
935	1,084,941	173,998	1,330,149	144,800	1,293,162	164,006	1,284,909	133,074
936	1,228,573	154,702	1,094,896	147,954	1,222,920	150,372	1,236,532	146,671
937	1,224,818	153,430	1,435,170	163,042	1,251,927	153,748	1,137,197	158,499
938	1,221,032	146,487	1,096,360	144,542	1,179,156	149,567	1,441,188	159,752
939	1,100,970	152,526	1,315,602	141,015	1,188,275	145,886	1,197,506	156,376
940	1,198,020	142,490	1,098,043	145,002	1,277,913	158,159	1,245,630	151,331
941	1,128,765	143,640	1,203,758	155,560	1,264,330	175,825	1,289,814	135,361
942	1,226,175	139,808	1,235,696	143,536	1,271,691	159,918	1,261,060	167,846
943	1,129,525	138,393	1,122,444	135,332	1,163,310	136,044	1,496,418	158,243
944	966,629	145,948	1,284,291	146,405	1,140,155	146,963	1,142,509	161,412
945	1,068,288	154,178	1,221,514	149,442	1,401,205	159,357	1,283,427	169,010
946	1,033,298	162,364	1,370,469	165,623	1,268,370	152,453	1,553,050	149,929
947	1,081,058	147,036	1,117,363	155,382	1,207,394	157,363	1,126,862	153,954
948	1,232,281	137,894	1,136,328	163,806	1,497,205	152,123	1,276,171	149,738
949	1,176,107	137,200	1,326,354	146,410	1,122,637	166,404	1,304,327	148,450
950	1,043,127	166,472	1,354,072	154,342	1,263,766	149,559	1,336,548	153,251
951	1,514,385	143,997	1,140,940	148,559	1,216,859	151,365	1,368,476	154,825
952	1,116,689	138,395	1,513,693	146,775	1,309,758	155,564	1,529,212	161,383
953	1,167,771	148,586	1,169,500	157,914	1,254,918	155,884	1,527,413	164,459
954	1,332,011	136,446	1,229,126	162,371	1,304,798	148,922	1,415,583	164,774
955	1,134,902	149,849	1,109,539	149,700	1,147,114	148,089	1,391,599	150,937
956	1,216,579	155,465	1,525,700	144,030	1,565,046	135,702	1,333,326	179,722
957	1,159,219	151,342	1,213,276	146,874	1,147,752	145,446	1,370,511	152,539
958	1,098,866	159,787	1,459,012	164,687	1,178,568	175,559	1,321,490	164,460
959	1,241,178	160,078	1,426,359	141,813	1,163,056	142,433	1,137,829	151,597
960	1,051,544	145,013	1,388,921	146,627	1,445,737	145,389	1,339,217	156,630

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
961	1,201,765	171,668	1,446,254	150,314	1,430,816	159,059	1,298,378	161,752
962	1,235,007	147,933	1,309,009	160,749	1,098,328	143,101	1,488,463	147,819
963	1,054,596	147,466	1,067,164	160,808	1,325,495	162,249	1,544,055	161,110
964	1,250,318	133,558	1,236,147	179,675	1,228,060	168,324	1,691,279	152,974
965	1,138,807	157,497	1,185,197	149,658	1,283,511	132,001	1,399,103	175,100
966	1,076,475	156,412	1,220,477	135,500	1,137,366	146,655	1,229,345	167,656
967	1,267,791	126,639	1,258,880	164,001	1,117,055	160,586	1,277,711	171,915
968	1,074,241	127,014	1,359,908	157,147	1,090,318	148,925	1,592,028	151,617
969	1,195,885	152,515	1,346,919	122,608	1,190,181	134,850	1,596,068	152,873
970	1,183,764	168,671	1,469,489	149,005	1,302,760	156,169	1,353,023	143,934
971	942,941	156,463	1,299,176	164,098	1,575,485	154,863	1,511,288	161,383
972	1,095,790	151,348	1,293,343	166,164	1,307,719	159,591	1,444,533	142,420
973	1,246,870	143,658	1,399,032	156,604	1,238,508	151,147	1,398,145	147,903
974	1,137,640	135,675	1,006,710	151,869	1,203,487	177,429	1,290,789	154,729
975	1,196,415	141,418	1,185,939	163,905	1,213,978	170,900	1,248,076	148,246
976	1,330,746	135,488	1,154,359	146,664	1,160,980	147,138	1,331,057	162,880
977	1,177,441	143,414	1,165,184	153,842	1,199,937	142,431	1,565,641	159,912
978	1,372,430	148,986	1,199,802	140,348	1,429,295	143,799	1,119,895	167,144
979	989,658	160,992	1,213,470	145,803	1,024,950	132,788	1,413,053	169,606
980	1,476,051	185,063	1,269,502	153,147	1,422,536	143,873	1,157,441	159,989
981	1,162,486	134,560	1,180,021	138,748	1,394,804	142,509	1,388,053	165,597
982	1,200,143	148,874	1,158,217	143,646	1,167,642	154,929	1,412,198	155,017
983	1,320,373	154,458	1,157,758	156,904	1,217,451	144,172	1,332,806	166,706
984	1,320,602	149,498	1,292,526	172,990	1,204,360	160,298	1,478,222	136,766
985	1,177,398	149,340	1,260,781	136,573	1,325,689	149,979	1,157,606	140,396
986	1,120,514	155,039	1,217,402	148,316	1,385,933	142,498	1,372,227	143,302
987	1,298,912	146,838	1,146,840	149,248	1,358,192	155,740	1,272,599	164,207
988	1,141,712	138,182	1,317,632	165,310	1,131,279	144,951	1,223,429	166,558
989	1,325,743	136,532	1,204,118	166,961	1,511,460	156,458	1,338,585	171,338
990	1,386,577	139,190	1,316,524	151,347	1,465,025	154,867	1,280,895	165,153
991	1,286,521	149,763	1,348,890	155,586	1,339,988	148,444	1,375,809	175,022
992	1,081,312	148,673	1,060,411	142,982	1,426,305	143,169	1,271,469	151,795
993	1,022,306	149,042	1,091,863	154,735	1,122,787	162,901	1,251,988	159,642
994	1,012,022	150,562	1,145,083	157,232	1,387,825	153,198	1,472,657	164,666
995	1,155,006	168,156	1,183,596	151,941	1,287,448	134,965	1,253,133	156,147
996	1,322,728	136,278	1,241,680	164,894	1,350,156	152,488	1,336,792	145,891
997	1,217,391	123,544	1,343,145	152,667	1,275,455	145,128	1,506,156	150,934

Calculation No.	As-Built Trucking Distance (M = 1)		M = 2 Trucking Distances		M = 3 Trucking Distances		M = 4 Trucking Distances	
	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)	Embodied Energy (GJ)	CO_2 Emissions (tonnes)
998	1,249,402	150,484	1,214,056	146,451	1,333,090	156,034	1,366,942	146,386
999	1,031,421	145,146	1,125,107	130,833	1,248,904	139,776	1,399,525	169,067
1000	1,269,382	154,958	1,240,308	138,749	1,324,540	163,864	1,313,965	163,718

Q.3 REFERENCES

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Appendix R: Permissions for Use of Published Material

This Appendix contains permissions letters for reuse of previously published materials that are included in this dissertation. It also contains permissions for the direct use of the output from JMP Pro software.

Chapter 2: Energy and Carbon Assessment of Ground Improvement Works I: Definitions and Background.

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Title: Energy and Carbon Assessment of Ground Improvement Works. I: Definitions and Background

Author: Craig M. Shillaber, James K. Mitchell, Joseph E. Dove

Publication: Journal of Geotechnical and Geoenvironmental Engineering

Publisher: American Society of Civil Engineers

Date: 09/17/2015

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Chapter 3: Assessing Environmental Impacts in Geotechnical Construction: Insights from the Fuel Cycle.

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Conference Proceeding:	Geo-Congress 2014 Technical Papers: Geo-Characterization and Modeling for Sustainability
Conference Proceeding Paper:	Assessing Environmental Impacts in Geotechnical Construction: Insights from the Fuel Cycle
Author:	Craig M. Shillaber, James K. Mitchell, Joseph E. Dove
Publisher:	American Society of Civil Engineers
Date:	02/24/2014

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Title:	Energy and Carbon Assessment of Ground Improvement Works. II: Working Model and Example
Author:	Craig M. Shillaber, James K. Mitchell, Joseph E. Dove
Publication:	Journal of Geotechnical and Geoenvironmental Engineering
Publisher:	American Society of Civil Engineers
Date:	09/17/2015

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VirginiaTech Invent the Future

Craig Shillaber <cmshill@vt.edu>

Question Regarding Exclusive Copyright Agreement for Deep Mixing 2015

3 messages

Craig Shillaber <cmshill@vt.edu> Wed, Apr 22, 2015 at 9:15 AM
To: tengler@dfi.org
Cc: staff@dfi.org

Good Morning Theresa:

I have a question regarding the exclusive copyright agreement for publication of a paper in the proceedings of the Deep Mixing 2015 Conference. I was wondering if based on item 4 of the agreement, it was acceptable for me to use the paper in its final format in my Ph.D. dissertation, with a reference to where it was originally published? Ultimately, dissertations are published by the university and accessible (publicly available) through university libraries.

If not, I would like to maintain the rights to do so, and could attach an addendum to the publishing agreement to that effect.

Thank you,

Craig

Craig M. Shillaber
Ph.D. Candidate
Via Department of Civil and Environmental Engineering
Virginia Tech
Blacksburg, VA

Theresa Engler <tengler@dfi.org> Wed, Apr 22, 2015 at 3:59 PM
To: Craig Shillaber <cmshill@vt.edu>
Cc: Staff <Staff@dfi.org>

Craig,

As described in item #4, you retain ownership of the paper but you must acknowledge and reference DFI's publication in which it was originally published. Therefore, yes, you can use it in your dissertation and as long as the acknowledgement remains with it, the university can publish it.

I hope this answers your question.

Best regards,

Theresa

Permissions for Use of EIO-LCA Results from the Carnegie Mellon University Green Design Institute EIO-LCA Website.

Craig Shillaber <cmshill@vt.edu>

Usage and Copyright When Using Results from the EIO-LCA Website

5 messages

Craig Shillaber <cmshill@vt.edu> Fri, Nov 13, 2015 at 7:52 AM
To: green-design@andrew.cmu.edu

Hello,

I have been working on quantifying the embodied energy and carbon associated with the construction of geotechnical works (e.g., foundations, ground improvement). As part of my work, I've been developing unit coefficients of energy and carbon for materials that can be easily used for quantifying the impacts from multiple case history projects. To develop a coefficient for bentonite clay, which is widely used for drilling mud, I used the EIO-LCA website in conjunction with information in the following publication:

Jiang, M., Griffin, M. W., Hendrickson, C., Jaramillio, P., VanBriesen, J., and Venkatesh, A. (2011). "Life cycle greenhouse gas emissions of Marcellus shale gas." *Environmental Research Letters*, 6(3).

Essentially, I used the mass and price of bentonite per well as presented in the above publication to determine the amount of carbon and energy per kilogram of bentonite from the EIO-LCA website results.

My question is, if I want to use the coefficient I derived in a spreadsheet tool that could potentially be released or used beyond my current academic research, what is appropriate and fair use of bentonite energy and carbon coefficients derived in this manner?

Thank you,

Craig

Craig M. Shillaber
Ph.D. Candidate
Via Department of Civil and Environmental Engineering
Virginia Tech
Blacksburg, VA

Michael Griffin <wmichaelgriffin@cmu.edu> Fri, Nov 13, 2015 at 8:33 AM
To: Craig Shillaber <cmshill@vt.edu>

Craig,

You are free to use the information that is in the public domain for your research. We ask, as all academics do, to cite the paper and the EIOLCA model.

Good luck in your work.

MG

W.Michael Griffin, Ph.D.
Associate Research Professor,
Engineering and Public Policy

Craig Shillaber <cmshill@vt.edu> Fri, Nov 13, 2015 at 8:54 AM
To: Michael Griffin <wmichaelgriffin@cmu.edu>

Dr. Griffin:

Thank you for the prompt reply. I will certainly make sure everything is cited.

Is the Fair Use situation different if the calculation spreadsheet I have been developing (including the coefficients I derived for bentonite) is released outside my dissertation and academic papers? A few faculty here would like to see my work and method reach practitioners through the Center for Geotechnical Practice and Research (CGPR) here at Virginia Tech, in order to advance sustainability considerations in geotechnical engineering. The CGPR is a forum for communication, interaction and exchange of ideas among geotechnical engineers in practice and academia. If any of my work is released through the CGPR, practitioners may use it in some of their commercial work.

Thank you,

Craig

Craig M. Shillaber
Ph.D. Candidate
Via Department of Civil and Environmental Engineering
Virginia Tech
Blacksburg, VA

[Quoted text hidden]

Michael Griffin <wmichaelgriffin@cmu.edu> Fri, Nov 13, 2015 at 9:18 AM
To: Craig Shillaber <cmshill@vt.edu>

No. You are developing this work for your degree. The dissertation is a public document. People would be free to use your data.

MG
[Quoted text hidden]

Permissions for use of JMP Software Output.

Craig Shillaber <cmshill@vt.edu>

[SAS 7611589858] FW: JMP 11 Pro License Question

1 message

SAS Education <training@sas.com> Fri, Sep 11, 2015 at 12:17 PM

To: Craig Shillaber <cmshill@vt.edu>

Hi, Craig:

I am an instructor and Curriculum Consultant with SAS Institute. Your question has been forwarded to me for response.

According to our Legal Department, SAS doesn't claim copyright ownership of output created by using our software, including JMP, so no permission is required.

I hope this information clarifies that you do not need copyright permission to use your reports and output examples in your dissertation. If I can be of further assistance with training questions, please let me know.

Sincerely,

Cynthia Zender

SAS Education

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