A Framework for Benchmarking and Monitoring Building Construction Embodied Carbon Footprint Using Building Information Models

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ABSTRACT

In recent years, the application of Life Cycle Assessment (LCA) databases has enabled architects/engineers to quantify the environmental impact of building materials for whole building analysis and comparative analyses of design alternatives. The application of building information modeling (BIM) has facilitated this process by providing designers and engineers with the detailed bill of materials required for LCA. However three limitations exist: First, LCA assessments have been limited to the design phase of a project delivery or post completion phase. Consequently, it does not help incentivize the choice of suppliers and delivery strategies that minimize the cradle-to-site impacts. Second, majority LCA tools ignore the impact of construction means and methods during the construction phase. Third, there is a lack of metrics and visualization tools that assess environmental impacts of decisions made during pre-construction and construction phase. As a result, little incentive exists for suppliers to provide embodied carbon footprint rates, and similarly, for contractors to balance project costs, schedule objectives with the corresponding environmental impact. To address these challenges, we propose and develop a new framework that applies BIM for reliable, effective benchmarking, monitoring, and visualization of embodied carbon footprint of construction projects. It comprises of a benchmarking module, and a monitoring and visualization module. In the experiments, this framework is implemented on concrete placement activities during the construction of the Center for the Arts facility at Virginia Tech. The developed framework can revolutionize construction by a) a rapid assessment and visualization of the deviations between expected and released carbon footprint, b) incentivizing contractors to request that manufacturers and suppliers gauge and share their carbon footprints as a part of contractor submittal process and c) incentivizing those construction firms that can complete their project with an overall carbon footprint rate lower than what is budgeted during the pre-construction or compared to the values from the design phase, while documenting and using the performance results as a benchmark for future similar projects.

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CHAPTER 1: INTRODUCTION

The construction industry is considered to be one of the major contributors of Green House Gas (GHG) emissions (EPA 2010). According to the U.S. Environmental Protection Agency (EPA), emission from 14 industrial sectors in the U.S. accounts for 84 percent of the industrial GHG emissions, while the construction sector is solely responsible for six percent of the total U.S. industrial related GHG emissions. This places the construction sector as the producer of the third highest GHG emissions among all sectors. 20 to 21 percent of this total emission (see Figure 1), embodied carbon footprint – the carbon associated with manufacture of materials and their transportation/delivery method to a jobsite – is released mainly during the first few years of a project, while the remaining 79-80 percent is released throughout the rest of the lifecycle (Lane 2007,UNEP 2009)). The relatively large amount of emission produced in a short period of time and the pressure on polluters to reduce their GHG emissions to 1990 levels by 2020 are growing eco-awareness towards the construction sector (EPA 2010). For example, in California a set of cap-and-trade regulations were recently endorsed, which provide covered entities the flexibility to seek out and implement the lowest-cost project alternatives and reduce GHG emissions (ENR 2010).

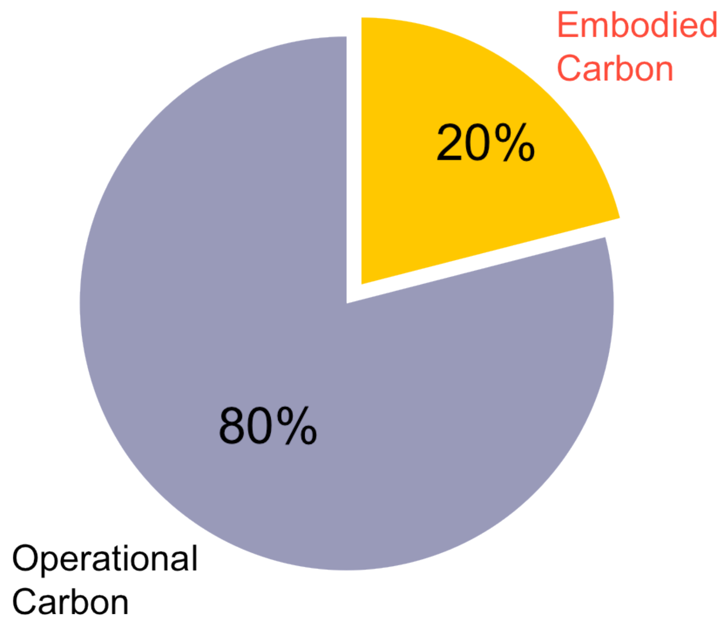


Figure 1. Total Carbon Footprint typical building: Embodied Carbon + Operational Carbon.

Over the past few years, several third party standards and rating systems such as Leadership in Energy & Environmental Design (LEED) and International Organization for Standardization (ISO) 14040 were formed to support carbon footprint assessment of a project. For example, LEEDv4 has new point categories in building product disclosure and optimization for environmental product declarations, sourcing of raw materials, and materials ingredient reporting (LEED MRpc63: Whole Building LCA). The application of Life Cycle Assessment (LCA) databases including material attributes, assembly details, architectural and engineering specifications, and environmental impact data has enabled architects and engineers to perform LCA more frequently and quantify the environmental impact of building materials for whole building analysis as well as comparative analyses of project design alternatives. Building Information Modeling (BIM) has also facilitated the process by providing designers and engineers with the detailed bills-of-material that is necessary for performing LCA. Several BIM authoring tools are integrated with comprehensive LCA databases from various manufacturers – e.g., Project Tally– for accurate and faster tracking and reporting environmental impacts across a range of categories and characterization schemes. Nevertheless, today's practice of LCA is primarily limited to the design phase of a project delivery or has been conducted after the construction is complete (Tally 2014).

During the design phase, such assessments are primarily based on general assumptions about the carbon footprint of the expected-to-be-used materials and their bill-of-quantities. For projects involving the large-scale use of various construction materials, the project manager may need to initiate the procurement process even before the selection of a contractor in order to avoid shortages and delays (Hendrickson 2008). In these situations, shop drawings, which reflect the accurate material information and the sources of procurement, are not available. Although the shop drawings must conform to the design intent reflected in the architects and engineers' documents and at the same time meet owner's expectations, the carbon footprint associated with the manufacturing is not estimated from these drawings. The changes on the source of materials or their suppliers can have a reasonably large impact on the carbon footprint associated with raw material extraction and processing and final manufacturing and assembly.

In the meantime, since contractors or subcontractors are not typically in the freight business, they do not properly plan or perform the tasks of freight delivery efficiently (Hendrickson 2008). As a result, the carbon footprint associated with the intermediate transportation and delivery of materials or pre-assembled modules to the jobsite – which can account for up to 6% of the overall cradle-to-grave carbon footprint (Lane 2007, D-Carbon8 and Skanska 2008) (See Figure 2) – is not typically considered as part of the environmental impacts. Benchmarking these impacts at the pre-construction phase and comparing them with the values estimated during the design phase can help minimize these impacts. Nevertheless, currently there is no framework or tools that can easily and quickly assess the carbon footprint associated with the procurement and delivery of different material and update their values in the underlying project BIM (Memarzadeh and Golparvar-Fard 2012).

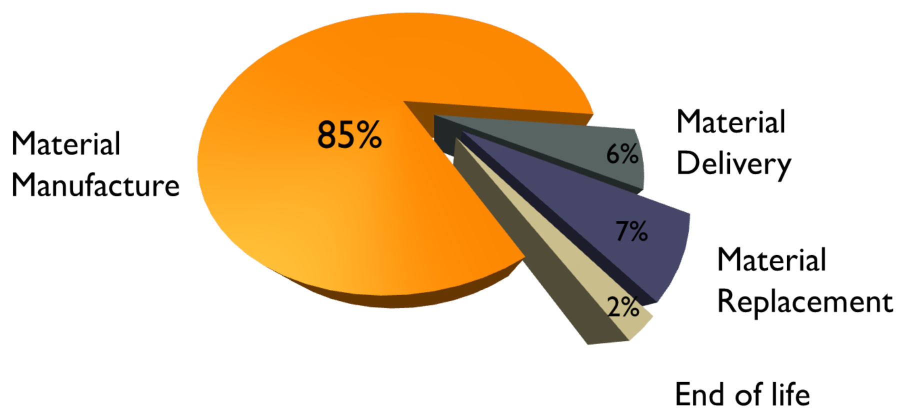


Figure 2. Embodied Carbon: Life Cycle Distribution

The submittal review process during the preconstruction stage and the early stages of the construction phase can provide an excellent opportunity to perform the cradle-to-gate and cradle-to-site carbon footprint assessment associated with the different materials and their delivery methods. Currently during the submittal review process, the shop drawings and sample submissions are reviewed to make sure they comply with the drawings and the project specifications. Nevertheless, the architect, engineers or project managers' reviews do not include approvals of the embodied carbon associated with the manufacturing and delivery of the materials, construction methods and/or their associated procedures. As a result, material cost, delivery time, quality, and availability are often the main criteria to select the material supplier and the choice for the lowest embodied carbon associated with the manufacturing process as well as the transportation to the site are not considered. Consequently the contractors also do not have enough incentive to force upstream supply chains to provide accurate data on the embodied carbon footprint of their products. Without a proper knowledge about the sources of materials, their manufacturing processes, the shop drawing and submittal details, and final delivery methods, any estimates on carbon footprint may be inaccurate or such assessments may be deemed optional.

The management of the construction phase also suffers from the lack of established frameworks for monitoring embodied carbon footprint. While contractor submittals and field reports can be used to document the released (actual) carbon footprint for each construction activity, currently none of the existing LCA platforms support monitoring of the actual footprint associated with a project. The main limitations are: 1) the lack of analytical framework for comparing expected and actual carbon footprint rates; and 2) intuitive metrics and visualization tools that can illustrate the excessive carbon footprints or reductions associated with decisions during contractor coordination processes. Without a systematic mechanism for benchmarking and monitoring carbon footprint during the submittal process, manufacturers do not face any pressure from the end users to minimize the carbon footprint associated with the extraction of the raw materials or their manufacturing techniques. The same applies to contractors and subcontractors, as currently there is no mechanism to support them in selecting the most environmentally friendly manufacturers, suppliers, jobsite delivery solutions, or construction means and methods with the least negative environmental impacts, while considering cost and schedule objectives. All in all, project stakeholders cannot easily and quickly benchmark and monitor embodied carbon footprint of their construction operations.

Embodied carbon of a building material is a key concept in this thesis and will be defined as the carbon dioxide released over its lifecycle. According to its boundary condition, it will include certain phases of the lifecycle of a material. When considering cradle- to- grave, it refers to all carbon dioxide released until the end of the product's lifetime, throughout the processes including extraction, manufacturing, transportation, use (installation on site) maintenance, waste disposal and end of life phase. A cradle-to-gate approach includes the extraction of raw materials, manufacturing, and transportation until the product leaves the factory gate and a cradle-to-site includes all carbon released until the product has reached the point of use. (Hammond and Jones, 2011). The boundary condition used in the implementation of the case study is cradle-to-site, which includes all of the carbon dioxide emitted from the extraction of the raw materials until the product has reached the job site.

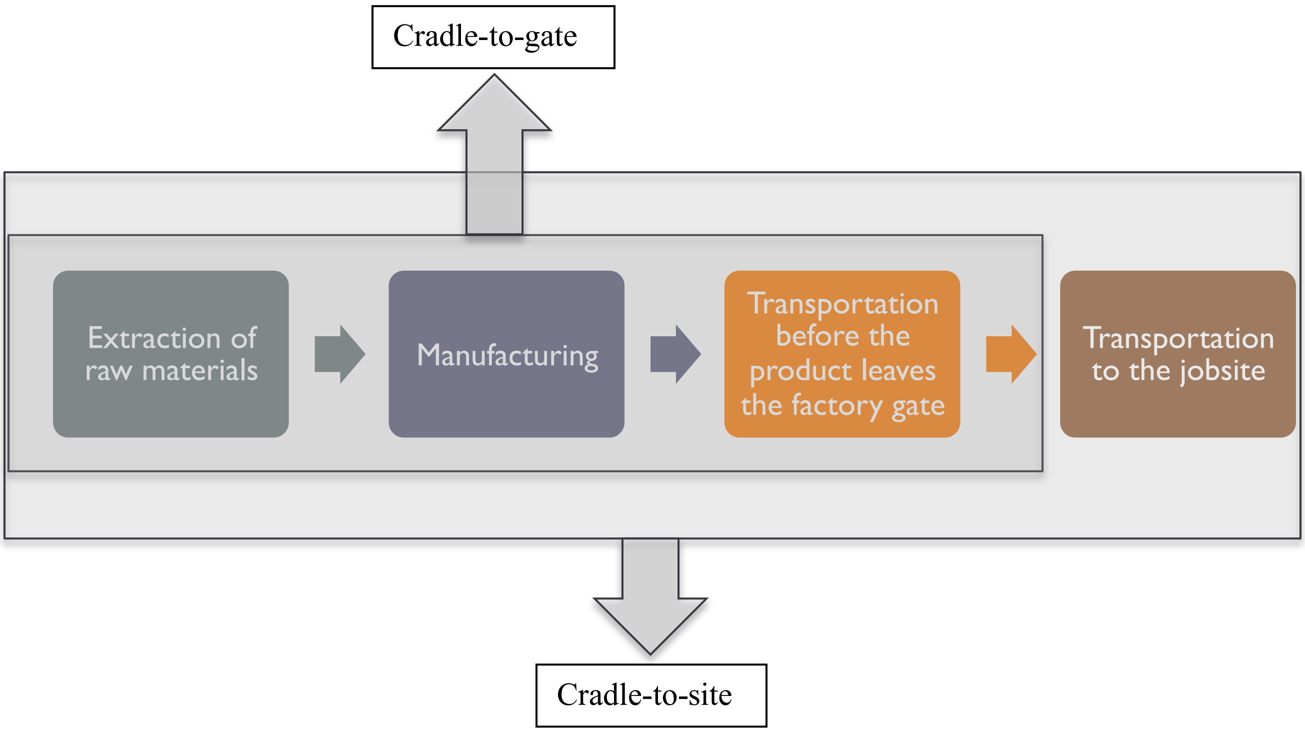


Figure 3.Boundary Condition Analysis Embodied Carbon

1.1. Limitations of the current research studies

Despite the important contribution of the state-of-the-art studies regarding the quantification of carbon footprint, these are several limitations that require further examination. These limitations are outlined in the following:

1. A majority of the state-of-the-art frameworks and tools developed to benchmark the energy consumption and carbon footprint are geared toward applications during the design and use/occupational phases. Thus, how the upstream supply chain can be incentivized to provide embodied carbon footprint data and how different supply and delivery techniques can be compared at the pre-construction phase of a project to enable the analysis of environmental impacts together with cost and schedule have not been fully explored. Consequently, today's practice has primarily looked at minimizing cost and time associated with those choices made during the design phase, overlooking the potential in choosing the most environmental friendly suppliers and their delivery techniques to construction sites;

2. There are no analytical frameworks or workflows for monitoring embodied carbon footprint during the construction phase. While Earned Value Analysis can provide a great platform for tracking cost and schedule, no considerations have been made for the environmental impacts of a project; and
3. There is a need for intuitive metrics and visualization tools that can easily and quickly communicate the excess or reductions from the benchmarked emissions associated with construction decisions associated with construction decisions. As a result, stakeholders have remained unaware of the choices that can satisfy environmental objectives while keeping cost and schedule parameters in mind.

Figure 3 highlights the gap in existing knowledge and represents the focus of this thesis, which is highlighted in contrast to the body of knowledge on embodied carbon footprint benchmarking and monitoring as well as LCA related studies. To minimize the "excessive" environmental impacts associated with the poor construction decisions and provide more incentive for choosing environmental friendly supply, delivery, and construction methods, there is a need for research on frameworks that can leverage state-of-the-art BIM and LCA tools for benchmarking, monitoring and visualization of carbon footprint. Further details regarding the gap of knowledge in each of the recent studies is presented in Chapter 2 of this thesis.

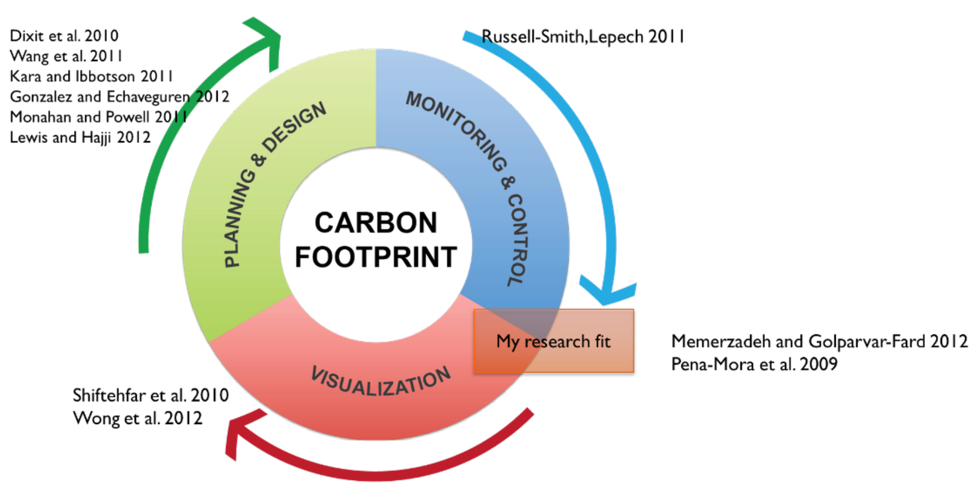


Figure 4. Gap-in-knowledge analysis diagram

1.2. Research Objectives

The over-arching goal of this research is to create, implement and validate a new management framework together with intuitive metrics and a visualization tool using BIM for the purpose of benchmarking and monitoring carbon footprint of on-site and off-site construction activities. While the proposed method is generic and can be applied to all construction projects, it does not intend to assess and track all kinds of construction operations or machinery emissions. Rather the specific scope of the validation is on concrete placement operations involving procurement and delivery of steel rebar and formwork, as well. Concrete placement operations are typically part of the critical activities and can also have a significant contribution to the carbon footprint. Figure 4 shows their contributions to the overall embodied carbon footprint in a case study project.

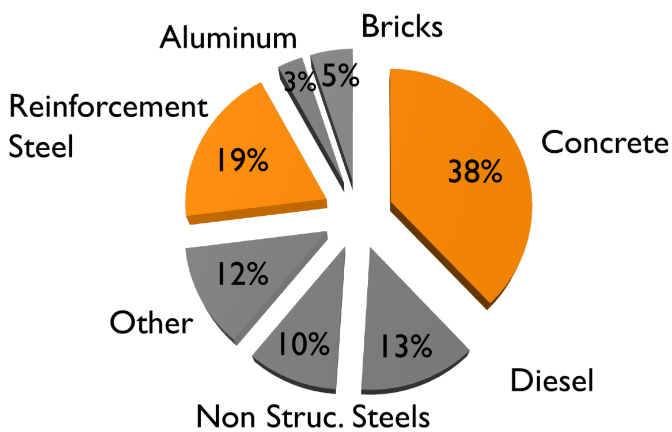


Figure 5. Materials contribution to embodied carbon in a typical building project. (Adapted from D-Carbon8 and Skanska 2008). Used under fair use, 2014.

Within the defined over-arching goal for this project, the objectives are as follows:

4.1 Identify the current practices and limitations regarding benchmarking cradle-to-gate and construction/assembly carbon footprint during pre-construction phase of a project, and monitoring and visualization of performance deviations during construction phase;

4.2 Develop a management framework with supporting research prototype tools for benchmarking, monitoring and visualization of carbon footprint during the preconstruction and construction phases, using building information models; and

4.3 Validate the applicability of the proposed framework.

The successful implementation of the proposed research has potential to improve the way construction operations are currently being benchmarked and monitored. It can provide new guidelines to project stakeholders on how benchmarks for carbon footprint can be accurately established. The analytical framework also has potential to 1) provide incentives to suppliers to release their carbon footprint rates to subcontractors and contractors; 2) provide opportunities for incentivizing those subcontractors and contractors who choose more environmentally friendly delivery and construction methods as opposed to purely assessing progress based on cost and schedule, as it is done in today's practice of Earned Value Analysis. The monitoring metrics and the visualization tools can also bring more awareness to the excess or reductions in environmental impacts associated with different construction decisions.

1.3. Research Methodology

This section discusses the overall research methodology that was conducted as part of this research. The flowchart is illustrated in Figure 5. It summarizes the steps followed to conduct this research and the associated case study. A thorough literature review of embodied carbon, LCA and carbon footprint monitoring and visualization studies have been performed to identify the gaps in the current body of knowledge. Methods that can potentially validate the proposed method of monitoring carbon footprint have also been reviewed. After the research objectives were formulated, the practitioners involved in the Virginia Tech Center for the Arts construction project were contacted to collect the necessary data for this study. Access to the contractor submittal platform and project construction documents were requested and granted. After several initial interview sessions, the data collection began in the summer of 2013. After the data collection was completed, the benchmarking and monitoring prototype was developed and verified to determine if there was evidence that the posed hypothesis could be supported. The experimental results were utilized to derive a conclusion for the study and develop this thesis. Each step will be documented in detail in this section to further explain the methodology of this research.

Figure 6. Research methodology flow chart

The specific hypothesis to be tested in this research is whether the proposed carbon footprint benchmarking and monitoring framework explained in detail in Chapter 3 has potential to be used as an analytical and management tool during the delivery of capital projects. By choosing a flexible design strategy – conducting a case study – the proposed framework was implemented and tested. As mentioned earlier, the data required for this project was collected from the Center for the Arts construction project at Virginia Tech. This data comprises concrete activities related submittals, shop drawings and the construction documents of the project. The Center for the Arts was chosen because it was an ongoing construction project and access to the submittal and shop drawings system and construction document was granted. A LOD300 BIM was developed using the construction documents. The scope of the data collection for LCA was limited to concrete placement alternatives. The placement of concrete and the activities associated to these operations are typically part of the critical activities in a construction schedule and can have a significant contribution to the carbon footprint.

This framework is intended to support decision-making at two steps: 1) pre-construction phase: by providing a tool for benchmarking and assessment of different material procurement and transportation delivery options during the submittal review process, and 2) construction phase: by providing a mechanism that can support integrated monitoring of schedule and released carbon footprints. Therefore the implementation of the research prototype through a case study contributes to testing and validating the proposed framework.

In order to address objective No.1, which entails the identification of the current practices and limitations regarding benchmarking cradle-to-site and construction/assembly carbon footprint during pre-construction phase of a project, and monitoring and visualization of performance deviations during the construction phase, a thorough literature review was performed. The literature review comprised of the analysis of key studies related to the areas of LCA, embodied carbon and monitoring and visualization of carbon footprint. The aim of the literature review was to highlight the lack of a benchmarking, monitoring and visualization tool of carbon footprint during the preconstruction and construction phases of a project. The contribution of a systematic framework will facilitate the environmental impact assessment of practitioner's decisions related to materials, delivery technique and construction methodologies.

Objective No.2 entailed the development of a management framework for benchmarking, monitoring and visualization of carbon footprint during the preconstruction and construction phase using building information models. To create this, the initial idea of a fellow colleague was the inspiration but it was decided to be adapted to be used with Building Information Modeling since in the past year a new Revit add in tool was released to assess whole building life cycle analysis of embodied carbon, therefore a significant and practical approach was taken. The refining of the original framework also included the consideration of the construction methodology impacts in the monitoring phase of the project.

Objective No.3 comprised the applicability of the proposed framework as a management tool in the construction industry for which we performed a case study. A case study was chosen because it demonstrated how the framework could be implemented in an ongoing construction project and it helped communicate how it will be used in the construction industry as part of the management activities of the practitioners. As mentioned earlier, the data required for this project was collected from the Center for the Arts construction project at Virginia Tech. This data is composed of concrete activities related to submittals, shop drawings and the construction documents of the project. The Center for the Arts was chosen because it was an ongoing construction project while access to the submittal and shop drawings system and construction document was granted. A LOD300 BIM was developed using the construction documents. The scope of the data collection for LCA was limited to concrete placement alternatives. The reason for looking into placement of concrete and the activities associated to these operations is because these are typically part of the critical activities in a construction schedule and can have a significant contribution to the embodied carbon footprint of a building.

The construction documents that were reviewed in order to implement the study were: the original and updated schedules to identify the construction activities to be analyzed, the BIM of the project to extract material information of the activity analyzed, contractor submittals and construction project reports that allowed for the identification of the specifications and actual quantities of the materials which allowed for further calculation of both their expected and actual embodied carbon footprint.

The initial proposed framework's inventory currently does not include the environmental impact produced by the construction operations that occurred during the installation procedure of the materials selected. The main reason is the absence of a dataset related to construction methodology. Manual calculations can be performed but intensive input is needed. For the purpose of our study, several assumptions related to the onsite operations are made for different scenarios.

During pre-construction phases, the benchmarking module was where the calculations of expected carbon footprint took place. This allowed for an alternative-scenario analysis where the decisions were taken regarding material selection, supplier's selection and delivery technique. In the monitoring module, during construction, the data from construction project reports were assumed to be available, and the actual material's quantities, supplier's location and distances, transportation mode and product's data were used to calculate the actual release of CO_2 and its overall contribution to embodied carbon of the buildings. Further discussion of the methodology used is explained in Chapter 3 and Chapter 4.

1.4. Validation of the proposed research framework

The validation phase of this research project comprised testing of the proposed framework and the supporting research prototype by applying the framework to the case study. In order to implement the framework we collected the data from the ongoing project; this data comprises:

BIM, shop drawings, baseline/updated schedules, contractor's submittals, shop drawings, construction project reports, and the specification document of the project (See Figure 6).

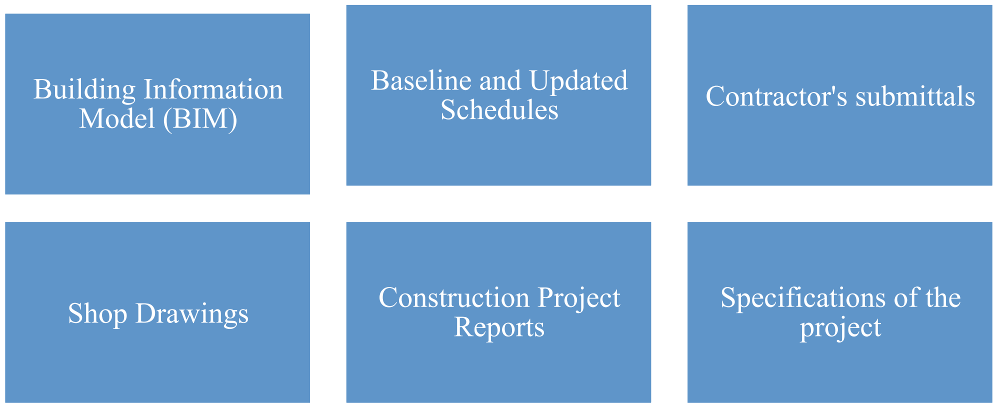


Figure 7. Different type of data collected from the case study site.

Feedback from practitioners was solicited both before and after implementing the framework on the following questions:

- What are the current process and workflows for the procurement process?
- What is the current practice in benchmarking and monitoring carbon footprint, if any?
- How could we implement an automated process that facilitates decision-making that benefits construction operations?
- What are the best practices to ensure benchmarking expected emissions during the planning phase of a project?
- What are the most beneficial elements of the proposed framework and what are the opportunities for further improvements?

This process provided useful information on how the proposed framework and the developed prototype can improve existing processes. The input received by the stakeholders was very valuable, since it allowed a better understanding of the industry practices and needs, and identified the perceived benefits and limitations of this study.

1.5. Manuscript Overview

The discussion in this manuscript is broken down into the following chapters. In Chapter 2, the existing literature in the areas of carbon footprint lifecycle analysis and visualization are reviewed. Chapter 3 proposes the embodied carbon benchmarking and monitoring framework and showcases the research prototype. In Chapter 4, the experimental setup is discussed which further explores the application of the benchmarking and monitoring framework proposed in Chapter 3. An example case study is developed, and the experimental results obtained are discussed. Chapter 5 concludes the discussion, by summarizing the conducted research, the contributions, perceived benefits and limitations, and proposes future work in this area of research.

CHAPTER 2: RELATED WORK

The state of knowledge presented here outlines current research related to carbon footprint assessment and the research efforts in automating assessment of construction footprint.

2.1. Current Research in Life Cycle Assessment and Embodied Carbon in Construction

Over the past few years, there have been several studies that have focused on measuring and assessing embodied carbon in the construction industry. Hammond and Jones (2008,2011) developed the most recent database for embodied energy and carbon emissions for over 200 different types of construction materials, cradle-to-gate and cradle-to-site data that allows benchmarking the carbon footprint. Their work is significant since there was no previous extensive database developed for embodied energy and carbon dioxide emissions associated to the construction industry. Therefore it has become an important reference for succeeding publications and practices related to carbon footprint. The study of Hammond and Jones (2008) was chosen because it was the first extensive database developed for embodied carbon in construction materials in the industry and its findings were used as the embodied carbon database in the case study implementation.

Dixit et al. (2010) analyzed the existing literature related to embodied carbon footprint in order to identify differing parameters that would facilitate the development of a consistent and comparable database. Their work revealed that there were 10 parameters that influenced the quality of embodied energy results. Those are: 1) system boundaries, 2) method of embodied energy analysis, 3) geographic location, 4) primary and delivered energy, 5) age of data, 6) data source, 7) completeness of data, 8) manufacturing technology, 9) feedstock energy consideration and 10) temporal representation. This study points out the need for developing a reliable standardized approach to embodied energy data collection that could be used by researchers and practitioners worldwide. In this study, the embodied energy was expressed in two fundamental units: mega joule (MJ) and kilogram of carbon dioxide equivalent (kg CO2eq). Dixit et al. (2011) study allowed for the understanding of the parameters that influence the embodied carbon results and evaluate critically the different data associated with the values found in other studies.

Kara and Ibbotson (2011) approached the study of embodied carbon by analyzing the life cycle of a product that was manufactured in several scenarios of a supply chain using the LCA software SimaPro. Three key supply chain factors: 1) supplier location, 2) transportation type and 3) travel distances were varied across these scenarios. This study highlights the significance of the mode and distance of transportation, and the impact it can make on the cradle-to-site LCA. Kara and Ibbotson's (2011) conclusions helped understand some of the key phases that influence the values of embodied carbon and supports the arguments of how the supplier location, transportation type and travel distances influences the embodied carbon values.

Chrishna et al. (2011) presented a process based cradle-to-gate and cradle-to-site Life Cycle Analysis (LCA) in order to quantify embodied energy and CO2 of the dimension stone production in the UK. Despite their contributions to the body of knowledge, this study did not include several upstream and downstream processes related to each stage of the life cycle (upstream: i.e.; raw material extraction and on-production site transportation, downstream: transportation to site or vehicles consideration). Therefore, it did not represent a realistic picture of the overall carbon footprint. It also pointed out the extensive input needed to assess a reliable LCA study. This allowed for a better understanding of the components that comprise a LCA and the extensive input needed to assess a result. This supported the argument that a material's source location has a significant environmental impact in its overall embodied carbon.

Monahan and Powell (2011) quantified and compared the embodied carbon in the construction of a house using a modern method of construction with traditional methods using a cradle-to-site LCA during the design phase. Their analysis suggests evaluating alternative materials and construction methods during the design phase could result in a significant contribution towards the minimization of the carbon footprint. This particular study helped us understand the importance of construction decisions but it also sparked the idea of a carbon footprint tool that facilitated the assessment and tracking of the actual environmental impact during the preconstruction and construction phase of a project.

All of these previous studies have contributed to techniques that can be used as part of decision-makings on design alternatives and have repeatedly pointed out the difficulty in finding a consistent reliable embodied carbon database for all the materials and the amount of input work needed to perform a product life cycle analysis.

2.2. Embodied carbon, LCA integration with BIM

A new trend in research has looked into integrating Building Information Modeling (BIM) with LCA in order to automatically perform quantity take offs, generate bills-of-materials, and perform a more comprehensive analysis of the facilities carbon footprint. One of the most recent studies by Smith and Lepech (2011) developed a computational framework that integrates LCA and Building Information Modeling (BIM) to construct dynamic life cycle models that capture environmental impacts of facilities associated with every life cycle. Such methods facilitate the quantification of the sustainability impacts and the decision making process during the design and construction phase by adopting the variance control technique in construction management in order to assess environmental impacts associated with every life cycle phase. Nonetheless, their work did not discuss how the actual carbon footprints during the construction phase could be more accurately benchmarked or monitored. Smith and Lepech (2011) contributed to a possible solution to the challenges encountered when performing LCA in construction and it supported the idea of a future automatized computer framework that could assess environmental impact at every lifecycle stage of the building.

Wang (2011) conducted a case study which looked at the potential of utilizing BIM to perform whole building LCA using Autodesk Ecotect. From the study, it was concluded that BIM and Ecotect could be very helpful in performing LCA since they can provide the majority of the necessary information and calculation tools for performing LCA. Despite their novel contribution, this study was also limited to applications during the design phase of the project.

These studies promote the early integration during the design phase, but also highlight the lack of a tool that could help benchmark and monitor the embodied carbon during the pre-construction and construction phases. Its findings suggested that there was room for improvement in finding solutions that facilitate the environmental assessment; they supported the idea of developing a framework that facilitated environmental assessments in a more efficient way.

2.3. Current Research for Carbon footprint measurement of on-site construction processes

Over the past few years there have been several studies that have focused in quantifying the carbon emissions on the project site by presenting different frameworks for models that assess the energy and environmental impact of construction activities. Palaniappan et al. (2012) has conducted several case studies to measure the carbon emissions on the construction site. One of them is the quantification of carbon emissions related to on-site equipment use in the post-tensioned slab foundation construction process of production homes in Phoenix, Arizona where it analyzed the environmental impact (in terms of carbon emissions) of the most important trades and the construction activities associated. This study is important, as it is among the very first that focuses on possible ways to minimize environmental impacts associated with decisions made during the construction phase of a project. It also highlights the importance of measuring carbon emissions to help contractors understand and improve the environmental performance of onsite processes. Palaniappan's et al. (2012) contribution adds to the idea that minimization of environmental impact could be pursued through the measurement of carbon emissions associated with the construction methodology and on-site equipment decisions during the construction phase. This helped explain how the framework that was proposed could be utilized as a management tool during the construction phase to monitor the actual carbon emission released consequence of the decision taken by contractors earlier in the preconstruction phases of a project.

Nonetheless, these studies do not present a unified framework that can be used for benchmarking and monitoring both cradle-to-site and construction carbon footprint. Moreover, no workflows have been proposed for assessing and visualizing the actual emissions and carbon footprint. The main reason is the non-existence of accurate material databases and the lack of systematized techniques that allows the benchmarking and tracking of the embodied carbon for construction processes.

2.4. Current Research in Monitoring and Visualization of Carbon Footprint in Construction

Memarzadeh and Golparvar (2012) proposed the first framework for monitoring embodied carbon footprint. Their method was based on the D^nAR - n dimensional augmented reality - models in which the expected and released embodied carbon footprint of a project were jointly represented in a common 3D environment. Their framework has potential to provide practitioners with an opportunity during coordination and submittal processes to not only ensure timely delivery of materials and keep projects on budget, but also minimize the cradle-to-site carbon footprint of their projects. Another important novel approach, Wong (2012) has been the use of virtual prototyping (VP) technology and mixed reality (MR) for the carbon emissions visualization and prediction of the construction project's processes on site. Despite the importance of these preliminary works, there is a lack of an integrated framework and supporting prototypes for facilitating the process of benchmarking, monitoring, and visualizing carbon footprint on construction sites. These limitations in the current literature are the basis of this research project. Wong's proposal strengthens the argument that there is a lack of a systematic approach that facilitates the benchmarking and monitoring of carbon footprint on construction sites (2012).

All of the previous studies mentioned were selected because they contributed to the overall idea of a need for a systematic approach of carbon footprint assessment at preconstruction and construction stages that allowed the benchmarking, monitoring and visualization of the embodied carbon footprint produced by building construction. Additionally, some of the previous studies highlighted how the embodied carbon in buildings is influenced by the material, delivery technique and construction methodology decisions, which are key components in our management proposed framework.

2.5 Limitations of the current research studies

Despite the important contribution of the state-of-the-art studies regarding the quantification of carbon footprint, these are several limitations that require further examination. These limitations are outlined in the following:

1. Majority of the state-of-the-art frameworks and tools developed to benchmark the energy consumption and carbon footprint are geared toward applications during the design and use/occupational phases. Thus, how the upstream supply chain can be incentivized to provide embodied carbon footprint data and how different supply and delivery techniques can be compared at the pre-construction phase of a project to enable the analysis of environmental impacts together with cost and schedule have not been fully explored. Consequently, today's practice has primarily looked in minimizing cost and time associated with those choices made during the design phase, overlooking the potential in

choosing the most environmentally friendly suppliers and their delivery techniques to construction sites;

2. There are no analytical frameworks or workflows for monitoring embodied carbon footprint during the construction phase. While Earned Value Analysis can provide a great platform for tracking cost and schedule, no considerations have been made for the environmental impacts of a project; and
3. There is a need for intuitive metrics and visualization tools that can easily and quickly communicate the excess or reductions from the benchmarked emissions associated with construction decisions. As a result, stakeholders have remained unaware of the choices that can satisfy environmental objectives while keeping cost and schedule in mind.

Figure 3 highlights the gap in existing knowledge and represents the focus of this thesis. The focus of this thesis is highlighted in contrast to the body of knowledge on embodied carbon footprint benchmarking and monitoring as well as LCA related studies. To minimize the "excessive" environmental impacts associated with the poor construction decisions and provide more incentive for choosing environmentally friendly supply, delivery, and construction methods, there is a need for research on frameworks that can leverage state of the art BIM and LCA tools for benchmarking, monitoring and visualization of carbon footprint.

CHAPTER 3: METHOD OVERVIEW

The proposed workflow for benchmarking and monitoring carbon footprint of a project involves three key components: 1) an overall method on how the embodied carbon footprint rates can be estimated using BIM, schedule, and contractor submittals together with the construction field reports; 2) an analytical framework for assessing and monitoring the carbon footprint at the pre-construction phase as well as the construction phase; and 3) intuitive metrics and visualization tools that can communicate the deviations between expected and actual carbon footprint rates. In the following each of these components are discussed in detail.

During the benchmarking phase, the practitioner will create an expected estimation of the carbon footprint to be released during a particular construction activity based on the embodied carbon data provided by suppliers for the materials during the preconstruction phase, the carbon associated with the material during its installation phase on the site and the quantity of this material as scheduled in the BIM of the project. This will allow the decision making process to consider the environmental impact evaluation of the different alternatives for materials, assemblies, project delivery methods and construction methodologies during the submittal review process, giving room to discuss it as metrics like cost and schedule are discussed.

During the monitoring phase, when the activity is about to start and while the activity is being performed, the data from the contractors and subcontractors is available together with the construction field reports, allowing the environmental performance of the construction activity to be assessed, compared with the benchmarked and represented visually using the Earned Value Analysis concept and the color coded representation in the BIM environment. This permits the visualization of the excess or reductions from the benchmarked emissions associated with construction decisions, allowing the practitioners to take corrective actions if needed to achieve the environmental objectives.

The calculation of expected embodied CO_2 emissions are based on materials' estimates extracted from BIM. The method chosen for embodied CO_2 calculations was applied to two construction activities taken from the schedule of the Center for the Arts project. The boundary condition chosen for the overall embodied carbon calculation was cradle-to-site. The cradle-to-site approach was taken because it was a consistent approach in previously done studies related to embodied carbon in buildings. First, the cradle-to-gate of the construction materials was calculated based on the Hammond and Jones's embodied carbon's coefficients database. The Hammond and Jones's database for construction materials was chosen to make the calculations and illustrate the framework implementation because it is an open-access, peer reviewed, transparent and frequently updated database used as the key point of reference in most previous and current studies related to embodied carbon in construction materials. Although this study was conducted in the UK, the data that was compiled was derived internationally, making this study more comprehensive and applicable to the United States construction industry (Mpakati et. Al. 2011). Additionally, this database is freely available to the public. The other component of cradle-to-site embodied carbon, which is the transportation of the material from the factory to the jobsite, is calculated based on assumptions of supplier's location for concrete, rebar steel and formwork for our particular case study. Assumptions were made in terms of mode of transportation and distance to the supplier based on the information collected during the initial interview with the project manager. Some of the assumptions of supplier's distances were hypothetical with the intent of illustrating how the framework can be useful in making decisions.

The method to obtain the cradle-to-site embodied carbon consisted in two steps. The first step consists in multiplying the mass quantity of each material associated with the analyzed activity in the schedule by the embodied carbon cradle-to-gate specific coefficients of embodied CO_2 for the materials produced by Hammond and Jones (2011). It should be highlighted that if the embodied carbon coefficient becomes available for a particular material (manufacturer's data), it can replace the generic coefficients from Hammond and Jones's database. The second step was to calculate the carbon released in the transportation of the materials from the factory gate to the jobsite, which is the gate-to-site material delivery CO_2 emissions. It was assumed that the vehicles used for material delivery consumed gasoline fuel.

To summarize, the calculation that I used was the following:

Cradle-to-site embodied Carbon (EC_{CS}) = EC_{CG} + EC_{GS} = Cradle-to-gate CO_2 emissions + Gate-to-site material delivery CO_2 emissions; where,

EC_{CG} = Cradle-to-gate CO_2 emissions = W × ω

EC_{GS} =Gate-to-site CO_2 emissions= # gallons consumed by delivery trucks x $8.92\ kg\ of\ \frac{CO_2}{gallon\ of\ gasoline}$

Where:

EC_{CS} = Cradle-to-site embodied carbon

EC_{CG}= Cradle-to-gate CO_2 emissions =CO_2 emissions of material's extraction of raw materials, transportation within the factory, processing and manufacturing

EC_{GS} = CO_2 emissions of material's delivery to the jobsite

W = Weight of the material in kg

ω = The correspondent material's embodied carbon coefficient (kg CO_2 /kg material) from Hammond and Jones database.

$8.92\ kg\ of\ \frac{CO_2}{gallon\ of\ gasoline}$ = CO_2 produced per gallon of gasoline consumed (EPA, 2010).

The original values are calculated in terms of kg CO_2 released and then expressed in terms of metric tons/tonnes of CO_2 for ease of data representation. A more detailed explanation is given in Chapter 4 according to the scenario analyzed.

This approach signifies the exclusion of the material's installation, use/maintenance and end of life phases. While there is an embodied carbon contribution attributed to the construction methodology, it was not part of the calculation since our main purpose was to propose and illustrate how the tool could help assess the environmental impact and not necessarily a thorough impact study of all the components comprised in embodied carbon.

3.1. Proposed Benchmarking and Monitoring Method

Figure 7 shows an overview of the proposed framework for benchmarking and monitoring the carbon footprint rates. In this framework and the developed research prototype, all owner tasks, contractor submittals, critical project deliveries, construction and inspection tasks are all integrated with the underlying 4D (Schedule + 3D) BIM at the pre-construction phase of the project. For example, for "FRPS (forming, reinforcing, pouring, and stripping) East Concrete Foundation Walls", the schedule activities related to delivery of formwork, reinforcement bars in addition to concrete and all their related submittal are integrated with the underlying 4D BIM. An inventory of carbon footprint rates in addition to the databases of supplier distances is integrated with the underlying system. Here, the actual data related to manufacturer's products are used. In recent years, several projects have been undertaken that facilitate collection of such data. One recent example is the database collected in project Tally (Tally 2014), which draws from and contains 78 product-specific EPDs (environmental product declarations) ranging from cladding systems to flooring. Such projects continue to expand the number of manufacturer-specific products as more manufacturer EPDs become available and thus are ideal for being part of our proposed framework and integration into our developed research prototype.

In the current prototype, a new user interface is designed (See Figure 7), which enables the selection of different manufacturers and delivery alternatives at the pre-construction phase. It also allows the actual project field reports to be used during the monitoring phase to enter the released carbon footprint rates. Once the analysis is conducted, the deviations will be visualized on the BIM elements using a color coding scheme. Other metaphors are also introduced as part of the communication/reporting module that highlight the excess or reductions associated with decisions made during the construction phase of the project.

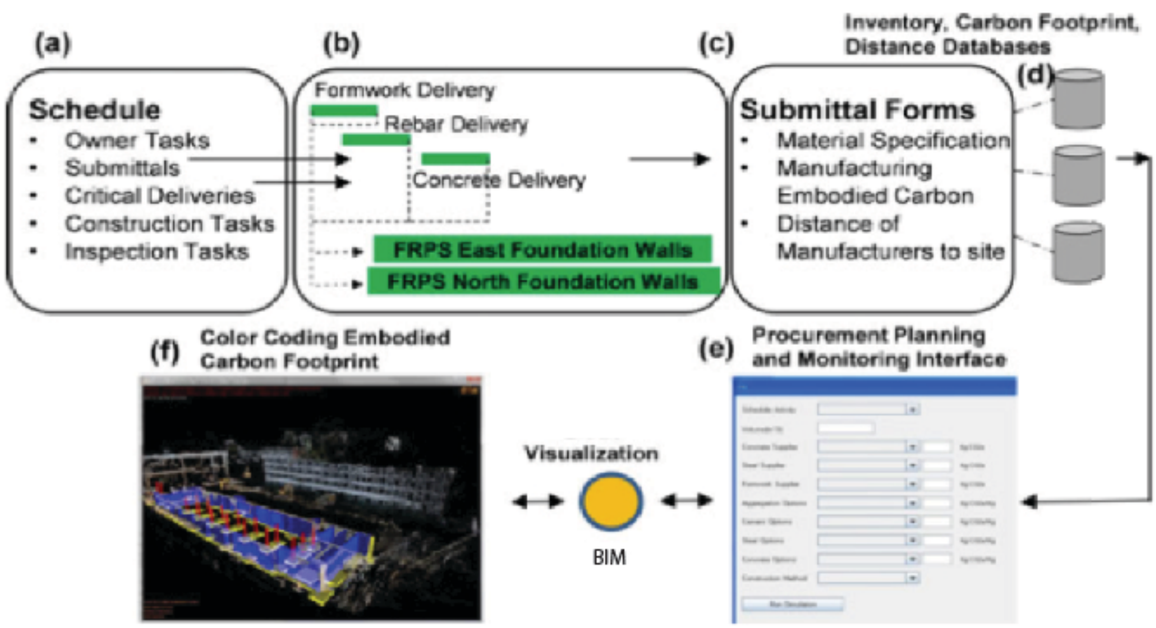


Figure 8. Proposed benchmarking and monitoring framework prototype

3.2. Benchmarking Carbon Footprint of Construction Operations

The benchmarking module consists of two key components: 1) estimating the carbon footprint associated with offsite operations and 2) estimating the carbon footprint associated transportation and delivery of materials to the jobsite. These two can facilitate benchmarking of the cradle-to-gate and cradle-to-site carbon footprint rates. In the following two sections, the methods adopted for estimating these rates are discussed in detail.

3.2.1. Estimating Carbon Footprint of Offsite Operations

In this thesis, the Hammond and Jones (2008) inventory is used to estimate carbon footprint associated with the offsite operations. A comprehensive dataset of different delivery alternatives for concrete placement materials including aggregates, cements and reinforcement bar in addition to the required formwork is also put together related to the case study. The embodied carbon coefficients include the material extraction, manufacture, transportation and any fabrication before the product is ready to leave the factory gate. The embodied carbon values of this dataset resulted from a cradle-to-gate boundary condition when performing the LCA studies of the materials.

During the last phase of this project, the more comprehensive Tally database, which draws from and contains 78 product-specific EPDs ranging from cladding systems to flooring was also introduced, which is already integrated into Autodesk Revit. While this database is not used for this study, integration of it should follow the same guidelines conducted for the Hammond and Jones's dataset.

3.2.2. Estimating Carbon Footprint of Transportation

The supply inventory in the developed prototype includes the distance of several local and major U.S. suppliers to the jobsite. In the proposed method, the carbon footprint associated with the transportation of materials to the jobsite is calculated based on the gallons of gasoline consumed by the delivery trucks using the following equation and is in the form of carbon dioxide (CO_2) :

(EPA 2010): 0. 125 $\frac{mmbtu}{gallon} * 71.35\, kg \frac{CO_2}{mmbtu} * 1\, metric \frac{ton}{1000\, kg} =$

$$8.92\, Kg\ of \frac{CO_2}{gallon\ of\ gasoline} = \ 8.92 * 10^{-3}\ metric\ ton/tonne\ of \frac{CO_2}{gallon\ of\ gasoline} \quad (1)$$

3.2.3. Estimating Carbon Footprint of Onsite Operations

Our inventory currently does not include the environmental impact produced by the construction operations occurred during the installation procedure of the materials selected. The main reason is the absence of a dataset related to construction methodology. Manual calculations can be performed but intensive input is needed. For the purpose of our study, several assumptions related to the onsite operations are made for different scenarios. These assumptions are presented for the relevant case study in Chapter 4.

3.2.4. Carbon Footprint Monitoring (CFM) Tool

The proposed method includes a module for monitoring carbon footprint during the construction phase. The method builds upon Earned Value Analysis (EVA). In traditional EVA, the earned value (EV), and planned value (PV) are continuously measured and the actual cost (AC) is monitored. In the EVA framework, the schedule and cost performance index (i.e., SPI and CPI respectively) help identify schedule and cost variations and are calculated using the following equations:

$$SPI = \frac{EV}{PV} \quad \text{and} \quad CPI = \frac{EV}{AC} \quad (2)$$

wherein SPI and CPI greater than 1 demonstrate favorable performance on schedule and cost respectively. Our Carbon Footprint Monitoring module (CFM) builds upon a similar concept.

It is introduced a set of new carbon footprint metrics: $BCFWP$, $BCFWS$ and $ACFWP$ which are the budgeted Carbon Footprint (CF) of the work performed, budgeted CF of the work scheduled, and the actual CF of the work performed, respectively. Based on these metrics, the following indexes are formed and used to monitor the embodied carbon footprint:

$$CFPI = \frac{BCFWP}{ACFWP} \quad \text{and} \quad SPI_{CF} = \frac{BCFWP}{BCFWS} \quad (3)$$

The $CFPI$ (carbon footprint performance index) and the SPI_{CF} (the CF-based schedule performance index) help identify deviations in the release of embodied carbon footprint. Figure

8 shows the schematic representation of the CFM diagram. In this case, $CFPI > 1$ means that the actual carbon footprint is less than the expected amount. This indicates that the contractor choice of materials, delivery method and/or construction methodology is more environmental friendly than the expected performance. Similarly, $CFPI < 1$ means that the contractor's actual performance is more environmentally destructive.

3.2.5. Measuring Environmental Impacts

We also introduce a new metric to measure the impact of the overall project performance in a form that is easy to understand. Similar to Shiftehfar et al. (2010) we use the EPA metric for measuring the number of trees seedlings grown for 10 years that are impacted by a given construction operation through gauging the number of trees which need to be planted to compensate for the loss caused by every $Kg\ or\ tonnes\ CO_2$ released. For each construction activity, based on the level of physical construction progress, we measure both cumulative to-date and total number of trees seedlings grown for 10 years required to compensate the loss using the following equations (US DOE 1998):

$$23.2\ lbs\,\frac{C}{tree} * \left(\frac{44\ units\ CO_2}{12\ units\ C}\right) * \frac{1\ metric\ ton}{2204.6\ lbs} = 39\ Kg\ CO_2\ per\ urban\ tree\ planted =$$
$$0.039\ \text{metric ton}\ /\text{tonne}\ CO_2\ per\ urban\ tree\ planted \quad (4)$$

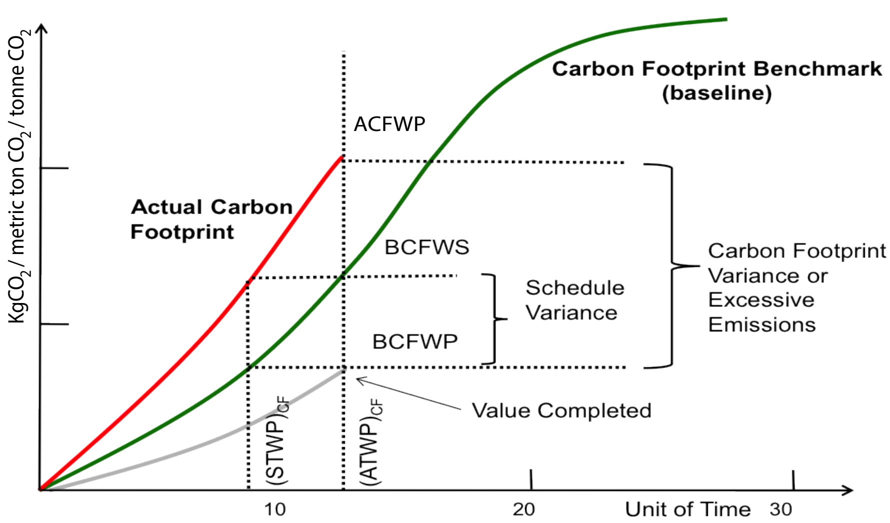


Figure 9. Carbon Footprint Monitoring (CFM) concept diagram

3.2.6. Visualization of CFM Metrics

Depending on the values of $CFPI$ and SPI_{CF}, the to-date embodied carbon footprint of every construction activity will be color coded at BIM element level using the color coding pallet shown in Table 1. In this case, green and red colors represent acceptable and unfavorable environmental and schedule performances, respectively. Yellow represent an unfavorable schedule or carbon footprint value. These colors were chosen to simulate a traffic light, where the color green transmits the idea of a favorable condition in both carbon footprint and schedule while the red one will indicate an unfavorable condition for both. The yellow will indicate caution since one of the performances (either the schedule or the carbon footprint) is performing poorly.

Table 1. Color coding pallette for visualization of environmental impacts

Color		**SPI_{CF}**	**CFPI**
Green		>=1	>=1
Yellow		>1	<1
Yellow		<1	>1
Red		<1	<1
Gray		No Change	No Change

Given the submittal forms information, schedule and BIM, making the assumptions that we have the carbon footprint of materials data available and a linked BIM with the construction activities of the project; an estimation of the carbon footprint associated with the offsite and onsite operation would be calculated by entering the information on the procurement planning and monitoring interface. This will result in two things: an Earned Value Analysis (EVA) and an according color code that will be represented in the Building Information Model environment in order to facilitate the visualization of the carbon footprint.

This procedure will allow testing if the tool actually could be beneficial for the purposes for what it was created and analyze what construction practices could be improved in order to minimize the environmental impact.

The color coding palette could also be additionally illustrated by different colors of a gradient, representing value ranges depending on the value of the environmental and schedule impact throughout the period of time of the activity or to visualize the performance to date of the project and at the end of the project. Figure 10 will build upon on the concept previously explained introducing gradient variations of the color to detail, explain and communicate the environmental and schedule performance status of the project to-date and at the end of the project.

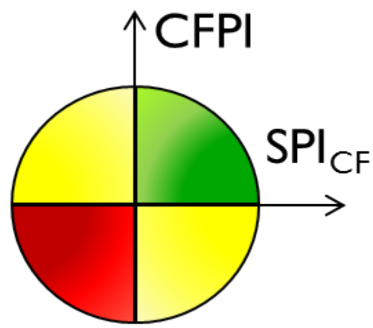


Figure 10. Color radial gradient to visualize project's performance

CHAPTER 4: EXPERIMENTS

The following sections present the case study, the experimental results and findings of the research undertaken for this thesis, which is followed by a discussion on the perceived applications and potential benefits for the Architecture/Engineering/Construction (AEC) industry.

4.1.Case study on the proposed carbon footprint benchmarking and monitoring framework

A case study is performed on a recently completed 130,000 S.F. facility Center for The Arts at Virginia Tech (Moss Arts Center), $100 million project; LEED Gold certified that includes a 1.260 seat performance hall and a visual arts gallery. The performance hall of approximately 66,000 gross square feet holds the theater, music and dance performances. The visual arts gallery of approximately 7,000 gross square feet will exhibit arts, digital media and educational outreach programs. This project also includes a laboratory space "The Center for Creative Technologies in the Arts" designed to hold educational forums for collegiate and K-12 levels in areas including web design, graphics, animation and digital audio film. (Holder Construction Company).

Figure 11. Rendering snapshots of the Center for the Arts at Virginia Tech project. Used with permission of Ruth Waalkes,2014.

The Performing Arts Center is a complex concrete and steel structure, which includes a substantial amount of vertical concrete work. As described by Wayne Brothers, subcontractors for the Center for the Arts, the project utilized job-built wall forms, pre-engineered handset wall and column forms, pre-engineered crane set wall forms, a climbing wall form system, and a climbing elevator core forming system to form approximately 157,000 square feet of vertical contact area.

The LEED gold certified building contains 18,168.25 cubic yards of concrete supplied by seven different subcontractors. Forty different mix designs were supplied by seven different sub-contractors completing various sections of the project, with 90% of the concrete going to Wayne Brothers, Inc. and McKinney Drilling Company (Chandler Concrete 2013).

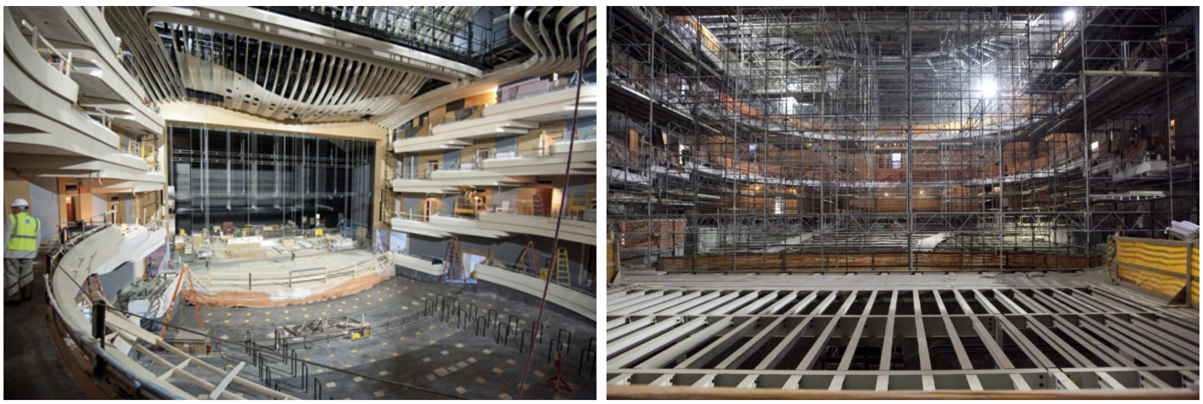
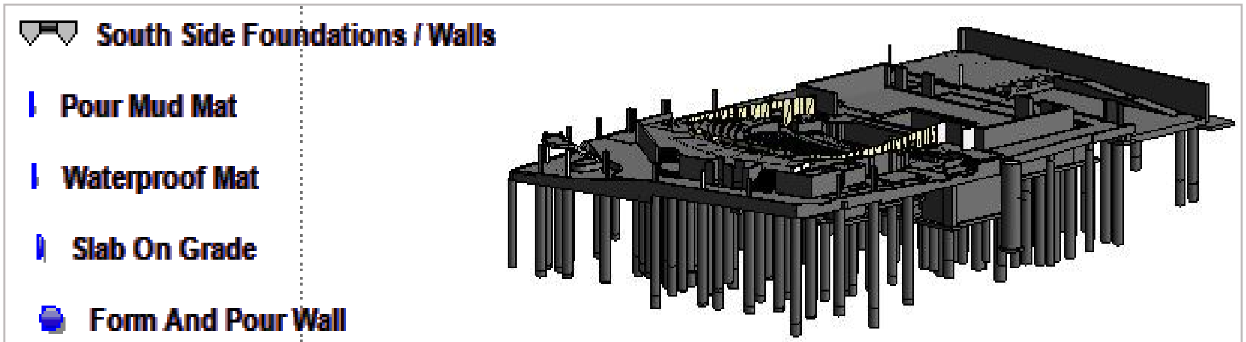


Figure 12. Photographs taken during the construction of the Center for the Arts project. Used with permission of Ruth Waalkes, 2014.

This project is composed of a complex of new and renovated buildings adjacent to and including Shultz Hall, and it was scheduled to start in 2010 and completed by the summer 2013. Due to unanticipated construction events, the project was opened Fall 2013. The software used to create and maintain the schedule updated was Primavera P6. The project delivery method was Construction Management at Risk. The general contractor was Holder Construction. This project included green practices such as the recycling of the building materials and implementation of lean construction practices by eliminating waste and collaborative scheduling.

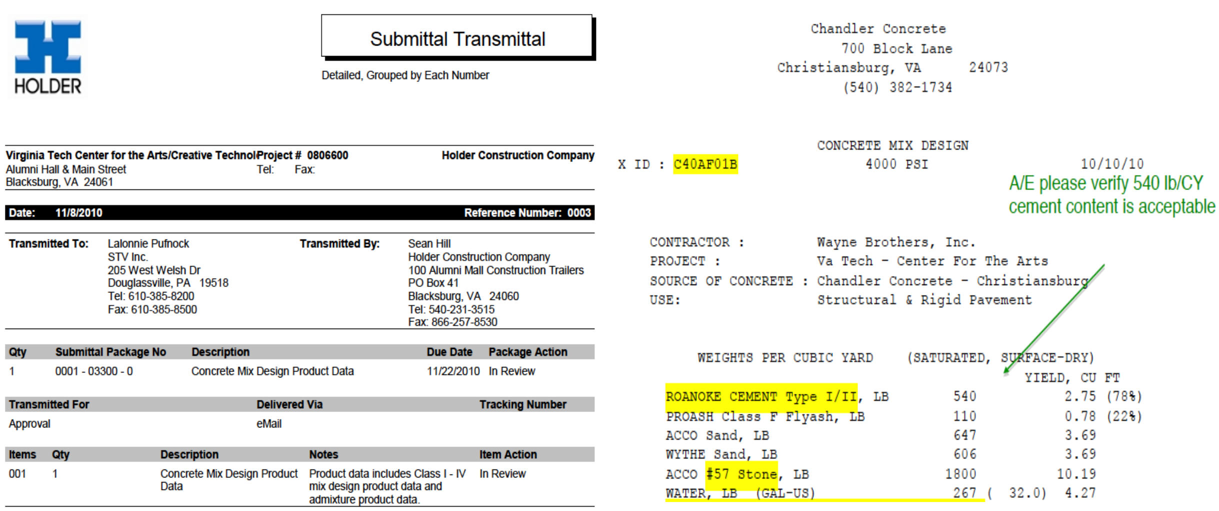
The construction management company Holder developed the BIM for this $100 million project using Autodesk Revit Architecture. The BIM was used to coordinate, detail and communicate changes and updates. To test and implement our proposed method, we only looked into a few of the key concrete placement construction activities. The BIM and the schedule activities are presented in Figure 11.



South Side Foundations / Walls Elevation 80'	25 days	Tue 4/19/11	Mon 5/23/11
Pour Mud Mat	3 days	Tue 4/19/11	Thu 4/21/11
Waterproof Mat	1 day	Fri 4/22/11	Fri 4/22/11
Slab On Grade	4 days	Mon 4/25/11	Thu 4/28/11
Form And Pour Walls	15 days	Fri 4/29/11	Thu 5/19/11

Figure 13. Concrete structure BIM elements and original schedule activities.

Figure 12 shows two examples of project concrete submittal documents that were issued during this construction project. All submittal have been collected for this study.



HOLDER

Submittal Transmittal

Detailed, Grouped by Each Number

Virginia Tech Center for the Arts/Creative Technol Project # 0806600 **Holder Construction Company**
Alumni Hall & Main Street Tel: Fax:
Blacksburg, VA 24061

Date: 11/8/2010 **Reference Number: 0003**

Transmitted To: Lalonnie Pufnock, STV Inc., 205 West Welsh Dr, Douglassville, PA 19518, Tel: 610-385-8200, Fax: 610-385-8500

Transmitted By: Sean Hill, Holder Construction Company, 100 Alumni Mall Construction Trailers, PO Box 41, Blacksburg, VA 24060, Tel: 540-231-3515, Fax: 866-257-8530

Qty	Submittal Package No	Description	Due Date	Package Action
1	0001 - 03300 - 0	Concrete Mix Design Product Data	11/22/2010	In Review

Transmitted For	Delivered Via	Tracking Number
Approval	eMail	

Items	Qty	Description	Notes	Item Action
001	1	Concrete Mix Design Product Data	Product data includes Class I - IV mix design product data and admixture product data.	In Review

Chandler Concrete
700 Block Lane
Christiansburg, VA 24073
(540) 382-1734

CONCRETE MIX DESIGN
X ID : C40AF01B 4000 PSI 10/10/10

A/E please verify 540 lb/CY cement content is acceptable

CONTRACTOR : Wayne Brothers, Inc.
PROJECT : Va Tech - Center For The Arts
SOURCE OF CONCRETE : Chandler Concrete - Christiansburg
USE: Structural & Rigid Pavement

WEIGHTS PER CUBIC YARD (SATURATED, SURFACE-DRY)

		YIELD, CU FT
ROANOKE CEMENT Type I/II, LB	540	2.75 (78%)
PROASH Class F Flyash, LB	110	0.78 (22%)
ACCO Sand, LB	647	3.69
WYTHE Sand, LB	606	3.69
ACCO #57 Stone, LB	1800	10.19
WATER, LB (GAL-US)	267 (32.0)	4.27

Figure 14. Project Concrete Submittal Documents Center for the Arts at Virginia Tech.

4.2. Benchmarking and Monitoring Framework Implementation

4.2.1. Implementation and description on material and delivery methods alternatives

The embodied carbon coefficients used for this analysis are from the database "Inventory of Carbon and Energy (ICE) Version 2.0, 2011" published by Hammond & Jones from the University of Bath in United Kingdom. In these scenarios, it is intended to show how the carbon footprint benchmarking module of the framework can help practitioners make decisions that are both environmentally friendly, and cost effective during the preconstruction and construction phase of a project.

In order to highlight the importance of how a contractor will be able to use the carbon footprint benchmarking and visualization tool to make faster decisions regarding material selection and delivery methods, three different scenarios with the activities related to concrete, steel and formwork were created. The following section outlines the assumptions used in the alternative scenarios in order to calculate the embodied carbon and cost of the materials.

4.2.2. Assumptions and limitations for the different scenarios and the embodied carbon calculations

The first scenario will consider the concrete material selection, the second scenario will focus in steel alternatives and the third scenario will comprise of formwork material selection.

1. The quantity of the materials used for the calculation of the embodied carbon was extracted and queried from the BIM of the project.
2. Chandler Concrete plant, located in Christiansburg, VA, is assumed to supply the concrete for this project in the benchmarking and first alternative case for the concrete scenario. Chandler's Concrete plant, located in Roanoke, VA is assumed to supply concrete in the other alternatives.
3. The concrete is delivered assuming each truck carries 9 cubic yards.
4. The source of the aggregates and the cement is Roanoke, VA.
5. Every coefficient used for the case study implementation was extracted from (Hammond and Jones 2008, 2011).
6. The concrete embodied carbon coefficient used is 0.139 kg CO2 /kg for benchmarking. This corresponds to a ready mix concrete made with 100 % Portland cement and designed strength

of 4000 psi. The coefficient that corresponds to a 4000-psi ready mix concrete where 25-30% of the cement is replaced by fly ash is 0.116 kg CO2/Kg.

7. CMC Steel Northern Virginia, located in Fredericksburg, VA, is assumed to supply the rebar steel for this project.
8. The steel embodied carbon coefficient used is 1.82 kg CO_2/ kg. This corresponds to rebar steel that has an average recycled content of 35.5 % based on the average steel consumption of non-European countries.
9. Peri Systems, located in Baltimore, MD, is assumed to supply the formwork for this project. In an alternative scenario the formwork is supplied from a nearby jobsite in Christiansburg.
10. The embodied carbon coefficient used is 0.42 kg CO_2/ kg. This corresponds to plywood under the timber category.
11. The distance for each truck unit is calculated from the manufacturing plant to the location of the project. It does not consider the return to the manufacturing plant.
12. The mileage of each truck-mixer unit is assumed to be same as 3.22 miles per gallon irrespective of the engine or truck model.
13. The mileage of each truck-trailer unit is assumed to be same as 7.7 miles per gallon irrespective of the engine or truck model.
14. The vessel's fuel consumption assumed is 60 tons per day. Assuming it is a 4000-5000 TEU vessel that will be sailing at 20 knots (Notteboom and Carriou 2009).
15. All truck-trailer and truck mixer units consume gasoline fuel and any other fuel alternate is not considered for this study.
16. The installation method used for the material is the same for every alternative.
17. The carbon emissions related to equipment used for the installation of the materials on-site are assumed to be the equivalent to the amount of carbon emissions released through the different scenarios.
18. The cost of the concrete includes its delivery and installation on the jobsite.
19. The baseline's embodied carbon coefficients are cradle-to-site values extracted from Hammond and Jones 2008. It is indicated in the assumption's table as the benchmarked value.
20. The cradle-to-site embodied carbon in Figure 13 is the result of the calculation based on the assumptions listed previously.

4.3. Concrete Scenario

Table 2 summarizes the assumptions made in the concrete scenario in order to calculate the embodied carbon. Figure 15 illustrates the alternatives supplier's locations. Figure 14 summarizes the findings in this scenario. During the preconstruction phase of a project, this tool can be used to create a benchmark of the material analyzed to later monitor its real environmental impact during the actual construction phase. This is an important step into reducing environmental impact and maintaining cost effectiveness since construction projects are always facing constant changes.

Table 2. Concrete scenario assumptions

List of Assumptions				**Benchmarking**
Description	**Alternatives**			0.139 kg CO2/ kg
	1	**2**	**3**	
Location	Christiansburg,VA	Roanoke,VA	Roanoke,VA	
Concrete Specification	4000 psi			
	Portland Cement Type I or II		Cement (25% fly ash)	
Source of aggregates and cement	Roanoke,VA			
Source of ready-mixed concrete	Christiansburg,VA	Roanoke,VA	Roanoke,VA	
Distance to jobsite(miles)	8.9	42.3	42.3	
Delivery time concrete (< 90 min)	11	45	45	
Concrete Delivery Truck Mixer Type	Three axles with a rear end discharge unit			
Average Fuel Consumption (mpg) (NRMCA 2012)	3.22			Embodied Carbon Coefficient
Price per cubic yard(US $ /CY)	172.72	178	175.5	

Calculation example of the cradle-to-site embodied carbon of the concrete with a 25% Portland cement substitution for fly ash. The assumptions for the calculations were the following:

1. Chandler Concrete plant, located in Roanoke, VA, is assumed to supply concrete in this calculation.
2. The concrete is delivered assuming each truck carries 9 cubic yards.
3. The source of the aggregates and the cement is Roanoke, VA.
4. The concrete cradle-to-gate embodied carbon coefficient that corresponds to a 4000-psi ready mix concrete where 25- 30% of the cement is replaced by fly ash is 0.116 kg CO_2/kg.
5. The distance for each truck unit is calculated from the manufacturing plant to the location of the project. It does not consider the return to the manufacturing plant.

6. The mileage of each truck-mixer unit is assumed to be same as 3.22 miles per gallon irrespective of the engine or truck model.
7. The expected to be poured kg of concrete queried from the BIM for the construction activity analyzed was 359,444.56 kg.
8. To determine CO_2 emissions, the following methodology was used: vehicle miles traveled (VMT) was divided by average gas mileage to determine gallons of gasoline consumed per total miles traveled. Gallons of gasoline consumed were multiplied by carbon dioxide per gallon of gasoline to determine carbon dioxide emitted per vehicle per year.

Cradle-to-site embodied Carbon (EC_{CS}) = EC_{CG} + EC_{GS} = Cradle-to-gate CO_2 emissions + Gate-to-site transportation CO_2 emissions; where

EC_{CG} = CO_2 Cradle-to-gate = Σ (W × ω) = 359,444.56 kg x 0.116 kg CO_2/kg = 41,580 kg CO_2 =41.58 metric ton /tonnes CO_2

EC_{GS} = Gate-to-site transportation CO_2 emissions = # gallons gasoline consumed by delivery trucks x $8.92 * 10^{-3}$ $metric\ ton\ /tonnes\ of \frac{CO_2}{gallon\ of\ gasoline}$ = 13.11 gallons of gasoline x 0.00892 $tonnes\ of \frac{CO_2}{gallon\ of\ gasoline}$ = 0. 12 metric ton/tonne of CO_2

No. gallons consumed by delivery trucks : 41.2 miles (VMT = distance from supplier to jobsite) / 3.22 miles/ gallon

EC_{CS} = EC_{CG} + EC_{GS} = 41.58 metric ton /tonnes CO_2 + 0. 12 metric ton/tonne of CO_2 = 41.7 metric ton/tonne of CO_2

Where:

EC_{CS}= Cradle-to-site embodied carbon value

EC_{CG}= Cradle-to-gate CO_2 emissions =CO_2 emissions of material's extraction of raw materials, transportation within the factory, manufacturing

EC_{GS} = CO_2 emissions of material's delivery to the jobsite

W = Mass/volume of the materials in kg for the particular activity analyzed

ω = The correspondent material's embodied carbon coefficient (kg CO_2 /kg material) from Hammond and Jones database.

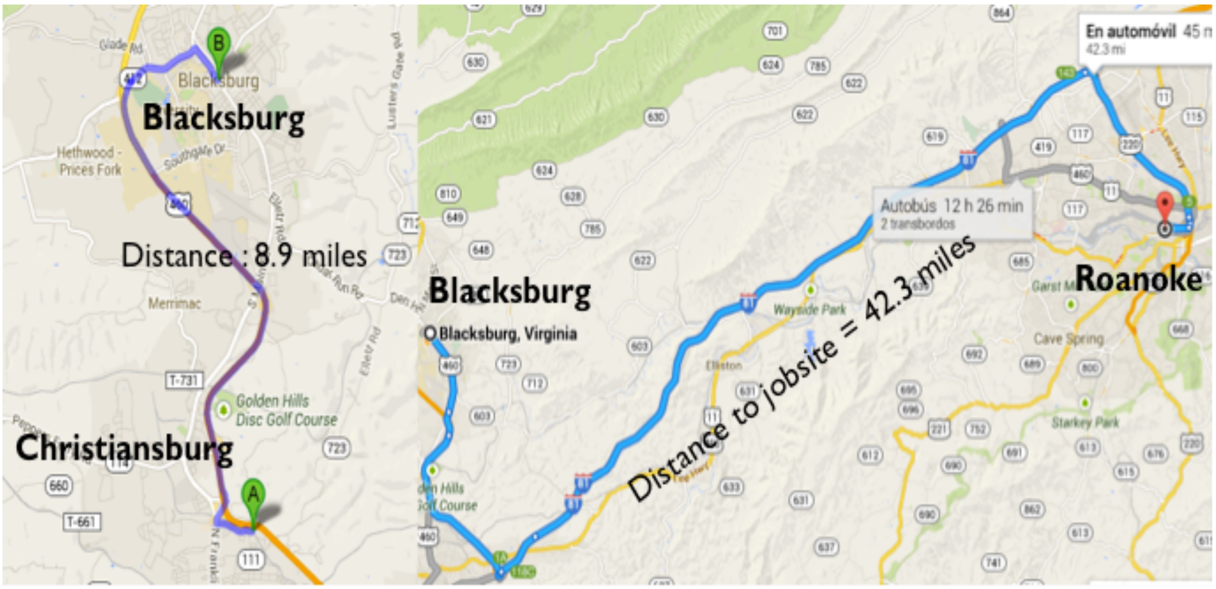
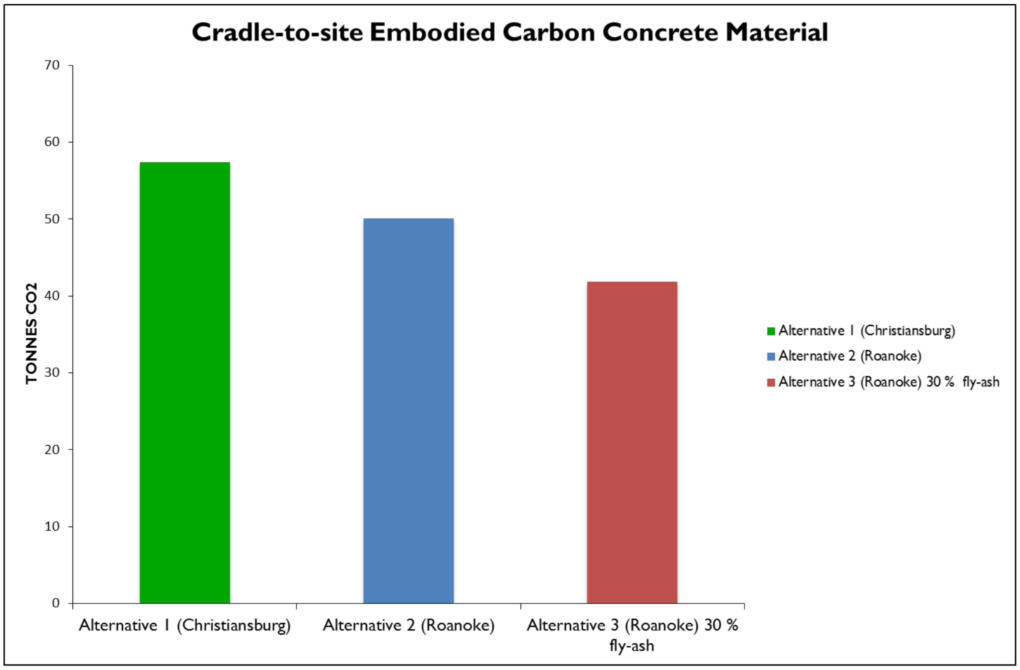


Figure 15. Concrete Scenario a) Alternative I- Christiansburg b) Alternative II-Roanoke

In this scenario, the contractor has an agreement to purchase all the concrete from Chandler's Concrete. In the day "X" of the project, an unexpected failure in the concrete plant forced the project manager to look for different concrete suppliers. The project manager used the benchmarking and monitoring tool for carbon footprint and cost to create a comparative graph to make an informed decision. Figure 13 illustrates the alternatives. The alternatives considered are the following:

1. 100% Portland cement-Ready Mixed Concrete- Chandler Concrete from Christiansburg, VA
2. 100% Portland cement- Ready Mixed Concrete- Chandler Concrete from Roanoke, VA
3. 25% Fly ash cement - Ready Mixed Concrete- Chandler Concrete from Roanoke, VA



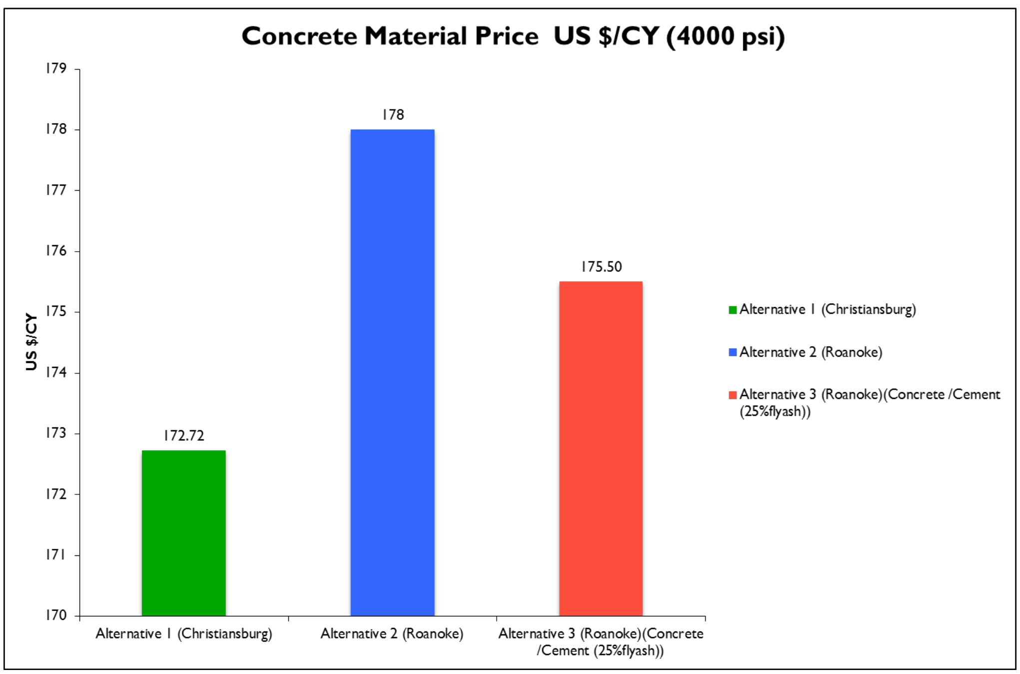


Figure 16. Concrete Scenario (a) Embodied Carbon graph and (b) Cost Comparison graph

4.3.1. Discussion on concrete scenarios

Figure 14 shows the comparison of the overall CO2 emissions and cost per cubic yard for the concrete from different sources. The highest embodied carbon and the lowest cost corresponded to the ready mix concrete that was supplied by Chandler Concrete in Christiansburg, the closest supplier to the jobsite. It was also found that the lowest embodied carbon corresponded to the ready mix concrete with a 25 % cement substitution for fly ash. The highest cost corresponded to the ready mix concrete with 100% Portland cement content supplied by the plant located in Roanoke, VA. The lowest cost corresponded to 100% Portland cement concrete supplied by the plant located in Christiansburg, VA.

It can be concluded that material's embodied carbon is influenced not only by its delivery method and distance to project site but also by its manufacturing process. It is the case when comparison is made between Alternative 1 and Alternative 2; the aggregates source for the concrete produce is located in Roanoke, VA resulting in a different embodied carbon value. When comparing Alternative 2 and Alternative 3, the value difference is caused by the 25% Portland Cement for fly ash used during the production of concrete. Also, in terms of cost it can be observed when comparing alternatives 2 and 3 that the most environmentally friendly concrete has the lowest price, from which it can be concluded that it is possible to minimize environmental impact while maintaining a low cost.

Looking into the alternative concretes, traditionally the contractor would have gone for the lowest cost looking into the concrete example, but there is the decision of selecting a more environmentally friendly concrete with a 25% cement substitution for fly ash and paying a higher price or selecting the 100% Portland cement concrete with a higher embodied carbon at a lower cost. The framework implementation allows contractors to discuss another important metric when considering materials that otherwise might have been deemed optional.

4.4. Steel Scenario

Table 3 lists the assumptions related to the steel scenario that were used to calculate the embodied carbon.

Table 3. Steel Scenario Assumptions

List of Assumptions			Benchmarking
Description	**Alternatives**		1.82 kg CO2 / kg
	1	**2**	
Location	Fredericksburg,VA	Rio de Janeiro, Brazil	
Supplier	CMC Steel Northern Virginia	GERDAU	
Steel Specification	Reinforcing Steel A 615 Grade 60		
Distance to jobsite(miles)	219.97	5123.6	
Sea Transportation	0	4813.22	
Road Transportation	219.97	310.38	
Delivery time Estimate	3 hrs 40 min	25 Days 8 hrs	
Delivery Truck Type	Flatbed truck trailer		
Average Fuel Consumption (mpg) (NRMCA 2012)	7.8		
Vessel Type	Cargo/ Container Vessel		
Vessel Average Fuel Consumption	60 tons/day		Embodied Carbon Coefficient
Cost per ton (US $ /ton)(Detailed,cut,bent and delivered)	956	814.2	

Figure 15 and Figure 16 illustrates the alternative suppliers' location. In this scenario, the project manager has two alternatives:

1. Procure steel rebar from CMC Steel Northern Virginia in Fredericksburg, VA
2. Procure steel rebar from Gerdau in Brazil

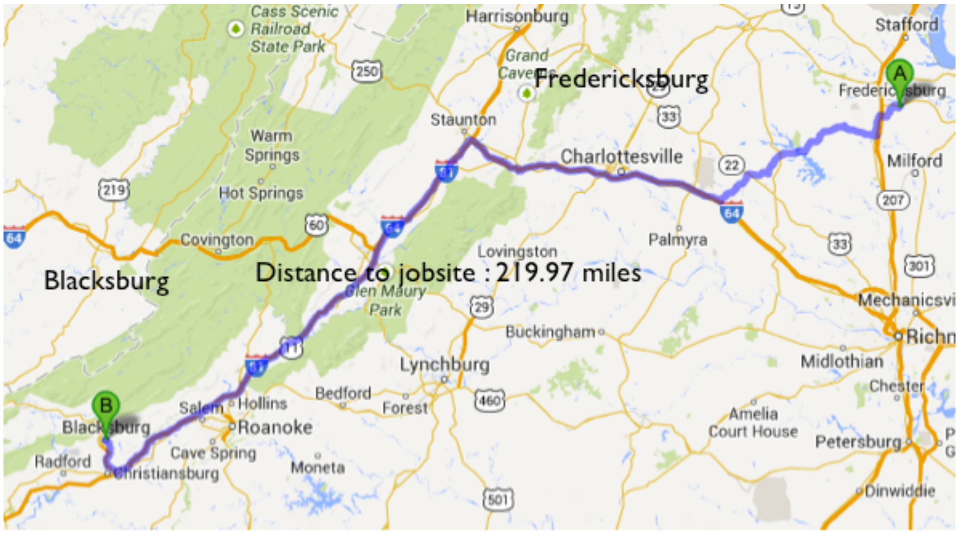


Figure 17. Steel Scenario-Alternative 1 Supplier: Fredericksburg, VA

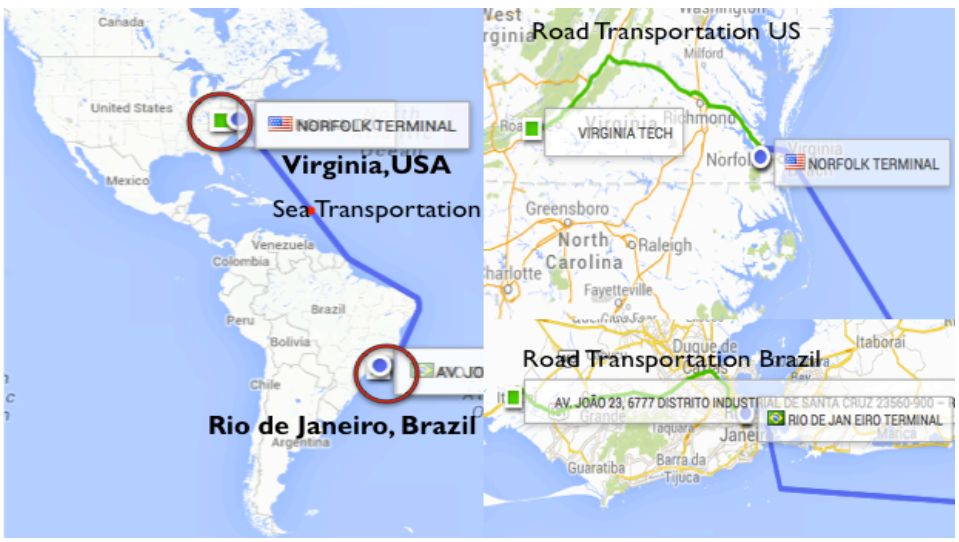


Figure 18. Steel Scenario-Alternative 2 Supplier: Brazil

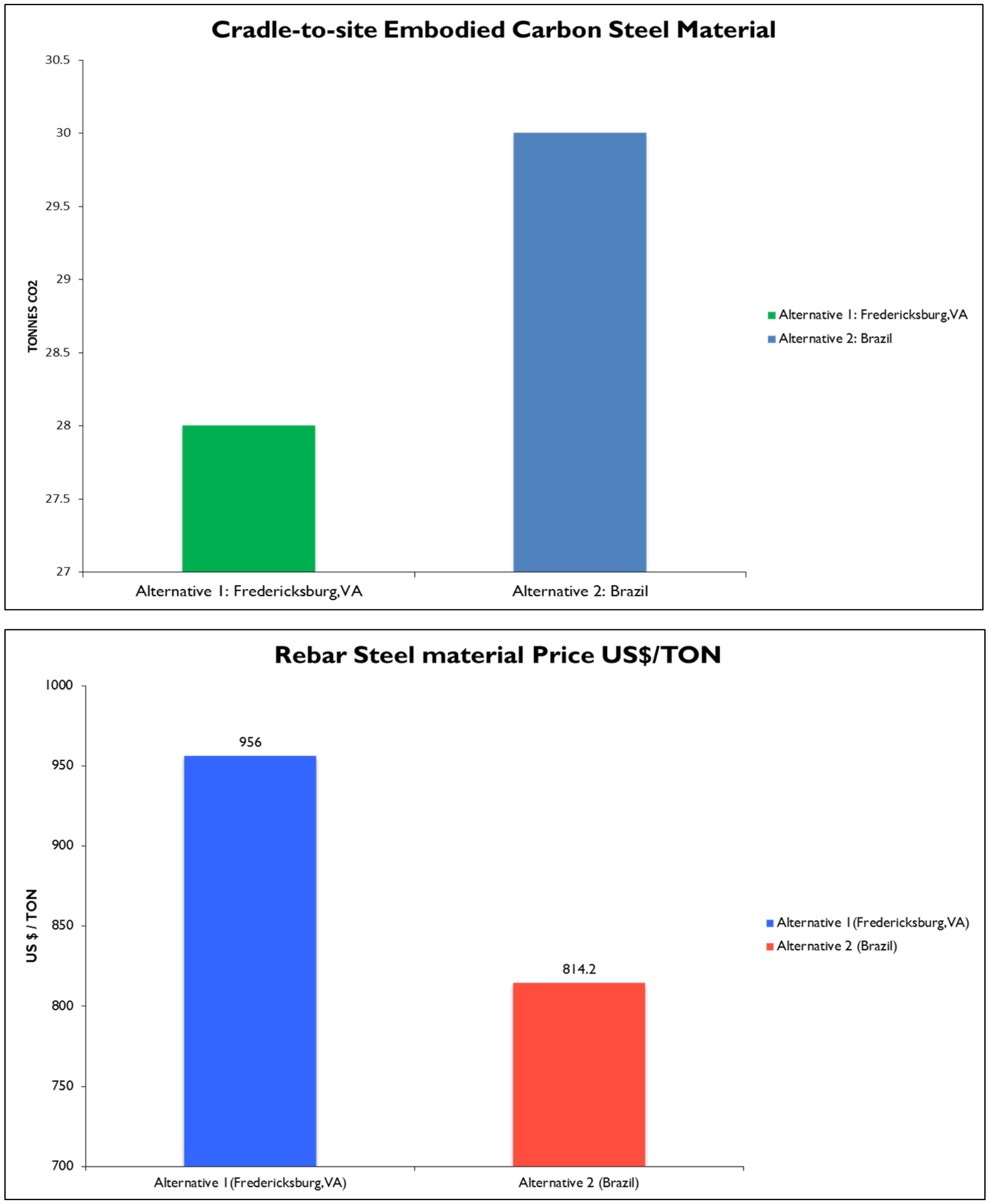


Figure 19. Steel Scenario (a) Embodied Carbon graph and (b) Cost Comparison graph

Calculation example of the cradle-to-site embodied carbon of the rebar steel that comes from Fredericksburg. The assumptions for the calculations were the following:

1. CMC Steel Northern Virginia, located in Fredericksburg, VA is assumed to supply the rebar steel for this project.
2. The steel embodied carbon coefficient used is 1.82 kg CO2/kg. This corresponds to rebar steel that has an average recycled content of 35.5 % based on the average steel consumption of non-European countries. The embodied carbon value for the steel rebar from Brazil was assumed to be the same as the USA, since there is no available data. We assumed an adjustment factor for the carbon footprint would account for the difference in carbon emissions due to the mix of energy of the manufacturing process. This is sufficient since our purpose is to demonstrate how the tool could be implemented.
3. The distance for each truck unit is calculated from the manufacturing plant to the location of the project. It does not consider the return to the manufacturing plant.
4. The mileage of each truck-trailer unit is assumed to be same as 7.7 miles per gallon irrespective of the engine or truck model (Transportation Data Energy Book 2011).
5. The expected to be collocated kg of rebar steel queried from the BIM for the construction activity analyzed was 15,680.65 kg.
6. To determine CO_2 emissions, the following methodology was used: vehicle miles traveled (VMT) was divided by average gas mileage to determine gallons of gasoline consumed per total miles traveled. Gallons of gasoline consumed were multiplied by carbon dioxide per gallon of gasoline to determine carbon dioxide emitted per vehicle per year.

Cradle-to-site embodied Carbon (EC_{CS}) = EC_{CG} + EC_{GS} = Cradle-to-gate CO_2 emissions + Gate-to-site transportation CO_2 emissions; where

EC_{CG} = CO_2 Cradle-to-gate = Σ (W × ω) =15,680.65 kg x 1.82 kg CO_2/Kg =28,538.78 kg CO_2 =28.54 metric ton /tonnes CO_2

EC_{GS} = Gate-to-site transportation CO_2 emissions = # gallons gasoline consumed by delivery trucks x $8.92 * 10^{-3}$ $metric\ ton\ /tonnes\ of \frac{CO_2}{gallon\ of\ gasoline}$ = 28.57 gallons of gasoline x 0.00892 $tonnes\ of \frac{CO_2}{gallon\ of\ gasoline}$ = 0.25 metric ton/tonne of CO_2

No. gallons consumed by delivery trucks : 219.97 miles (VMT = distance from supplier to jobsite) / 7.7 miles/ gallon = 28.57 gallons

EC_{CS} = EC_{CG} + EC_{GS} = 28.58 metric ton /tonnes CO_2 + 0.25 metric ton/tonne of CO_2 = 28.83 metric ton/tonne of CO_2

4.4.1. Discussion on steel delivery scenarios

Figure 17 shows the comparison of the overall CO2 emissions and cost per ton for the rebar steel from the 2 alternatives:

1. The Virginia supplier has a lower embodied carbon than the local supplier in Virginia.
2. The Brazilian supplier has a lower cost than the local supplier in Virginia.

It is important to notice that not necessarily a longer transportation travel of the material leads to a higher embodied carbon. In this particular case, cost is lower at expense of a higher embodied carbon, so the decision to be made here will depend on the project's goals and objectives. But it must be taken into account that a higher upfront cost in reduction of embodied carbon now can signify an overall future significant reduction in carbon emissions.

4.5. Formwork Scenario

Table 4 lists the assumptions related to the formwork scenario that were used to calculate the embodied carbon and the cost comparative among the alternatives.

Table 4. Formwork Scenario Assumptions

List of Assumptions				Benchmarking
Description	**Alternatives**			0.42 kg CO_2 /kg
	1	**2**	**3**	
Location	Baltimore,MD	Baltimore,MD	Nearby jobsite Christiansburg	
Situation	Procure	Rent	Reuse from another jobsite	
Supplier	Peri Systems	Peri Systems	Contractor(self)	
Formworks Specification	Steel Framed Plywood			
Distance to jobsite(miles)	298	298	8.9	
Delivery time	4 hrs 38 min	4 hrs 38 min	11	
Delivery Truck Type	Flatbed Truck Trailer			
Average Fuel Consumption (mpg) (NRMCA 2012)	7.8			Embodied Carbon Coefficient
Material Cost per SFCA (US $ /SFCA)	11.26	0.76	0	

The project manager for the Center for the Arts of Virginia Tech needs to make a decision regarding the formwork material. He created a comparative graph of cost and environmental impact to make an informed decision. **Error! Reference source not found.** illustrates the different locations and distances from the supplier to the jobsite. The alternatives are:

1. Procure Formwork from Peri Systems
2. Rent Formwork from Peri Systems
3. Reuse from a nearby jobsite

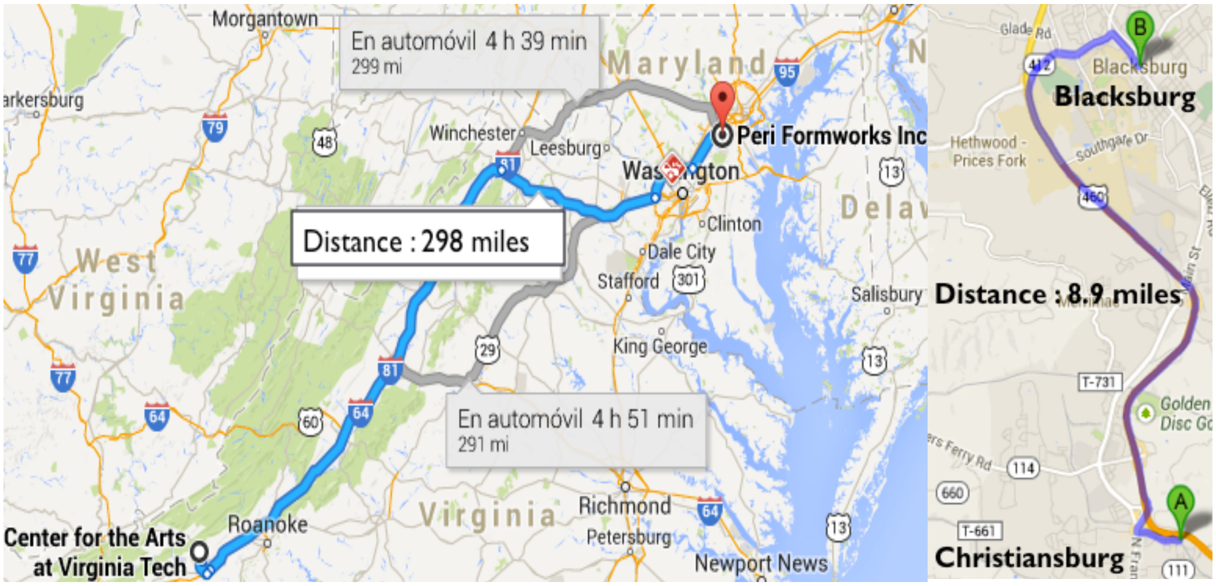


Figure 20. Formwork Scenario-Supplier Location a) Alternatives I & II-Buy or rent : Fredericksburg, VA b) Alternative III-Reuse from another jobsite:Christiansbur,VA.

Calculation example of the cradle-to-site embodied carbon of the formwork that comes from Baltimore, MD. The assumptions for the calculations were the following:

1. Peri Systems located in Baltimore, MD is assumed to supply the formwork for this project. In an alternative scenario, the formwork is supplied from a nearby jobsite in Christiansburg, VA.
2. The embodied carbon coefficient used is 0.42 kg CO2 /kg. This corresponds to plywood under the timber category.
3. The distance for each truck unit is calculated from the manufacturing plant to the location of the project. It does not consider the return to the manufacturing plant
4. The mileage of each truck-trailer unit is assumed to be same as 7.7 miles per gallon irrespective of the engine or truck model**. (**Transportation Data Energy Book 2011)
5. The expected to be collocated kg of rebar steel queried from the BIM for the construction activity analyzed was 6,338.15 kg.
6. It is assumed that the formwork material rented and borrowed have a lower embodied carbon since the emissions were already accounted for in previous projects.
7. To determine CO_2 emissions, the following methodology was used: vehicle miles traveled (VMT) was divided by average gas mileage to determine gallons of gasoline

consumed per total miles traveled. Gallons of gasoline consumed were multiplied by carbon dioxide per gallon of gasoline to determine carbon dioxide emitted per vehicle per year.

Cradle-to-site embodied Carbon (EC_{CS}) = EC_{CG} + EC_{GS} = Cradle-to-gate CO_2 emissions + Gate-to-site transportation CO_2 emissions; where :

EC_{CG} = CO_2 Cradle-to-gate = Σ (W × ω) =6,338.15 kg x 0.42 kg CO_2/Kg =2,662 kg CO_2 = 2.66 metric ton /tonnes CO_2

EC_{GS} = Gate-to-site transportation CO_2 emissions = # gallons gasoline consumed by delivery trucks x $8.92 * 10^{-3}$ $metric\ ton\ /tonnes\ of\ \frac{CO_2}{gallon\ of\ gasoline}$ = 38.7 gallons of gasoline x 0.00892 $tonnes\ of\ \frac{CO_2}{gallon\ of\ gasoline}$ = 0.35 metric ton/tonne of CO_2

No. gallons consumed by delivery trucks : 298 miles (VMT = distance from supplier to jobsite) / 7.7 miles/ gallon = 38.7 gallons

EC_{CS} = EC_{CG} + EC_{GS} = 38.7 metric ton /tonnes CO_2 + 0.35 metric ton/tonne of CO_2 = 39.05 metric ton/tonnes of CO_2

4.5.1. Discussion on formwork scenarios

Figure 21 shows the comparison of the overall CO2 emissions and cost per SFCA for the formwork from different sources. Results and conclusions:

1. The highest embodied carbon corresponds to the purchase of the formwork. The lowest embodied carbon contribution is given by the rent of the formwork.
2. The embodied carbon impact in the alternatives is relatively the same. Reusing the formwork from another jobsite has a slightly lower environmental impact.
3. The highest cost comes from the purchase of formwork.
4. The lowest cost for the formwork comes from reusing the material from another nearby jobsite.

It can be highlighted the fact that it is possible to both reduce cost and carbon emissions when selecting materials in a project, which is the particular case of renting formwork in this case study. This would be the contractor's ideal selection in terms of materials (since he is saving both in carbon and in costs), but without a framework that allows assessing the possibilities, this analysis for material selection would not have been possible.

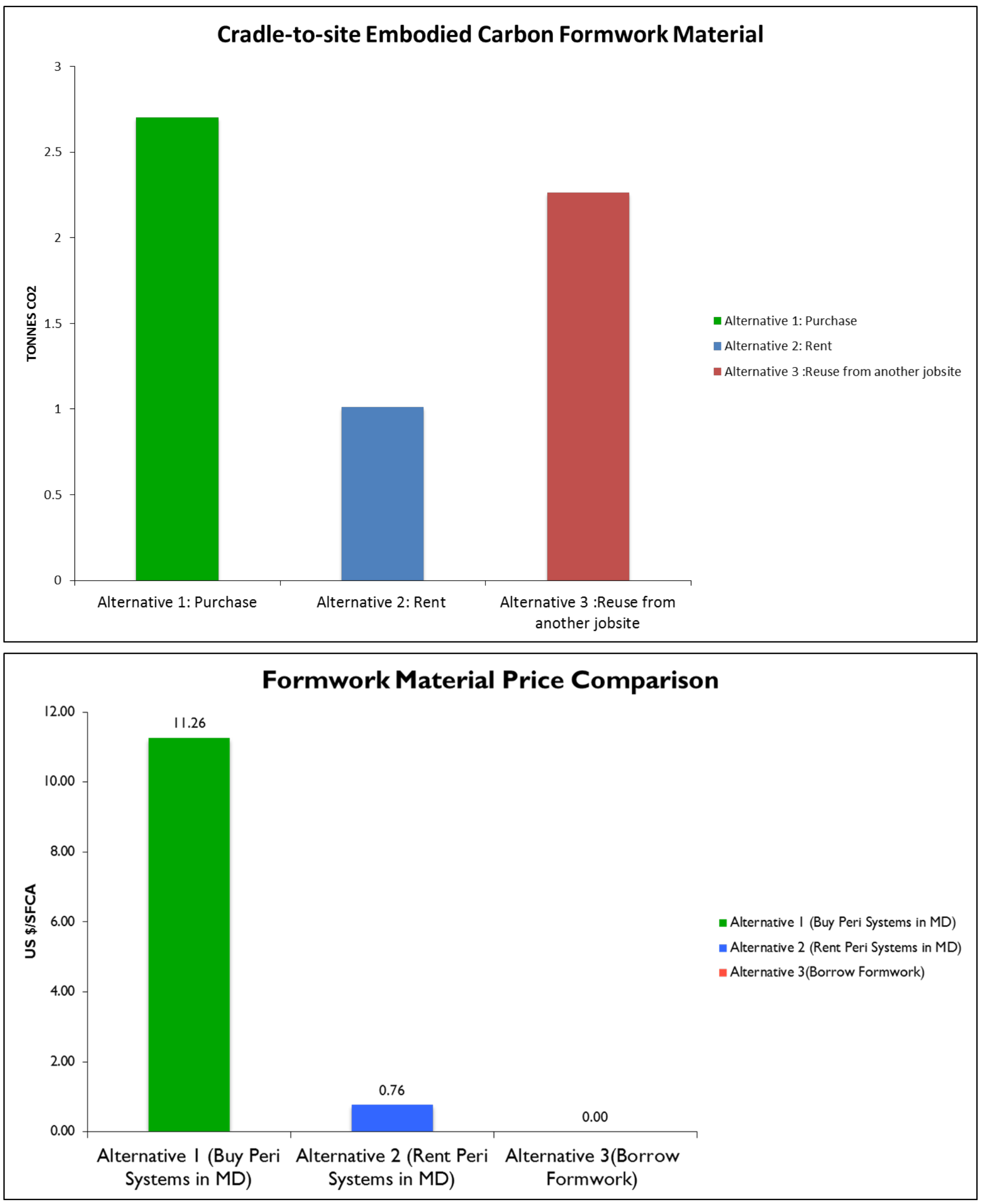


Figure 21. Formwork Scenario (a) Embodied Carbon Graph and (b) Cost Comparison Graph

4.6. Monitoring Framework Implementation

As discussed in the CFM framework in Chapter 3, the module for monitoring carbon footprint during the construction phase builds upon Earned Value Analysis (EVA). In traditional EVA, the earned value (EV), planned value (PV) are continuously measured and the actual cost (AC) is monitored. In our method, $BCFWP$, $BCFWS$ and $ACFWP$ which are the budgeted Carbon Footprint (CF) of the work performed, budgeted CF of the work scheduled, and the actual CF of the work performed, respectively are being measured and represented in a graph for visualization and measurement of the performance indicators $CFPI$ and SPI_{CF}.

This section will focus on implementing the proposed framework in two hypothetical scenarios where the new concepts based on Earned Value Analysis are applied to track environmental deviations during the construction phase of a project. The first scenario will look into the implementation of the framework in a concrete placement activity. The second scenario will look into the implementation of the framework in three concrete related activities.

4.6.1 Implementation of carbon footprint monitoring in scenario 1

Following assumptions and limitations are made while calculating the expected and actual embodied carbon of a concrete placement activity for the first scenario implementation.

1. Chandler Concrete plant, located in Christiansburg, VA, is assumed to supply the concrete for this project.
2. The concrete is delivered assuming each truck carries 6 cubic yards.
3. Every coefficient used for the case study implementation was extracted from the ICE version 2.0 (Hammond and Jones 2011).
4. The concrete embodied carbon coefficient used is 0.139 kg CO_2/ kg. This corresponds to a ready mix concrete made with 100 % Portland cement and designed strength of 4000 psi. The coefficient that corresponds to a 4000 psi ready mix concrete where 15% of the cement is replaced by fly ash is 0.129 kg CO_2/kg. The coefficient that corresponds to a 4000 psi ready mix concrete where 30% of the cement is replaced by fly ash is 0.116 kg CO_2/kg.
5. It was assumed that a cubic yard of concrete weighs 4,000 pounds in order to calculate the carbon footprint rates.
6. The distance for each truck unit is calculated from the manufacturing plant to the location

of the project. It does not consider the return to the manufacturing plant.

7. The mileage of each truck-trailer unit is assumed to be same as 3.22 miles per gallon irrespective of the engine or truck model.
8. All truck mixer units consume diesel fuel and any other fuel alternate is not considered for this study.
9. The carbon emissions related to equipment used for the on-site concrete placement is assumed to be the equivalent to the amount of carbon emissions released during its transportation to the site.
10. The material quantity was taken from the BIM of the project provided by Holder Construction.
11. The total quantity of concrete used in this example is 600 CY to be poured during a time frame of 10 days.
12. The rate of concrete placement scheduled is 6 cubic yards per day.
13. These calculations exclusively include the concrete pouring.

During the monitored days, the following questions are asked and answered in order to obtain the three basic parameters:

•BCFWS = What carbon footprint should have been released to date if the schedule was perfect?

•BCFWP = What was the planned carbon footprint to be released for the actual work completed to date?

•ACFWP = What is the actual carbon footprint that has been released to date?

Then, calculations of the performance indexes are conducted and further visual representation of the results are created using graphs and BIM platforms, where the status of the embodied carbon footprint and schedule performance is represented.

For this particular example, 600 CY of concrete needs to be placed during a period of 10 days. The planned daily output estimate is 60 CY/day. The scheduled carbon footprint rate is 210 Kg CO_2/CY =0.21 metric ton/tonne CO_2/CY using a 15% fly ash cement concrete. The daily activity progress reports are shown in Table 5.

Table 5. Concrete placement activity progress report

Time	Quantity of concrete (CY)		Notes Taken
Days	**Scheduled**	**Actual**	
1	60	-	CF rate scheduleled:0.234 tonnes CO2/CY
2	60	-	
3	60	100	
4	60	100	
5	60		
6	60	200	Unexpected change in material specification (Higher CF rate)
7	60	-	CF rated released =0.254 tonnes CO2/CY
8	60	-	
9	60	200	CF rated released =0.214 tonnes CO2/CY
10	60	-	

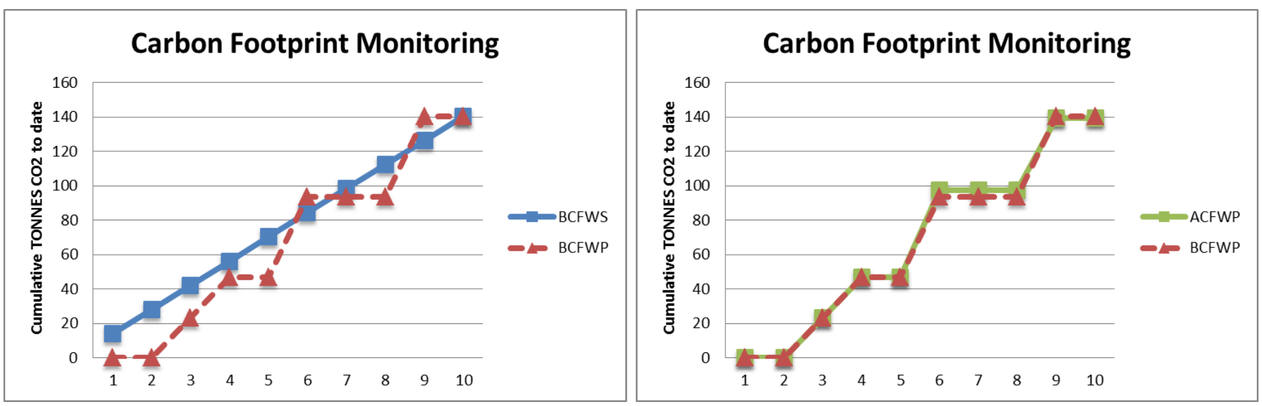


Figure 22. Monitoring Tool (a) BCFWS and BCFWP graph and (b) BCFWP and ACFWP graph

Assuming monitoring is performed 5 times during these activities in days 2, 4, 6, 8, and 10, the values of BCFWS, BCFWP, and ACFWP were calculated and/or measured. It is assumed for this implementation that in day 6, the concrete plant that supplies concrete to the project runs out of fly ash for the concrete production, so 100 % Portland Cement Concrete is poured in the remaining days with a carbon footprint rate of 252.19 kg CO_2/CY =0.252 metric ton/tonne CO_2/CY. This decision increased the CO_2 emissions when compared to the expected benchmarked emissions .The project manager, in an attempt to balance the carbon footprint and improve the overall carbon dioxide released, chooses to modify the concrete specification for concrete where 30% of the cement is replaced by fly ash producing a carbon footprint rate of 234.05 kg CO_2/CY =0.234 metric ton/tonne CO_2/CY. Consequently, there is an environmental impact change produced, which reflects in Figure 20. Figure 20 illustrates the CFM graphs where BCFWS, BCFWP, and ACFWP values of carbon footprint are represented in Tonnes CO_2. Particularly, Figure20a shows that for the first 4 days, as well as days 7 and 8 of the activity, that the performance is behind schedule, and then it rapidly improves to a point where it is continually ahead of schedule for the remaining days. This could mean that the original time assigned for the activities scheduled was overestimated, or that worker's productivity was better than estimated. This information could further help the project manager to adjust and assign a more approximate estimate in related activities and in future similar projects. Figure 20b shows that the generated actual carbon footprint was greater than the benchmarked values almost for the entire duration of the activities. In this example, it is clear that the main reason was the unexpected change of material specification during the project's progress, but there were certain days where concrete poured was less than the estimated. This result could also have been due to reasons such as change of supplier, quantity of the material estimated, construction methodology for the concrete placement and many others. Monitoring the carbon footprint of construction activities can help detect any deviation from the benchmarked values and take corrective actions to ensure that the overall environmental impact is minimized.

4.6.2. Implementation of carbon footprint monitoring in scenario 2

The second scenario will look into the implementation of the framework in three concrete related activities. This section will focus on implementing the proposed framework using the Center for the Arts data and applying the Earned Value Analysis concept to track environmental deviations during the construction phase of this project. Given the submittal forms information, schedule and BIM, making the assumptions that we have the carbon footprint of materials data available and a linked BIM model with the construction activities of the project, an estimation of the carbon footprint associated with the offsite and onsite operation would be calculated by entering the information on the procurement planning and monitoring interface. This will result in two ends: 1) monitoring performance metrics, and 2) color coding of the BIM elements based on the values of these metrics.

The embodied carbon coefficients used for this analysis are from the ICE database Version 2.0, 2011 of Hammond & Jones. This database provides a cradle-to-gate evaluation of different construction materials and summarized the findings in a form of an embodied energy (Mega Joules/Kg) and embodied carbon (Kg CO2) for each material. These values were used to benchmark the embodied carbon of the materials used in the activities analyzed. The boundary condition used in the implementation of this case study is cradle-to-site, which includes all of the carbon dioxide emitted from the extraction of the raw materials until the product has reached the job site.

4.6.3. Assumptions on the case study and limitations

Following assumptions and limitations are made while calculating the expected and released embodied carbon of the concrete related activities:

1. Chandler's concrete batching plant, located in Christiansburg, VA, is assumed to supply the concrete for this project.
2. The concrete is delivered assuming each truck carries 9 cubic yards.
3. Every coefficient used for the case study implementation was extracted from the ICE version 2.0 (Hammond and Jones 2011).
4. The concrete embodied carbon coefficient used is 0.139 kg CO_2/kg. This corresponds to a ready mix concrete made with 100 % cement and designed strength of 4000 psi. The coefficient that corresponds to a 4000-psi ready mix concrete where 25- 30% of the cement is replaced by fly ash is 0.116 kg CO_2/kg.
5. CMC Steel Northern Virginia, located in Fredericksburg, VA, is assumed to supply the steel rebar for this project.
6. The steel embodied carbon coefficient used for benchmarking during the preconstruction phase is 1.74 kg CO_2/kg. This corresponds to steel rebar that has an average based on the world average 3 year steel consumption of with a recycled content of 39%. The steel embodied carbon coefficient used is 1.82 kg CO_2/kg. This corresponds to steel rebar that has an average recycled content of 35.5% based on the average steel consumption of non-European countries.

7. Peri Systems, located in Baltimore, MD, is assumed to supply the formwork for this project.
8. The embodied carbon coefficient used is 0.42 kg CO_2/kg. This corresponds to plywood under the timber category.
9. The distance for each truck unit is calculated from the manufacturing plant to the location of the project. It does not consider the return to the manufacturing plant.
10. The mileage of each truck-trailer unit is assumed to be same as 3.22 miles per gallon irrespective of the engine or truck model. (NRMCA 2012).
11. All truck-trailer and truck mixer units consume diesel fuel and any other fuel alternate is not considered for this study.
12. The carbon emissions related to equipment used for the installation of the materials on-site are assumed to be the equivalent to the amount of carbon emissions released during its transportation to the site.
13. The bill of materials was queried from the underlying BIM developed for this project.

4.6.4. Discussion on monitoring carbon footprint results

The original schedule for this activity was programmed to be 21 days and it was performed in 12 days. Assuming monitoring is performed every 2 days, a total of twelve times during these activities in days 2, 4, 6, 8,10,12, 14,16,18, 20 and 21, the values of BCFWS, BCFWP, and ACFWP were calculated and/or measured. Figure 21 illustrates the CFM graphs where the scheduled and the actual values of carbon footprint are represented in $\text{Tonnes } CO_2$. Particularly, Figure 21a shows that except for days 4, 6 and 8, the performance is ahead of schedule. This could mean that the original time assigned for the activities scheduled was overestimated. This information could further help the project manager to adjust and assign a more approximate estimate in related activities and in future similar projects.

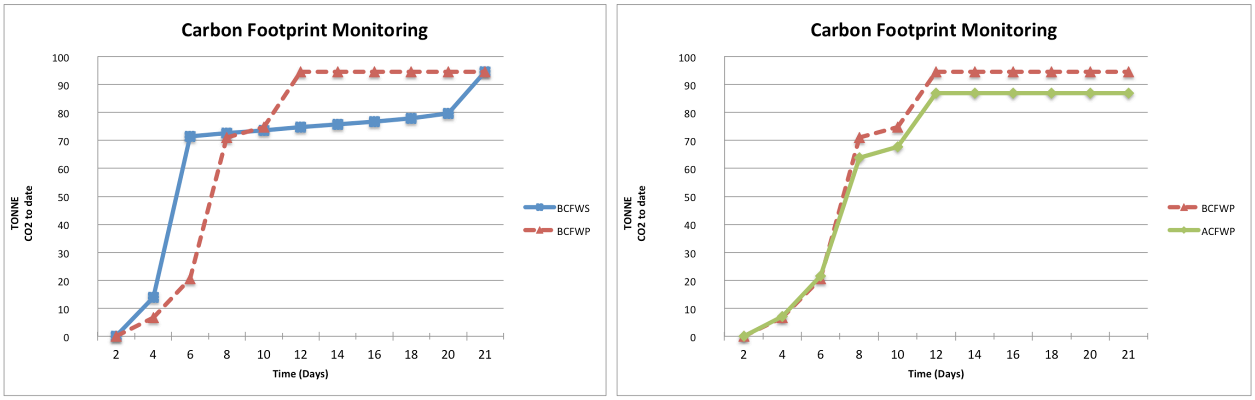


Figure 23. Center for the Arts VT (a) BCFWS and BCFWP graph and (b) BCFWP and ACFWP graph

Figure 21b shows that the generated actual carbon footprint in days 4 and 6 was greater than the benchmarked values and that environmental performance improved for the rest of the duration of the activities. This result could be due to reasons such as change of material specification and/or supplier, quantity of the material estimated and many others. In this particular implementation we assumed that the project manager, after looking at the environmental performance calculated based on the latest supplier's information in their submittal, decided to use concrete with a 25 % cement replacement for fly ash and this influenced and reduced the cradle-to-gate environmental impact of the material itself from 0.139 kg CO_2/kg to 0.116 kg CO_2/kg. In this implementation we also assumed that the embodied carbon coefficient of the steel reported to the managers at the time of construction rose from 1.74 to 1.82 kg CO_2/kg. The overall result was that the embodied carbon footprint of the reinforced concrete reduced from 0.26 kg CO_2/kg to 0.24 kg CO_2/kg resulting in the overall reductions in terms of carbon of around 649.6 kg CO_2=0.649 metric ton/tonne CO_2. This result is only looking at one particular activity of the schedule. If it was to be estimated for the overall construction project, reductions will be significant. Table 6 present the values resulted from the monitored days and its respective values for the performance indexes.

Table 6. CFM and Performance Indexes

Time (Days)	BCFWS (TONNE CO_2)	BCFWP (TONNE CO_2)	ACFWP (TONNE CO_2)	CFPI	SPI cf
2	0.13	0.00	0.00		
4	13.84	6.76	7.07	0.96	0.49
6	71.52	20.67	21.59	0.96	0.29
8	72.58	71.13	63.81	1.11	0.98
10	73.64	74.83	67.67	1.11	1.02
12	74.69	94.47	86.98	1.09	1.26
14	75.75	94.47	86.98	1.09	1.25
16	76.80	94.47	86.98	1.09	1.23
18	77.86	94.47	86.98	1.09	1.21
20	79.61	94.47	86.98	1.09	1.19
21	94.47	94.47	86.98	1.09	1.00

Once the values of BCFWS, BCFWP, and ACFWP are measured and updated for all inspection days, the developed system can calculate the CFPI and SPI_{CF} indexes. Next, using a color-coding palette in Table 1 the proposed method color codes all elements that are linked to these schedule activities in the underlying BIM elements. The calculated and visualized CFM indexes represent the carbon footprint associated with the manufacturing process of material and their delivery to the jobsite. This system provides an opportunity for practitioners to monitor carbon footprint of each building material/element along the project, discuss various delivery alternatives with contractors and their suppliers in an augmented reality environment as opposed to real-world which is less costly. This can ultimately help minimize the environmental impacts and cost of construction operations.

It can be concluded that distance to the jobsite and delivery method but also the manufacturing process (i.e. the source of the raw materials) of the materials used in a construction project influence its embodied carbon. It is important to highlight that the embodied carbon of materials could be reduced with the use of an increased percentage of recycled content in the materials, because this leads to a significant reduction of carbon emissions during the manufacturing phase.

Also, it is important to know that during the installation phase of the materials, carbon emissions generated will be dependent of the method selected for the installation: type of equipment, material specifications and contractor's planning and efficiency. This information has potential to empower the practitioners to select more environmentally friendly manufacturers, find different delivery alternatives and installation methods of the materials. The decision is more complex when we take into account that a material with a lower embodied carbon does not mean it will be the best choice in terms of performance. Other issues need to be considered, such as longevity, maintenance, material density and durability as highlighted by Tse (2011).

4.6.5. EPA's metaphor for the number of tree seedlings grown for 10 years

Table 7 and Figure 22 show the measured CFM values and the number of trees, which need to be planted for compensation of losses resulting from $Tonnes\ CO_2$ of emissions, based on the data used in the case study. The potential reductions/savings of number of trees seedlings provides an incentive for contractors to analyze their environmental impacts by comparing actual and expected performances. The analysis also highlights how looking into a cumulative tonnage of emissions for a particular activity as part of the monitoring module could help take corrective actions by choosing more sustainable materials, delivery alternatives, construction methodologies. The concept of trees seedlings needed to be grown for 10 years is analog to tonnage of CO2 and it is used in order to grasp a more tangible and clearer idea of the environmental impact while bringing awareness to the significance of minimizing environmental impact of construction projects through decisions taken in a daily basis during construction activities.

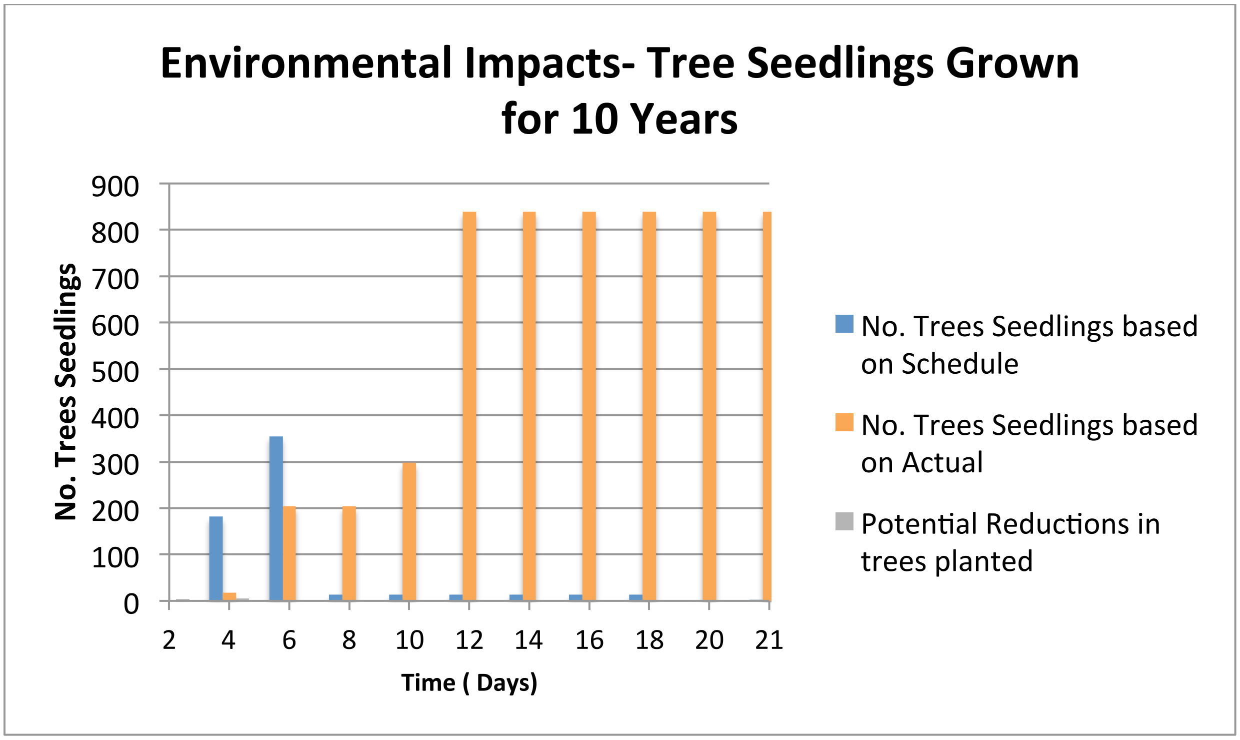


Figure 24. EPA's metaphor for number of trees seedlings grown for 10 years

In the case of the Center for the Arts Project, with the framework implementation of scenario 2, we found that the number of tree seedlings that need to be grown for 10 years to compensate for the loss caused by the released $Tonnes\ CO_2$ of emissions totaled 839. The environmental impact of the activity is calculated at the end of the activity, which is Day 21, and it is the difference between scheduled and released carbon emissions.

These values could also be assessed more frequently but as a mean to better understand the consequences of the decisions made in a daily basis and take corrective actions in terms of construction decisions related to material supplier, delivery method, and installation methods. For example looking into Table 7 in Day 4, the cumulative values difference of the scheduled and the released (22-17 = 5) results in a number of 5. This result indicates that less carbon dioxide than the expected has been released and in consequence there is no need for planting of any trees seedlings. If we were to offset the actual overall emissions of the cumulative value to date, the number of trees seedlings needed to be planted will be 17. Looking into day 6, the cumulative values difference of the scheduled and the released (48-204 = -156) results in a negative number of -156. This result indicates that more carbon dioxide than the expected has been released and in consequence there is a greater need for planting of trees seedlings grown for 10 years than the budgeted or expected number. If we were to offset the actual overall emissions of the cumulative value to date, the number of trees seedlings needed to be planted will be 204 versus the scheduled 34. This gives us an idea of how we are performing in terms of environmental impact and corrective actions could be taken to minimize and exceed the expectations in terms of environmental performance. It is important to highlight that if action were to be taken by practitioners regarding the trees seedlings planting, this calculation should be done at the end of the project since the number of trees seedlings will change dynamically as the project progresses and their main purpose throughout the project is to understand better the degree of environmental impact of the decisions made on the project, since the number of trees seedlings concept is a more familiar concept than the tonnes of CO_2.

When the number of tree seedlings grown for 10 years based on the original schedule is larger than the number of tree seedlings grown for 10 years in the actual schedule, the number of tree seedlings grown for 10 years reflected is the potential reductions in trees planted. When the number of tree seedlings grown for 10 years in the actual schedule is larger than the original schedule, it is a sign that there was a carbon release larger than what was expected; which means that to offset carbon emissions a larger number of tree seedlings grown for 10 years will be needed.

The environmental impact could be reduced by choosing more environment friendly manufacturers, different delivery alternatives of the materials to the jobsite and construction methodologies.

Table 7. The expected, actual, and the potential excess/reductions of carbon footprint.

Time (Days)	BCFWS (Tonnes CO_2)	ACFWP (Tonnes CO_2)	No. Trees Seedlings based on Actual	No. Trees Seedlings based on Schedule	Potential Reductions/savings in trees seedlings
2	0.13	0	0	3	3
4	0.84	0.66	17	22	5
6	1.34	7.94	204	34	0
8	1.87	7.94	204	48	0
10	2.40	11.63	298	62	0
12	2.93	32.72	839	75	0
14	3.46	32.72	839	89	0
16	3.99	32.72	839	102	0
18	4.52	32.72	839	116	0
20	5.74	32.72	839	147	0
21	20.45	32.72	839	524	0

4.7. Visualization of CFM Metrics – Color Coding BIM

As part of the monitoring and visualization module of the framework and depending on the values of $CFPI$ and SPI_{CF} from the day analyzed, the to-date embodied carbon footprint of the concrete related construction activity will be color coded at BIM element level using the color coding pallet shown in Table 1 and represented in the Building Information Model environment in order to facilitate the visualization of the carbon footprint. In the case study of the Center for the Arts at Virginia Tech, Figure 25 is a visual representation of some monitored days and their resulted color, which express the environmental and schedule performance of the activity studied.

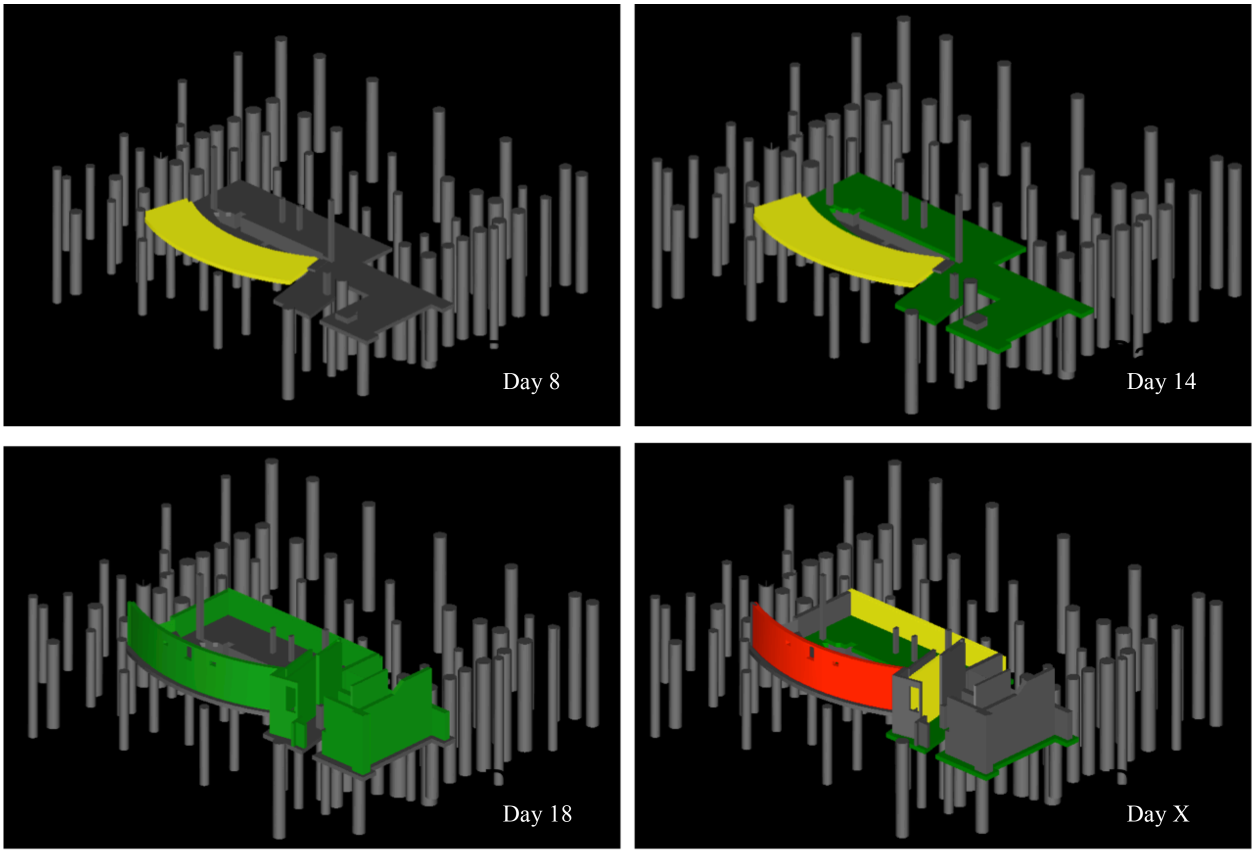


Figure 25. Color Coded BIM.

As it is reported in the Carbon Footprint Analysis Table 6 and Figure 25, in this figure, the colors are representing the CFM metrics following the concept introduced in Table 1. In day 8, the color yellow in the BIM environment indicates the environmental performance was CFPI >1 and the SPI_{CF} <1, which means that carbon emissions emitted were less compared to the expected to date carbon footprint for that particular activity, and the activity was behind schedule. Together these values explain more; we could speculate that because it was behind schedule, it was reasonable to think that the carbon emissions are less than expected but this could also mean that the choice or combination of choices of material selection, delivery technique and construction methodology influenced the final result. This means that the project manager before taking corrective actions should analyze the information that comes from both construction project reports and the material's information to confirm its hypothesis.

In day 14 and 18 it is illustrated how elements of the concrete related activity are progressing. The green color represent acceptable and favorable environmental and schedule performances. Day X is an example in the same activity at the project of how this implementation could quickly give information that can aid project managers to make more assertive decisions in a timely manner.

4.8. Validation of the proposed framework

Currently, there is no carbon footprint tool used in the construction industry that facilitates benchmarking and monitoring of the environmental impact of the materials during preconstruction and construction phases of a project. The majority of the state-of-the-art frameworks and tools developed to benchmark the energy consumption and carbon footprint are geared toward application during the design and use/occupational phase.

The submittal review process during the preconstruction stage and the early stages of the construction phase can provide an excellent opportunity to perform the cradle-to-gate and cradle-to-site carbon footprint assessment associated with the different materials and their delivery methods. Currently during the submittal review process, the shop drawings and sample submissions are reviewed to make sure they comply with the drawings and the project specifications. Nevertheless, the architect, engineers or project managers' reviews do not include approvals of the embodied carbon associated with the manufacturing and delivery of the materials, construction methods and/or their associated procedures. As a result, material cost, delivery time, quality, and availability are often the main criteria to select the material supplier. Therefore, the choice for the lowest embodied carbon associated with the manufacturing process as well as the transportation to the site is not considered. Consequently, the contractors also do not have enough incentive to force upstream supply chains to provide accurate data on the embodied carbon footprint of their products. Without a proper knowledge about the sources of materials, their manufacturing processes, the shop drawings and submittal details, and final delivery methods, any estimates on carbon footprint may be inaccurate or such assessments may be deemed optional.

A challenge exists in the adoption and implementation of carbon footprint assessments, but as awareness rises, frameworks and tools are developed and policies are implemented, the existence and significance of an automated systematic approach for benchmarking the carbon footprint during the submittal and construction process will signify a change in the way the industries perform. There would be pressure on manufacturers to minimize the carbon footprint associated with the extraction of their raw materials or their manufacturing techniques. Also subcontractors would be supported in the decision making of more environmentally friendly manufacturers, suppliers, jobsite delivery solutions and construction methods. Additionally, project managers will be able to quickly and easily benchmark and monitor the embodied carbon footprint of their construction activities.

Overall, the successful execution of the proposed research will transform the way construction operations are currently being monitored. The construction emissions will be more frequently assessed, and more informed decisions towards the reduction of carbon footprint of a project will become part of an integrated systematic management approach of a practitioner's daily basic tasks.

The contractors and subcontractors will have a mechanism to support them in selecting the most environmentally friendly manufacturers, suppliers, jobsite delivery solutions, or construction means and methods with the least negative environmental impacts, while considering cost and schedule objectives. All in all, project stakeholders will easily and quickly benchmark and monitor the embodied carbon footprint of their construction operations.

In order to ensure best practices during the benchmark and monitoring of carbon emissions, the practitioners must have relevant LCA data regarding the materials to be used in the construction and know that the supplier's data and considerations regarding product manufacturing process and delivery to site influences the environmental impact. Also, it is important that practitioners remember that during the installation phase of the materials, carbon emissions generated will be dependent of the methods selected for the installation: type of equipment, material specifications and contractor's planning and efficiency.

The knowledge of this information empowers the practitioners to select more environmentally friendly manufacturers, find different delivery alternatives and installation methods of the materials. The decision is more complex when we take into account that a material with a lower embodied carbon does not mean it will be the best choice in terms of performance. Other issues need to be considered, such as longevity, maintenance, material density and durability as highlighted by Tse (2011).

CHAPTER 5: CONCLUSION AND FUTURE WORKS

This thesis presented a new framework and the supporting tools for benchmarking, monitoring, and visualization of embodied carbon footprint. Based on the proposed method, the BIM is generated in which both actual and expected embodied carbon footprint of the project are represented in a common 3D environment. Moreover, based on material information queried from the underlying BIM in addition to an embodied carbon footprint inventory associated with different materials and the distance of the suppliers to the jobsite, the expected carbon footprint is calculated for each construction schedule activity. The information from the contractor submittals and the construction project progress reports is used to measure the released carbon footprint for the same activity. Finally, the expected and released carbon footprint associated with both material procurement and their delivery is compared using the Carbon Footprint Monitoring (CFM) analysis and its deviations are visualized in the BIM environment. The resulting visualization provides an opportunity for contractors and suppliers to minimize the carbon footprint of each building material in addition to managing cost and time for their delivery during contractor coordination and submittal processes.

By validating the proposed solution, this thesis discusses the potential of implementing such benchmarking and monitoring practices during the coordination and submittal processes to not only ensure timely delivery of materials and keep projects on budget but also minimize the cradle-to-site embodied carbon of the projects. The existence and significance of a systematic approach for benchmarking the carbon footprint during the submittal and construction process has the potential to improve how monitoring practices are being performed today. There would be incentives for manufacturers to minimize the carbon footprint associated with the extraction of their raw materials or their manufacturing techniques. Also subcontractors would be supported in the decision making of more environmentally friendly manufactures, suppliers, jobsite delivery solutions and construction methods. Additionally, project managers will be able to quickly and easily benchmark and monitor the embodied carbon footprint of their construction activities.

As the industry continues to evolve towards more sustainable practices, construction practitioners can influence the other sectors of the supply chain by creating demand for products with low carbon processes, address carbon impact by intelligent specification based on impact as well as ease of implementation, and encourage the use of recycled and recyclable products as pointed out by Rawlinson and Weight (2007). Additionally, it will be an opportunity to create a benchmark that is a reference to future similar projects. Motivating suppliers in the supply chain to disclose environmental data of their products could be a challenge, but as government initiatives, environmental guidelines, policies and tools that allow and facilitate its measurement and communication arise, adoption of this practice will increase. Other mechanisms such as contracts, environmental laws and/or clients committed to reducing the carbon footprint could also influence in the acceleration of the process. This research can be further expanded to:

1. Surveying the embodied carbon in concrete, formwork and rebar steel manufacturing processes from various manufacturing plants across the United States, especially leveraging a new comprehensive dataset such as Tally project.
2. Studying the effects of variable recycled contents used in manufacturing the materials.
3. Analyzing the various alternatives of transporting the materials to the job site.
4. Exploring mechanisms to reduce fuel consumption during the construction in order to minimize the overall embodied carbon through:
    - Improving equipment productivity
    - Reducing transportation time.
5. Measuring and analyzing effects of variations in specifications while using the same material.
6. Measuring and analyzing the impact of different installation equipment and/or methodologies in the embodied carbon of the material used on site.

REFERENCES

Chandler Concrete (2013). "Virginia ACI Commonwealth Award." Current Events, <http://chandlerconcrete.com/news.html >(December 15,2013).

Crishna, N., Banfill, P. F. G., and Goodsir, S. (2011). "Embodied energy and CO_2 in UK dimension stone." *J. Resour. Conserv. Recy.*

Dixit, M. K., Fernandez-Solis, J. L., Lavy, S., and Culp, C. H. (2010). "Identification of parameters for embodied energy measurement: A literature review." *J. Energy and Buildings*, 42, 1238-1247.

Engineering News Record (ENR) (2010). "California Board Endorses Cap-and-Trade Regulation"<http://enr.construction.com/policy/legal/2010/1221CapandTradeRegulation.asp>(Oct. 10, 2012).

Emmanuel, M. R., and Baker, K. (2012). *Carbon management in the built environment*. London: Routledge.

Golparvar Fard M. and Peña-Mora F. (2007). "Development of visualization techniques for construction progress monitoring." *Proc., ASCE Int. Workshop on Computing in Civil Eng*, Pittsburgh, PA.

Golparvar-Fard M., Peña-Mora F., and Savarese S. (2009a). "D4AR- A 4-Dimensional Augmented Reality model for automating construction progress data collection, processing and communication." *J. of ITCON ,* Vol. 14, 129-153.

Golparvar-Fard M., Peña-Mora F., Arboleda C. A., and Lee S. H. (2009b). "Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs", *ASCE J. Computing in Civil Eng*., 23 (6), 391-404.

Hajji, A. , and Lewis,P. .(2012). "Estimating the economic, energy and environmental impact of earthwork activities." *Proc., Construction Research Congress*, West Lafayett, IN.

Hammond, G. P., and Jones, C. I. (2008). "Embodied energy and carbon in construction materials." *Proc. Of the institution of Civil Engineers - Energy* 161(2), 87-98.

Hammond G., Jones C. (2011). "Inventory of Carbon and Energy (ICE) version 2.0", University of Bath, <http://www.bath.ac.uk/mech-eng/sert/embodied/>. (Sept.20, 2013).

Hendrickson C. (2008). Project Management for Construction: Fundamental Concepts for Owners, Engineers, Architects, and Builders. <http://pmbook.ce.cmu.edu/> (Sept. 5,2012).

Kara, S., and Ibbotson, S. (2011). "Embodied energy of manufacturing supply chains." *CIRP J. Manufacturing Sci. and Tech, 4(3), 317-323.*

Lane, T. (2007). "Our dark materials." UBM Built Environment: Building Issue 45. <www.building.co.uk/comment/our-dark-materials/3099435.article> (Oct. 5,2012).

Memarzadeh, M. and Golparvar-Fard M. (2012). "Monitoring and visualization of building construction embodied carbon footprint using nD augmented reality models." *Proc., Construction Research Congress*, West Lafayett, IN.

Monahan, J., and Powell, J. C. (2011). "An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework." *J. Energy and Buildings*. 43 (1), 179-188.

Mpakati-Gama E.C., Wamuziri S., Sloan B. (2011)."Applicability of inventory methods for embodied energy assessment of buildings in Sub-Sahara Africa." *J. The Built & Human Environment Review*, 4(2), 41-55.

Notteboom, T. and P. Carriou (2009) "Fuel surcharge practices of container shipping lines: Is it about cost recovery or revenue making?" *Proc., International Association of Maritime Economists (IAME) Conf.*, Copenhagen, Denmark.

Palaniappan,S. , Bashford, H.,li,K., Crittenden, J.,Fafitis, Apostolos, Stecker, L. , and Steven Hay (2012). "Carbon Emissions Of On-Site Equipment Use In Post-Tensioned Slab Foundation." *Proc., Construction Research Congress*, West Lafayett, IN.

Peña–Mora F., Ahn C., Golparvar-Fard M., Hajibabai L., Shiftehfar S., An S., Aziz Z. and Song S.H. (2009). "A Framework for managing emissions during construction." *Proc., Int. Conference and Workshop on Sustainable Green Building Design and Construction, NSF*.

Rawlinson, S., and Weight, D. (2007)."Sustainability: Embodied carbon." <http://www.building.co.uk/sustainability%E2%80%94embodiedcarbon/3097160.article> (Dec. 5 ,2013).

Russell-Smith S., and Lepech M. (2011). "Dynamic Life Cycle Assessment of Building Design and Retrofit Processes." *Proc. Of International Workshop on Computing in Civil Engineering 760-767.*

Shiftehfar R., Golparvar-Fard M., Peña-Mora F., Karahalios K., and Aziz Z. (2010). "Application of visualization for construction emission monitoring." *Proc., Construction Research Congress,* Banff, Canada, May 8-11.

Skanska (2008). "One Kingdom Street-Sustainability Case Study". < http://goo.gl/qnuOGw> (October 5th 2012).

Tally (2014). "Tally." < http://choosetally.com/faq/ >(Feb. 15,2014).

Transportation Data Energy Book (2011) "Chapter 5: Heavy Vehicles and Characteristics.", <http://cta.ornl.gov/data/tedb32/Edition32_Chapter05.pdf > (Sept. 15,2013).

Tse, P. (2011). "Low-carbon buildings need low embodied energy." <\https://www.bsria.co.uk/news/article/embodied-energy//> (Aug. 30, 2013).

United Nations Environment Programme (UNEP)(2009). "Buildings & Climate Change: A Summary for Decision-makers." <http://www.unep.org/sbci/pdfs/sbci-bccsummary.pdf > (Aug. 30,2013).

US DOE (1998). "Method for calculating carbon sequestration by trees in urban and suburban settings." Voluntary reporting of greenhouse gasses, US Department of Energy, Energy Information Administration, 1-16.

U.S Energy Information Administration, (EIA) (2011). "Voluntary Reporting of Greenhouse Gases Program Fuel Emission Coefficients." Voluntary Reporting of Greenhouse Gases Program Fuel Emission Program, <http://www.eia.gov/oiaf/1605/coefficients.html#tbl2> (September 15, 2013).

U.S Environmental Protection Agency (EPA) (2010). "Inventory of U.S. Greenhouse Gas Emissions and Sinks." Technical Report USEPA #430-R-11-005, 1-459.

Wang E., Shen Z., Berryman C. (2011). "A Building LCA Case Study Using Autodesk Ecotect and BIM Model." *Proc., 47th ASC Annual Int Conf.*

Wayne Brothers Inc. (2013). "Virginia Tech Center for the Arts." Wayne Brothers Incorporated: Projects,<http://waynebrothers.com/Projects/Educational/VTCenterfortheArts.aspx> (Oct. 10,2013).

Wong J.K.W., Li H., Wang H., Huang T., Luo E., and Li V., (2013). "Toward low-carbon construction processes: the visualization of predicted emission via virtual prototyping technology." *J. Automation in Construction*, 33, 72-78.

Zagula M., Hinkle J.,Mobley B.,Williams,D. Mullings,G.(2012) " 2012 NRMCA Fleet Benchmarking and Costs Survey.", National Ready Mixed Concrete Association (NRMCA),<http://www.nrmca.org/operations/documents/2012fleetsurveyfinalrepot.pdf> (Sept.15,2013).