

A DECISION-MAKING FRAMEWORK FOR VEGETATED ROOFING SYSTEM SELECTION

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Choosing By Advantages

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ABSTRACT

Design frequently involves a series of tradeoffs to obtain the “optimal” solution to a design problem. Green roofs have many different characteristics based on a variety of variables. Designers typically weigh the impacts of these characteristics in an implicit process based on intuition or past experience. But since vegetated roofing is a relatively complex and comparatively new technology to many practitioners, a rational, explicit method to help organize and rank the tradeoffs made during the design process is useful.

This research comprises the creation of a framework diagramming the decision process involved in the selection of vegetated roofing systems. Through a series of expert interviews and case studies, the available knowledge is captured and organized to determine the critical parameters affecting design decisions. A set of six case study projects in North America is analyzed and six critically important evaluative categories are identified: storm water management, energy consumption, acoustics, structure, compliance with regulatory guidelines and governmental incentives, and cost. These six factors are key decision-making parameters in the selection of vegetated roofing systems and they form the basis of this study. They are addressed in the context of a decision support system for green roof designers. A summation of the total importance of the advantages represented by each alternative is used to determine the most feasible green roof system for a particular project. The decision-making framework developed in this dissertation will ultimately be adaptable to digital processing and a computer-based design assistance tool.

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1. INTRODUCTION

1.1. Background

1.1.1. A Brief History of Green Roofs

Through time, green roofs have evolved from disparate sources that are reflected in the variety of their modern-day characteristics and performance. Theodore Osmundson (1999), in his book *Roof Gardens: History, Design and Construction*, gave an encyclopedic account of green roofing through the ages. The first historically referenced examples of green roofing were found in the “cradle of civilization”, the region of Mesopotamia lying between the Tigris and Euphrates rivers. According to archeological evidence found by Sir Leonard Woolley, the landings of ziggurats, or stepped pyramids found in sacred complexes, were planted with shade trees and other vegetation to provide relief along the hot climb to the top (Osmundson, 1999).

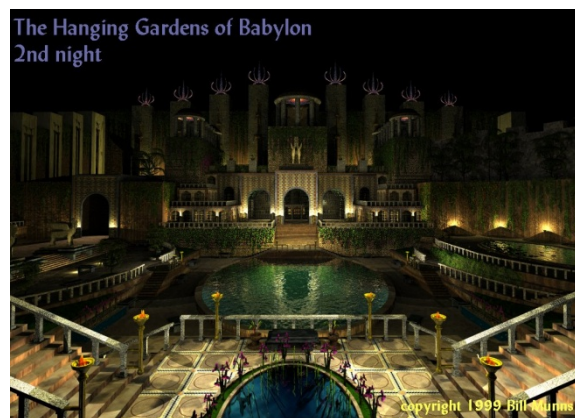


Figure 1.1 - Hanging Gardens of Babylon, permission to use granted by: Bill Munns (Jan. 15, 2007)

The most legendary of early roof gardens, The Hanging Gardens of Babylon, were likely built a few hundred years after the last of the ziggurats, around 500 B.C. Long since destroyed, and referenced only by later historical accounts, these gardens are shrouded in myth and are considered one of the Seven Wonders of the Ancient World. In contrast to the environmentally friendly image often conjured up by green roofs in the modern world, the Hanging Gardens were reputedly constructed by King Nebuchadnezzar II in direct defiance of nature, to artificially replicate the mountainous homeland of his wife using a system of vaults and water pumps to support and irrigate a terraced series of gardens (Osmundson, 1999). Vaulted structures topped with roof gardens were also discovered at the Villa of the Mysteries, buried in the ashes resulting from the eruption of Mount Vesuvius in 79 A.D. (Osmundson, 1999).

Medieval and Renaissance examples of roof gardens include the terraced Benedictine abbey of Mont-Saint-Michel, France, the Palazzo Piccolomini in Pienza, Italy, the Tower of the Guinigi in Lucca, Italy, and sites found in the city of Tenochtitlán, located in modern-day Mexico City (Osmundson, 1999). The common thread tying these projects together was the desire to exploit roofs as outdoor occupied space. Roof gardens were an indulgence of the wealthy, containing ornamental gardens often planted with imported or otherwise special plant varieties. The trend toward elaborate gardens, often featuring ambitious pond constructions, continued into the 1800s with examples including the Kremlin in Moscow, the Hermitage in Saint Petersburg, and a leaky roof commissioned by “mad” King Ludwig II in Munich (Osmundson, 1999).

Nigel Dunnett and Noël Kingsbury (2004), in their recent text *Planting Green Roofs and Living Walls*, viewed the sod roof as the precursor to the modern extensive green roof, while asserting that the roof gardens of the privileged classes evolved into the intensive green roofs of today. In contrast to the cultivated approach to green roofing seen in the projects mentioned above, the Scandinavians employed green roofs for much more pedestrian reasons. Rather than carefully executed gardens for recreation and amusement, Scandinavian sod roofs and their exported American pioneer counterparts were a practical innovation based on the use of turf as a widely available, highly insulating, mostly water resistive roofing material. While they were and are still imbedded deep within the collective nostalgia of the cultures that employed them, sod roofs were notoriously prone to leaking, required extensive maintenance and fairly frequent replacement, and were thus abandoned to more sophisticated roofing materials as they became available (Osmundson, 1999, Dunnett & Kingsbury, 2004).

While new world pioneers adopted the sod roof approach in the grassy plains states, the tradition of highly articulated roof gardens continued in America’s cities. Theodore Osmundson (1999) stated that the term “roof garden” was first used in reference to structures such as the original Madison Square Garden in New York City, a summer theater of the type popular before the advent of air conditioning. Hotels, penthouse apartments and high-rise corporate structures of the era also featured roof gardens as an amenity, with the five green roofs of Rockefeller Center in New York being a well-known example. Support was given to the age-old concept of the green roof as extended outdoor living space by two renowned and influential architects, Frank Lloyd Wright and Le Corbusier, who incorporated roof gardens into their design philosophies as well as some of their built work. The Great Depression, WWII and the post-war

housing crisis stalled the construction of roof gardens in the U.S., which did not resume significantly until the late 1950s. At that time, the roof garden trend shifted toward large, often publicly accessible green roofs located above parking garages or other substantial structures in urban centers where land was at a premium (Osmundson, 1999).

Concurrently in the German-speaking countries of central Europe, the focus on the relationship between the manmade and the natural environment, while rooted initially in the counterculture, had a more profound impact on the mainstream design community than it did in North America. This widespread acceptance of “green” building principles is perhaps epitomized by the popularity of the work of Friedensreich Hundertwasser, who constructed an ambitious and high-profile housing project called the Hundertwasser-Haus in Vienna, Austria, complete with roof gardens and façade greening. Researchers began to support this interest in the “greening” of the urban landscape through research into the ecological benefits of brownfields sites. In fact, early interest in extensive green roofing stemmed from studies investigating the benefits of natural colonization of plants on typical gravel roofs (Dunnett & Kingsbury, 2004). Once the energy and storm water benefits of roof greening began to be recognized, and the impact of buildings on the environment began to carry some economic weight in the design decision-making process, support for green roof technology could be found in the research, design and construction industries. Notably, the German Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), or Research Society for Landscape Development and Landscape Design, developed a branch to study green roofing in 1977. This organization was, and is, responsible for setting guidelines and standards for green roofing (Dunnett & Kingsbury, 2004). In the absence of established nationwide specifications in the U.S. and Canada for green roofing, the *FLL Guideline* (2002) is frequently referenced as a design standard in North America.

Two divergent sources of green roofs, the age-old roof garden tradition and the more recent, research-based extensive green roof movement, are at the root of the distinction between intensive and extensive green roofs, which according to Dunnett and Kingsbury (2004) was first made explicit in the mid-1970s. Contemporary vegetated roofing is frequently divided into two general categories by virtue of the depth of its growing medium: intensive green roofs, also called high-profile roofs or roof gardens, with medium depths generally exceeding 6 inches (150 mm), and extensive green roofs, also called low-profile roofs, eco-roofs or performance roofs, with medium depths generally less than 6 inches (150 mm).

1.1.2. Environmental Impact of Roofing

Due to its susceptibility to the elements, roofing is one of the most frequently replaced building systems. According to the Oak Ridge National Laboratories' R30/30 Roofing Systems research project website (2003), the average building in the U.S. requires roof replacement four times during its lifespan, and roofing constitutes the second-largest contribution to U.S. solid waste generation. Re-roofing projects account for the majority of roofing projects undertaken every year, as seen in Figure 1.2 and Figure 1.3 from the National Roofing Contractor's Association's 2002-2003 annual market survey, as reported by Beverly Siegel in Professional Roofing(2003).¹

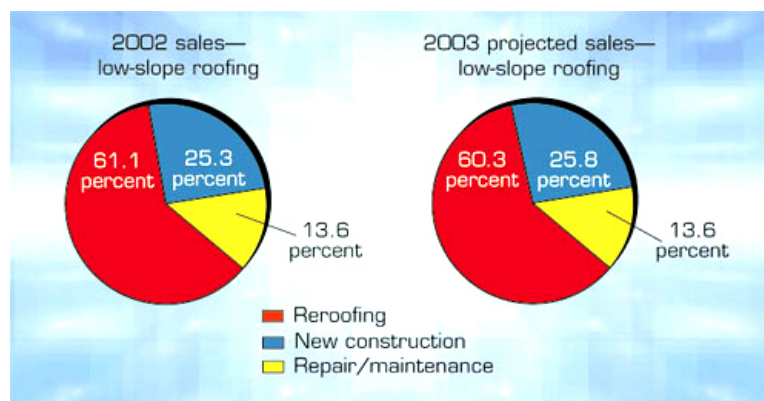


Figure 1.2 - Low-slope roof sales (Siegel, 2003, p. 4), permission to use granted by: Ambika Bailey, National Roofing Contractors Association (Jan. 10, 2007)

¹ Roofing is generally classified in terms of low-slope, or water-resisting, roofs with slopes less than or equal to 3:12 and steep-slope, or water-shedding, roofs with slopes greater than 3:12 (Patterson & Mehta, 2001).

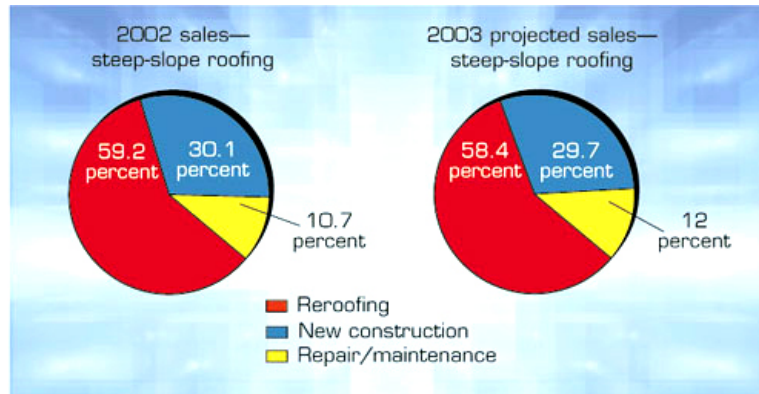


Figure 1.3 - Steep-slope roof sales (Siegel, 2003, p. 4), permission to use granted by: Ambika Bailey, National Roofing Contractors Association (Jan. 10, 2007)

These percentages have held steady since 2001. In a report to the U.S. Environmental Protection Agency, Franklin Associates (1998) estimated that 136 million tons of construction and demolition debris were generated by the building industry in 1996, and of this, 48% was attributable to demolition activities and 44% to renovations, with only 8% attributable to new construction. According to Russell K. Snyder (2001), executive vice president of the Asphalt Roofing Manufacturers Association, an annual load of 9 to 10 million tons of asphalt roofing materials alone are deposited in U.S. landfills, costing \$400 million annually in fees. Because of the magnitude of the waste stream they generate, roofing systems as a whole have a profound effect on the environmental impact of a building throughout its life. Strategies such as green roofs, which purportedly extend the life span of a roof system (see Section 3.6), are aimed at both minimizing waste and maximizing environmental performance. Vegetated roofing systems offer unique benefits which serve to mitigate the negative impact of buildings on the ecosystem and improve the quality of both interior and exterior living space. These benefits are discussed in detail in Chapter 3.

1.2. Problem Statement

The demand for vegetated roofs in North America is growing. Spurred in part by the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) program and other green building initiatives, many owners and architects are looking to green roofing as a strategy to minimize the negative environmental impact of buildings on the ecosystem. In Germany, significant research into the performance of green roofs and, perhaps more importantly, governmental and industry support of this technology have lead to its widespread use. In North

America, many practitioners are now being called upon to include green roofs in their project designs. A decision support system is needed to assist these designers in comparing the efficacy of various vegetated roofing systems in the context of specific projects.

When commissioned to design a green roof, architects, landscape architects and roof consultants rely on building codes, industry sources, local trends, and conventional wisdom as well as their own experience. Unfortunately, many of these sources have not yet significantly incorporated green roofing technologies, and do not typically represent a comprehensive picture of the information available to assist in the design process. The creation of a framework for vegetated roof system selection, which comprises the work of this dissertation, constitutes the first step in the effort to collect, organize and present the available knowledge on green roofing in North America in a form that is readily usable by designers of green roofing systems. The framework addresses many of the possible benefits as well as potential pitfalls of green roofing in the effort to provide a holistic view of the possibilities and limitations inherent to these systems.

The framework is in essence a comparison of the environmental impact of various green roof systems and a reference (non-vegetated) roof evaluated in the context of specific project constraints and designer priorities. The vegetated roofing systems evaluated represent a spectrum of green roof types from ultra-extensive to intensive. A series of user system inputs include the reference roof type and project location and decisions ranking the importance of the advantages represented by different green roof systems based on specific project characteristics and the user's perspective. Output from the framework consists of a solution in the form of a generic green roof type that has been assigned advantages with the greatest total importance by the decision-maker. The body of the framework is a set of value functions that assign value to the characteristics of the different green roof system types on a cardinal scale. These value functions are drawn from available research and data collected from green roof sites in North America, and from applicable industry rules of thumb. The framework also identifies gaps in the available knowledge that demand further investigation.

Because it evaluates green roof performance in light of multiple parameters, once fully implemented, the framework will allow designers to make appropriate, informed design decisions about the type of systems and subsystem characteristics to implement on a given building project. The framework will assist in creating roof systems that go above and beyond the stipulations of codes and industry standards. By focusing on the environmental impacts of

various roofing systems, the decision-making framework for vegetated roofing system selection will help designers provide more ecologically sound solutions for building owners.

1.3. Scope of Research

1.3.1. Goal of Research

The project comprises the creation of a framework diagramming the decision process involved in the design of vegetated roofing systems. Through a series of expert interviews and case studies, the available knowledge is captured and organized to determine the critical parameters affecting design decisions. The study begins with a mapping of the factors that determine the design of vegetated roofs, and concludes with testing of this framework through comparison with experts' methodologies.

1.3.2. Methodology

To create the framework for decision-making in the selection of vegetated roofing systems, the parameters involved in the design of these systems are identified through a literature review and case studies of successful vegetated roofing projects. A set of factors is established with reference to available tools for analysis of green roof systems where they exist and identification of areas for future research. The framework is evaluated for acceptability by comparison with the methods employed by experts in the field of green roof design as captured through an interview instrument, and by project-specific tests of the decision-making model. Case study methodology is presented in Chapter 3, and a detailed description of the remainder of the research methodology employed in this dissertation is presented in Chapter 5.

1.4. Contribution

1.4.1. Expected Benefits of the Framework

The expected benefit of the framework lies in its collection and organization of a set of factors affecting green roof design to provide a navigable path through the decision-making process. The environmental influence of emerging green roof technologies is compared with that of more traditional roofing systems. While cost and regulatory compliance are important factors in the equation, green roof systems are also judged for their contribution to the energy balance of the building and their impact on the environment over their life cycle.

1.4.2. Continuance

Following the creation, demonstration, and testing of the framework that forms the body of this dissertation, it will be possible to generate a more comprehensive decision-making methodology for the design of vegetated roofs based on specific and relevant input data. The usefulness of any such methodology will depend heavily on the availability and reliability of data related to the key parameters involved. Because of the computational complexity involved in evaluating multiple vegetated roofing sub-system variables over a range of levels, a computerized program will need to be developed with the capacity to discard non-compatible variable combinations and the ability to evaluate thousands of viable variable combinations. The ultimate goal of continuing research into the decision-making methodology for green roof system selection will be the creation of an interactive, computerized tool to assist roof designers in the selection of highly specific vegetated roofing systems. In the broader view, this tool will ultimately operate in conjunction with other tools being developed within the College of Architecture and Urban Studies at Virginia Tech to form an integrated framework to assist in the process of holistic building design.

1.5. Limitations

1.5.1. Boundaries of Study

The field of investigation into the efficacy of green roof systems is both broad and diverse. Including every potential element of study would lead to an unwieldy decision-making framework, defeating the ultimate goal of this research, which is the creation of a tool to assist designers of green roofing. It is therefore necessary to limit the number of parameters by which green roofs are evaluated to a reasonable number. The six main categories chosen for study are storm water, energy, acoustics, structure, cost and compliance with regulatory guidelines and governmental incentives. These categories are summarized in Chapter 3 and are selected based on their importance to green roof designers and owners, their frequent discussion within the literature, existence of sufficient data making them useful as gauges of a green roof's performance, and their relevance to larger architectural issues transcending the green roof as an isolated system.

Green roofs have additional benefits and properties that, while important, are not addressed substantively or in isolation by this study. These parameters include opportunities for gray water reuse and recycling, food production, cooling of water from mechanical systems, habitat for plants, insects and birds, fire protection, processing of carbon dioxide into oxygen to help

purify the air, and visual amenities to building occupants. As with any complex design problem, it is often impossible to completely isolate these excluded factors from those directly under study. For example, the visual amenity of a green roof affects its market value, which is accounted for in the cost valuation undertaken within this study. To permit the inclusion of such secondary or tertiary factors where appropriate, these are included as parameters falling under the six main categories of the framework. In many cases, these parameters take the form of placeholders for data to be generated by future research.

It is also necessary to set geographic boundaries for the study. Although it would perhaps be more succinct to limit research to the continental United States, the volume, rigor, and study period of most Canadian research exceeds that of most U.S. research at the present time. Fortunately, these data are frequently relevant to the United States' Northeast, Midwest, and Pacific Northwest regions due to the similarity of their climates to neighboring Canadian provinces. In this study, "North American" refers exclusively to the continental United States and those Canadian provinces lying south of 60° north latitude. Northern Canada, Alaska, Greenland, Mexico, Central America, and the countries of the Caribbean, while part of North America, will not be addressed due to the different climatic and economic factors present in those areas, and the paucity of examples of modern green roofs.

Finally, there is an important distinction to be made between the design of green roofs, and the selection of green roof systems. The framework discussed in this dissertation is not intended as a comprehensive design tool for green roofing. It is intended to assist designers in the selection of green roof systems. The framework provides a palette of project-appropriate green roof systems from which the green roof designer may choose. It does not provide the layout, combination, orientation, or ultimate design of green roofs.

The framework for decision-making is not exhaustive. Instead, the goal is to create a requisite model of the decisions faced by the designer of a green roof system by addressing the most cogent issues at a level of detail appropriate to the problem at hand. It is also understood that the tools used to evaluate green roofs are currently under development, and monitoring of many green roof projects in North America is ongoing. Therefore, areas for further research are identified within the framework, and it is expected that the framework will need to be updated as new information becomes available.

1.5.2. Author's Background

To identify any potential bias in the scope of research or in the construction and application of the framework for green roof system selection, a brief discussion of the author's background is offered here. The author is a registered architect in Virginia and Florida, with five years of architectural practice based in Gainesville, Florida, and three years of architectural practice based in Blacksburg and Christiansburg, Virginia. She is also a member of the Roof Consultants Institute, the licensing organization for roof consultants in North America. While she has considerable experience with the design of traditional roof systems, and with research into the functioning of wind-vented roofing systems, she has not yet specified a vegetated roof system for a building project. Therefore, the observations made in this dissertation are not affected by any previous familiarity with any particular green roof system during the course of a design project. It is hoped that this circumstance lends a degree of impartiality to this research effort.

2. GREEN ROOF SYSTEM COMPONENTS

Green roofs are composed of a series of layers, some of which may occasionally be combined, omitted, or articulated with a series of sub-components. However, the functions represented by each of these layers must be satisfied by some element in the green roof assembly. Figure 2.1 depicts a generic green roof system and illustrates the layers in their typical orientations.

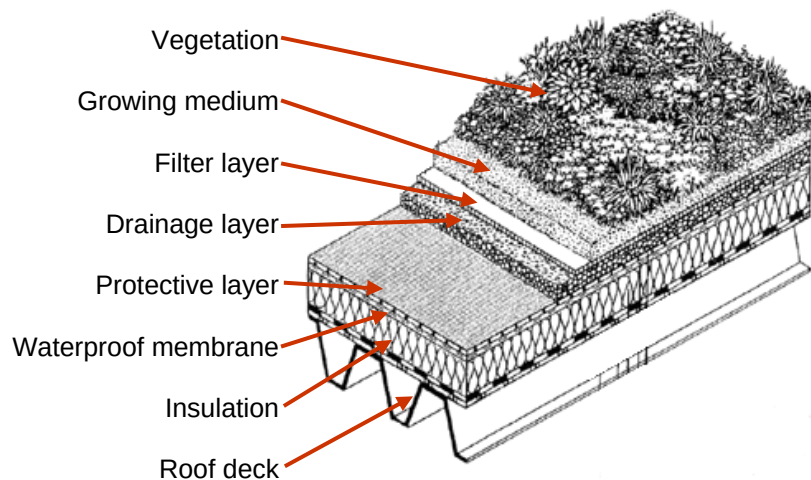


Figure 2.1 - Typical cross-section of a vegetated roofing system (Miller, 2006), permission to use granted by: Stefan Zeller, Optigrün International AG (April 10, 2007)

The choice involved in the specification of each of these layers makes each a variable in green roof system selection. Generally, the top two layers, vegetation and growing medium, are considered in the categorization of green roof types, while the other layers are selected to support this living portion of the roof.

Green roof system components obviously interact with, and affect, components of the basic roof design, particularly the membrane and drainage systems. An important philosophical distinction between green roofing and more typical roofing is often made by roof designers and suppliers. Traditional roof membranes generally fall under the category of weatherproofing, while the roof membranes required beneath green roofing systems, which periodically support damp growing medium, can be considered waterproofing. Gerald Teitsma (2004), Director of Educational Services at RCI, made this distinction in an article in *Interface*, the journal of the Roof Consultants Institute. Many suppliers of roofing membranes for green roof systems classify

green roof projects as waterproofing, not roofing, and provide their systems based on this definition. Waterproofing typically requires a thicker membrane than weatherproofing, and a very high standard of care in the furnishing and installation of materials is critical. Roof drainage systems used in conjunction with green roofs must also be designed to accommodate green roof system components. Roots and organic matter must be prevented from obstructing drainage pathways. Green roof systems contain specific components designed to protect the roof drainage system, while certain specially designed or adaptive components such as drain extenders to accommodate the increased thickness of the green roof profile must be considered in the specification of the roof drainage system itself.

Despite these interactions, in the majority of cases, green roof systems are considered additive to the basic roofing system required to keep a building dry. For this reason, and to contain the complexity of the framework for vegetated roof system selection, layers below and including the waterproof membrane are considered as reference roof system variables and are not discussed here. In this chapter the function of each green roof layer is described in detail, and the range of forms which it may take is demonstrated. Because these layers operate in concert with one another, interactions between them are also explained where relevant. Finally, attention is paid to existing research focused on the effects of each of these system variables on certain elements of the performance of green roofs.

2.1. Vegetation

Vegetation is the definitive, and most complex, element that distinguishes green roofs from their traditional counterparts. Theodore Osmundson (1999) emphasized the difficulty of the challenge posed to landscape designers when faced with selecting plants for green roofs. He described the project-specific nature of such a task, which entails weighing the benefits and disadvantages of each plant type considered. There are, however, several universal requirements for green roof plants in his estimation; they must not possess invasive roots (that can puncture or otherwise compromise waterproofing systems), drop large quantities of leaves or fruit (a potential maintenance concern with roof gardens), or exceed the load capacity of the structure supporting them. They should ideally be self-perpetuating, resistant to both dry and

wet conditions, compatible with the particular soil¹ contemplated, surface-rooting, and hardy enough to survive freezing. To this list of generic requirements for green roof plants Dunnett and Kingsbury (2004) added tolerance of temperature extremes and high winds, ability to quickly cover the growing medium and self-repair if damaged, efficient evapotranspiration of rainfall if the green roof is contemplated as a storm water management device, and suitability to the particular micro-climate of the roof in question.

Due to the intrinsically conservative nature of the building industry, and the inherently limited number of plants meeting these stringent criteria, plant selection for extensive green roofs has largely been limited to sedums or grass mixes that have survived the test of time on central European roofs. These plants are optimized for the rooftop environment, growing naturally in harsh, rocky environments with shallow soil. The question remains whether a broader range of plants, possibly including more indigenous species with potential benefits to local bio-diversity, might be appropriate for use in green roof systems, particularly those with slightly deeper (semi-intensive) substrates. Because of the challenges and opportunities inherent in providing a vegetated habitat atop a building, one would imagine that close attention would be paid to the effects of differing types of vegetation on green roof performance. However, this is not generally the case, as evidenced by the paucity of literature on the subject. Dunnett, Nagase, Booth and Grime (2005) observed that most green roof studies vary the type or depth of growing medium or other system components, while keeping the plant mix constant.

Dunnett et al. (2005) posited the question of whether or not green roof plant selection significantly affects green roof performance in terms of parameters such as storm water management or thermal characteristics. They reported the results of a study undertaken at the University of Sheffield, England for three years which compared the runoff quantity from eight elevated plots, planted with a diversity of plant types and mixtures. While not precisely identical to green roof assemblies, these plots were filled with quickly draining, high mineral content soil analogous to that found on green roofs (albeit with a higher organic content), and were connected to catch basins that measured the volume of water percolating through the assembly. The plots were planted with a range of mixes from monocultures to more complex combinations of species, with one plot left bare as a control. It was noted that percolate volumes were nearly

¹ Some green roof practitioners take issue with the term “soil” as most modern, extensive green roofs are planted in a “growing medium” with little or no organic content. Many of the roofs referenced in Osmundson’s text are older roof gardens planted in soils.

the same in all plots during the winter months, during which the soil was nearly perpetually saturated. Differences occurred in the summer months when precipitation was reduced. The plot with the bare soil actually produced the smallest volume of percolate. Dunnett et al. attributed this finding to the pitting of the soil surface due to sun, wind and rain, which increased soil evaporation. The next smallest volume of percolate was captured from the herb monoculture. The plant in question, *Leontodon hispidus*, was a ground cover with large flat leaves, which Dunnett et al. assumed intercepted much of the rainfall and provided high evapotranspiration (ET) rates. The plant also had a high soil water demand due to its high water content. A herb-only mix also performed well, which the researchers attributed to leaf shape and tap roots present in some of the species.² Essentially, plant species that efficiently remove water from the soil resulted in the consumption of more rainfall in the recharging of their soil, and consequently resulted in lower percolate volumes. The worst-performing plot was the grass monoculture. This was attributed to the low surface area of the grass blades that theoretically translated to lower ET rates. It was noted that the test plots were watered during periods of drought. It would seem logical to assume that the “better performing” plants with lower percolate and higher soil water demands might have also been most susceptible to damage from drought, though this was not addressed in the study. Dunnett et al. drew no sweeping conclusions from this test, but remarked that because all other factors were held roughly constant, vegetation can be expected to affect runoff³ attenuation in green roof assemblies. Further research is clearly needed to identify the nature of this effect.

The relationship between plant survival and growth rates and the depth of growing medium on green roofs has been investigated in two papers. The first, by Boivin, Lamy, Gosselin and Dansereau (2001) applies only to the areas of North America with significantly cold winter weather. The authors pointed out the inherent liabilities of winter conditions for green roof plants. First, it is generally unrealistic to provide winter protection in the form of geotextile fabrics for green roof plants due to their location and number, and the snow cover that often protects

² Taproots are notoriously problematic in green roof assemblies, as they may puncture the waterproofing membrane or penetrate its seams in search of available water during dry periods.

³ Green roof “runoff” is a bit of a misnomer. It typically refers not only to the water running off the surface of the growing medium, but also to any water that seeps through the entire green roof assembly and runs along the surface of the waterproofing below, to exit the roof via drains, gutters, or directly off eaves. In the Dunnett et al. (2005) study, runoff referred to all water seeping through the assembly to the catch basins below, the only outlet.

ground-dwelling plants can be blown off of rooftops, leaving plants exposed to temperature fluctuations and extremes. In the absence of external protective measures, plants must adapt to freezing temperatures through a process known as hardening. This natural adaptive process can be thwarted either by a rapid drop in temperature which freezes plants before they are hardened, or by upward swings in temperature that reverse the hardening process, leaving plants vulnerable to the next frost. A study at Laval University, Quebec, Canada, of six herbaceous perennials in 2, 4, and 6 inches (50, 100 and 150 mm) of medium led to the conclusion that the deeper the medium, the higher the minimum winter temperature and the smaller the range of daily temperature fluctuations. Based on observations of plant damage and death, the authors stated that at least 4 inches (100 mm) of medium should be used for green roofs in cold climates.

A paper by Dunnett and Nolan (2004) investigated the interaction of green roof substrate depth and the use of supplemental watering on plant growth for a range of plant species. The study was conducted in Sheffield, England, which has a reasonably moderate climate with typically frequent summer rainfall. The researchers found that in the absence of weekly supplemental watering, there was only a marginal difference between plant growth in 4 inches (100 mm) and 8 inches (200 mm) of substrate. When, however, supplemental watering was provided, plant growth was significantly increased in all species except for the sedum tested. The authors stated that this was likely due to the sedum's disfavor for moist root conditions, or due to competition from the other, larger species in close proximity.

These two papers not only illustrated the complex interactions of green roof plants with the medium that supports them, but also demonstrated the critical role of growing medium as heat exchanger, insulator, and sponge. The unique character of growing medium, and efforts to optimize it for various green roof conditions, are discussed further in Section 2.2.

2.2. Growing medium

Working downward, the next layer usually encountered on a green roof is growing medium; however, occasionally an additional layer called a “vegetation support layer” is interposed between the vegetation and the growing medium, or replaces the growing medium altogether. A team of researchers at the Pennsylvania State University (DeNardo, Jarrett, Manbeck, Beattie, & Berghage, 2003) used a 1 inch (25 mm) thick layer of Porous Expanded Polypropylene (PEPP) between the vegetation and the growing medium on a sedum test roof,

citing the runoff retention and detention characteristics and the thermal benefits of the material. Upon testing three types of PEPP material after saturation, gravity drying, and oven drying, they found that the density and porosity of these samples did not agree with the manufacturer's published values, and therefore asserted that these published values should not be relied upon in a green roof design situation. Further, there was great variability in the lab values for porosity and hydraulic conductivity between the three samples. The team cautioned that until green roof plants are well-established, the variation in hydraulic conductivity may mean that in some cases, water could run off the surface of the PEPP without seeping through it into the layers below, as desired.

Where a vegetation support layer is not used, growing medium directly supports the vegetation. Due to its low or altogether absent organic content, and the degree to which it is optimized for use in a vegetated roof, this material is seldom referred to as soil. A discussion of the impact of the organic content of green roof medium on the water quality of the resulting runoff is found in Section 3.1.2.

DeNardo et. al (2003) stated that green roof medium must simultaneously provide a root zone for the vegetation it supports, minimize structural impact on the building below, and retain sufficient water to both sustain plants and provide storm water detention and retention benefits. Depending on its depth, water content, and other factors, it may also contribute to the thermal characteristics of a green roof system.

Beattie and Berghage (2004) made the case that the plant layer and growing medium layer together are the most critical components of a vegetated roofing system; they must be carefully specified to ensure the success of any green roof project. They drew a loose analogy between green roof growing media and the container media used in plant nurseries; a green roof may be conceptually considered as a very wide, very shallow pot that must sustain plant life for an indefinite period. In the absence of standards to guide the selection of green roof growing media in North America, they suggested designers turn to experts in the more-researched area of container gardening for help in selecting an appropriate mix for a specific project.

They summarized the requirements for growing medium as follows: it must satisfy the needs of the plants it supports, it must not impose excessive weight on the underlying roof structure, and it must provide an optimum balance between water retention and drainage. They emphasized

that while German standards for green roof medium may be used as general guidelines, there are supplementary requirements in North America that must be addressed. In particular, designers must consider both the cost and availability of materials and the local hydrology of the area in which the green roof is sited. The wide climatic range and diversity of soil types in North America makes determining an optimum medium type for use throughout the continent inappropriate and unrealistic.

Beattie and Berghage (2004) did, however, propose some general rules of thumb. First, the organic content should be kept at or below 20% of the volume of green roof medium, to allow for some degree of water holding and cation exchange capacity. They predicted that most green roof media will eventually stabilize at about 2% to 5% organic content, so providing higher initial organic content may result in some settling of the medium over time. They also suggested the periodic use of slow-release fertilizer to compensate for the relative lack of nutrients in green roof medium. Second, acknowledging the important constraint imposed on the weight of green roof media in North America, they recommended a bulk density of approximately 5 pounds per square foot per inch (1 kilogram per square meter per millimeter) of depth of the medium. To achieve this, they suggested mixing a mineral such as expanded clay, shale or slate possessing a bulk density of 45 to 55 pounds per cubic foot (720 to 880 kilograms per cubic meter) with a lighter material such as perlite. This lighter material should make up less than 20% of the volume of the mix to prevent wind erosion. Third, they suggested an optimum equilibrium between aerated pore space (APS) and water holding capacity (WHC) in the medium of 20% APS to 40% WHC, with the remaining 40% by volume occupied by solids. They estimated that this mix, when dry, will retain approximately 0.4 inches (10 mm) of rainfall per inch of medium, and stressed that some method should be employed to allow incident rain in excess of that predicted to be retained to move laterally to the roof drainage system. Fourth, they observed that the pH of the medium must remain within boundaries that allow plants to take up nutrients, and must not be allowed to fluctuate substantially. To ensure this, the pH of the base mineral in the medium should be chosen to help neutralize the effects of acid rain in areas where this is a concern, such as in the eastern United States. Finally, they stated that green roofs with medium less than 3 inches (75 mm) thick require the implementation of additional water holding measures and can support only a restricted number of plant varieties, and they did not recommend medium depths of 1 inch (25 mm) or less for North American applications.

2.3. Filter layer

The filter layer's role is to contain the growing medium and plant matter and to prevent clogging of both the drainage layer and the roof's drainage system. Osmundson (1999) wrote that filter fabric must be water-permeable, decay-resistant, portable, inexpensive, tough, and durable. Both Osmundson and Dunnett and Kingsbury (2004) referred to the use of semi-permeable polypropylene fabric as the most typical and effective modern material used for this purpose. Quite often the filter layer is combined with the drainage layer immediately beneath it; some companies offer these two components in one integrated modular piece (see Section 2.4).

2.4. Drainage layer

DeNardo et al. (2003) described the drainage layer as a porous material that allows the free flow of water to the roof drainage system. Dunnett and Kingsbury (2004) elaborated upon this definition and discussed why the drainage layer is critical in nearly-flat roofs. First, green roofs, especially extensive systems, are generally planted with drought-tolerant species. Adequate drainage is required to avoid drowning the roots of these plants during and after storm events. Second, drainage of growing medium is necessary to maximize the thermal insulation provided by this layer. Dunnett and Kingsbury (2004) presented three general categories of drainage material. Granular materials are a simple and traditional method of drainage and provide additional root space for plants. Porous mats are made of spongy materials that absorb excess water and release it once they become saturated. Plastic or polystyrene modules are designed to lift the plant and growing medium layers off the roof surface, permitting water to flow freely along the waterproofing layer. The many available systems are diversely articulated; some simply provide drainage while others are designed to hold a certain amount of water to help plants survive between rain events, some allow for the incorporation of irrigation systems, and some also serve as a protective layer (see Section 2.5), effectively separating the green roof system from the waterproofing below.

Osmundson (1999) emphasized the importance of providing a well-functioning drainage layer to prevent ponding and potential water damage to the roof and structure below. He stated that the effectiveness of the drainage layer is largely dependent upon the performance of the filter layer and growing medium chosen. He presented the history of drainage materials for roof gardens in North America, beginning with the stone, pebbles and brick fragments (clinkers) used in the 1930s and the drain rock used in the 1950s and 1960s, all largely abandoned in North America due to their excessive weight. In the 1970s, a product called Grass-Cel, originally intended for

supporting turf to sustain vehicular traffic, was turned upside-down, and in this new orientation became a prototype for the plastic drainage mats in common use today. Similarly, Enkadrain, a web of stiff plastic threads, and Geotech, a mat of expanded polystyrene, were originally used in Germany to drain the backs of retaining walls and have now been incorporated into the green roof market as drainage layers, with available attached polypropylene filter layers.

2.5. Protective layer

The protective layer is a barrier between plant roots and the waterproofing membrane beneath. Plant roots naturally seek any and all available water, and many past green roof failures have been attributable to roots puncturing roof membranes and penetrating vulnerable joints in the waterproofing, such as roof seams, edges and curbs. Dunnett and Kingsbury (2004) observed that microorganisms found in green roof systems may digest oil based, organic roof components, contributing to root penetration. A continuous physical separation between roots and the waterproofing system is essential. Dunnett and Kingsbury (2004) described two strategies commonly used to provide this barrier. Rolls of PVC film can be laid above the prepared roof surface and heat welded together to provide an impervious barrier. Another more conservative approach is to install the green roof system within plastic or metal trays that are slightly elevated above the roof membrane, effectively isolating plant roots from the waterproofing.

The roofing industry has developed several other strategies to resist root penetration of waterproofing. Chemical root inhibitors added to roof membranes or filter layers are one option. Mechanical barriers comprised of copper sheets or foil, frequently laminated to the roof membrane, are also effective (Peck & Kuhn, 2000). Often the roof membrane material itself acts as the barrier to root penetration, as is the case with some elastomeric single-ply roof membranes (Osmundson, 1999). D'Antonio (2004) described the testing standards used to establish the root-resistant properties of root barriers in Germany and Switzerland and summarized the stringent test methodology imposed by the German *FLL Guideline* (2002). In the FLL test, roof membranes, or other types of barrier sheets or coatings, are placed in transparent containers as part of a specified green roof test system, then subjected to possible root penetration by particular plant varieties for 2 years (in a greenhouse) or 4 years (outdoors) to determine the presence and/or number of root penetrations through the root barrier. To be certified "root-resistance proofed" there must be no root penetrations in the barrier during the test phase (FLL, 2002). The manufacturer's FLL certificate for a particular product becomes

part of the contractor's submittal packet, to be reviewed by the design professional (D'Antonio, 2004). While there are as yet no similar requirements in North America, manufacturers who provide waterproofing membranes frequently cite FLL certification of their products as proof of their root-resistance.

3. GREEN ROOF EVALUATIVE CATEGORIES

To develop a useful framework for green roofing system selection, it is necessary to sort the pertinent selection parameters into a manageable number of categories. Six such categories have been identified based on driving concerns raised in the literature review, discussions with green roof designers and building owners, and analysis of case study projects. The categories are introduced and the main issues relevant to each category are discussed in Sections 3.1 through 3.6. The discussion includes available rules of thumb or other methods for evaluating vegetated roofing systems' performance relative to each category.

3.1. Storm Water

Vegetated roofing systems may be conceptualized as a means to replace much of the permeable land that has been displaced by the footprint of a building. The capacity for roof gardens to mitigate the flow of storm water has long been recognized as an architectural opportunity. In 1926, Le Corbusier (1926) included as one of his "five points towards a new architecture" the concept of covering a flat roof with greenery to cause storm water to flow off the roof more slowly. In German cities where green roofs have proliferated, green roofs are first and foremost viewed as storm water management devices. These roofs both slow and reduce the flow of water into storm sewer systems, which in urban, densely populated areas, can become overtaxed during storms (Solomon, 2003). According to Katrin Scholz-Barth (2001), an average of 75% of incident rainwater is retained by a typical extensive green roof, while the remaining 25% is released as runoff, with a substantial time delay that effectively reduces the peak flow to be accommodated by storm water management systems. These rule-of-thumb figures vary in response to a variety of factors, including the time of year, the duration and intensity of storms, and the moisture content of the soil prior to storm events (Liu, 2004). Research conducted on the storm water volume and peak flow reduction capabilities of green roofs are summarized in Section 3.1.1.

Filtration of storm water occurs as the water slowly passes through the layers of a green roof assembly. These layers prevent leaves, soil, and other particles from entering the storm water system, reducing the amount of sediment that ultimately finds its way into streams and rivers. Rainwater frequently contains pollutants from the air, such as nitrogen and phosphorus. By filtering out these substances, green roofs prevent them from entering the storm water system (Solomon, 2003). The efficacy of green roofs as storm water filtration devices varies according

to several variables, including the organic content of the growth medium and the concentration of ions present in the rainwater falling on the green roof. Studies evaluating the pollutant removal potential of green roofs are discussed in Section 3.1.2.

Another important phenomenon that must be considered when including a green roof as part of a storm water management control strategy is the possibility for downstream warming caused by runoff from the green roof. The surfaces of green roofs are typically much cooler than the surfaces of traditional roofs during the summer, so one can expect the initial runoff from green roofs to be cooler than that flowing off traditional roofs. However, because green roofs often detain rainfall for an extended period of time, they can potentially contribute to the warming of this runoff, in a fashion similar to that of a wet detention pond or storm water wetland. In areas with cold water streams, this temperature elevation can have a detrimental effect on downstream ecosystems, particularly on sport fish species such as trout. A study of a wet pond in Prince George's County in Maryland found a 9°F (5°C) increase in water temperature from the inlet to the outlet of the pond (USEPA, 2005a). While no studies have yet been reported on the effects of green roofs on stream warming, this effect merits further research and quantification, as discussed in Section 3.1.3.

3.1.1. Storm Water Volume and Peak Flow Reduction

When considered as storm water management measures, green roofs must inevitably be compared with other, more traditional storm water management devices. This becomes a tricky proposition because of the unique ways in which green roofs mitigate storm water. As an illustration of the difficulty of this comparison, it is useful to consider the difference between the dry extended detention pond, one of the most common and least expensive storm water management devices, and the green roof. While ponds have relatively predictable and controllable effects on peak flow reduction, they do not contribute as significantly as green roofs do to overall storm water volume reduction. According to the USEPA (2005a), extended detention basins or ponds are used for flood control and channel protection. They fulfill these functions by controlling the peak flow of runoff, rather than by substantially reducing the volume of runoff. Often, they are designed to control runoff from several different design storms, such as 2-year and 10-year storms. In order to effectively reduce downstream channel erosion, dry extended detention ponds should also be designed to control the more frequent 1-year design storm (Virginia Department of Conservation and Recreation, 1999). On green roofs, the loss of retained rainfall is facilitated in large part by plant evapotranspiration. While a positive feature in

warm weather, this means that overall rainfall retention by green roofs is significantly reduced when the plants are dormant or snow-covered in the winter months. While their rainfall retention capacities are considerable under certain conditions, there is still the question of the ability of green roofs to provide the peak flow rate control necessary to prevent flooding. Roofscapes, Inc. (2003), a leading provider of green roofs in North America, claims, “for communities where runoff controls are evaluated on the basis of the rational method (which emphasizes the impact of intense, short-duration rainfall events), green roofs can typically satisfy runoff management for 10-, 25-, in some cases even 100-year return design storms” (p. 2). This section discusses how green roofs have been evaluated to date in the context of the rational method, and describes studies that have attempted to quantify both peak flow rate and total volume reduction attributable to these systems.

The rational method is a traditional and somewhat simplified method of determining storm water design flow rates. This method has been used since the 1800s and relates peak storm water flow to rainfall through the use of a dimensionless coefficient called the Rational Coefficient (The Urban Water Resources Research Council of the American Society of Civil Engineers and the Water Environment Federation, 1992). It is useful only in small watersheds and can be expressed as shown in Equation 3.1:

$$Q = CiA$$

Equation 3.1 - The Rational Method

Where Q is the peak discharge in cubic feet per second, C is the dimensionless runoff coefficient, i is the average rainfall intensity in inches per hour, over a duration equal to the time of concentration for the contributing area, and A is the contributing area in acres¹ (Urban Water Resources Research Council, 1992, p. 90).

The rational method assumes that the peak discharge is proportional to the rainfall intensity for storm events with a duration equal to the time of concentration. The time of concentration is defined as the time it takes for rainfall from the most remote point in a watershed to reach the point under design consideration. It does not take into account long-term storage effects of

¹ The conversion factor of 1 acre-inch/hr = 1.008 cubic feet per second is usually omitted in hand calculations using the Rational Method.

rainfall due to ponding or other constructed drainage facilities. It is commonly used to give designers an approximation of peak storm water discharge for a given storm. The Rational Coefficient (C) can be seen as a measure of the degree to which a surface absorbs or detains storm water, through interception, infiltration, and temporary storage. It varies somewhat according to the intensity of the design storm considered. According to the Urban Water Resources Research Council (1992), the runoff coefficient of non-green roofs is between 0.75 and 0.95, similar to the value of other near-impervious surfaces such as asphalt and concrete. A green roof study undertaken at North Carolina State University was geared toward providing a runoff coefficient for green roofs, which would enable designers of storm water control systems to account for the improved capacity of green roofs, as compared with traditional roofs, to reduce peak storm water flow rates. This study is reviewed later in this section.

Green roofs are capable of reducing both the volume and the peak flow rate of runoff from a roof surface largely through the processes of evaporation and evapotranspiration. Guidelines quantifying the degree to which green roofs reduce runoff volume have been established in Germany. These were recently translated into English in the document entitled *Guideline for the Planning, Execution, and Upkeep of Green-Roof Sites* (FLL, 2002), referred to in this dissertation as the *FLL Guideline*. Table 3.1, adapted from this document, gives percentages of annual water retention and corresponding annual coefficients of discharge (Ψ_a) for green roofs of various course depths.² The dimensionless coefficient of discharge is the ratio between the volume of annual roof runoff and the volume of annual rainfall. It is used to calculate the size of drainage facilities. (FLL, 2002). The user of the table is cautioned to adjust the coefficient of discharge for local weather conditions and specific green roof products used. In describing the peculiar action of green roofs in retaining incident rainfall, the *FLL Guideline* points to the depth of a substrate, versus its makeup, as the most important factor in determining the volume of water a green roof can retain. The *FLL Guideline* also states that difference in the performance of substrates of different depths is most pronounced in summer, when water retention by the green roof is highest, and almost negligible in winter, when evapotranspiration is at a minimum. Finally, the document refers to “water retention capability” and “water permeability” of the substrate as lesser contributing factors to runoff reduction calculations.

² Course depth refers to the depth of the vegetation support course in the *FLL Guideline* (2002). This may generally be equated with the vegetation support layer and/or the growing medium layer described in Chapter 2.

Table 3.1 - Reference values showing percentage annual water retention on green-roof sites in dependence on course depth (adapted from FLL, 2002, p. 37)³

Type of greening	Course depth in inches	Course depth in cm	Water retention - annual average (percent)	Annual coefficient of discharge Ψ_a
Extensive greening	0.8 to 1.6	2.0 to 4.0	40	0.60
	>1.6 to 2.4	>4.0 to 6.0	45	0.55
	>2.4 to 4.0	>6.0 to 10.0	50	0.50
	>4.0 to 6.0	>10.0 to 15.0	55	0.45
	>6.0 to 8.0	>15.0 to 20.0	60	0.40
Intensive greening	6.0 to 10.0	15.0 to 25.0	60	0.40
	>10.0 to 20.0	>25.0 to 50.0	70	0.30
	>20.0	>50.0	>90	0.10

Kolb (2004) made additional observations on the water retaining properties of green roofs based on research performed in Germany. He listed air moisture content, type of plants, time of year, roof angle, substrate type, and the “length of watercourse” as factors influencing these properties. He asserted that intensive green roofs generally experience higher ET rates than extensive roofs. In support of this assertion he presented the results of two studies, the first demonstrating 47% evaporation of annual rainfall by extensive green roof plots with 2 to 5.6 inch (50 to 140 mm) course depths in Veitshöchheim, Germany, shown in Figure 3.1. The seasonal differentiation in evapotranspiration capacity was clear from the presented data, which showed negligible effects in winter and impressive results in the summer months, supporting the assertions of the FLL (2002).

³ Per the *FLL Guideline*, “All figures relate to locations with annual precipitation values of 650 - 800 mm [26 to 32 inches] where monitoring has been performed over a period of several years. In regions with lower annual precipitation values water retention is higher, in regions with higher annual precipitation it is lower.”

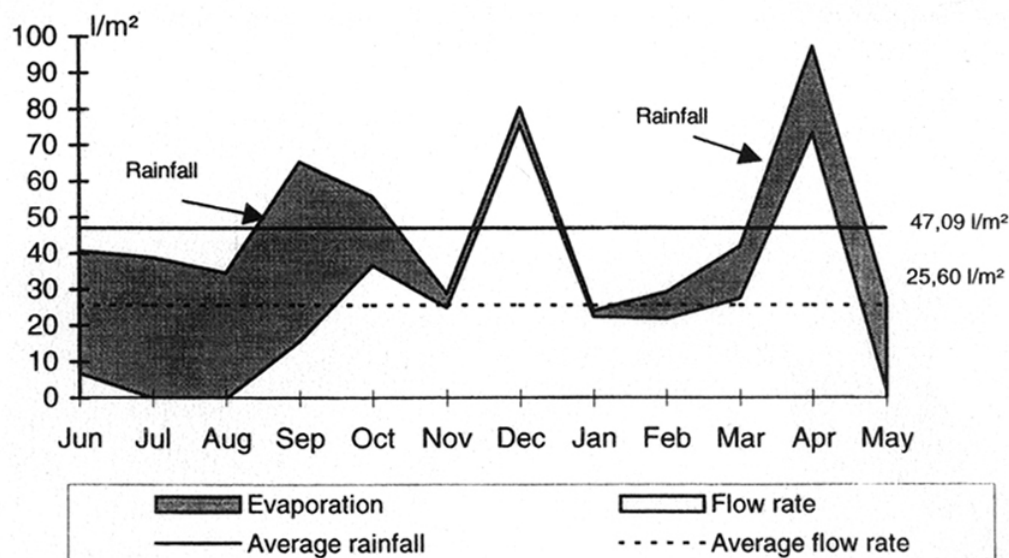


Figure 3.1 - Rainfall retained on 11 extensive test roofs over one year (Kolb, 2004, p. 299), permission to use granted by: Peter Vanderborcht, International Society for Horticultural Science (Jan. 10, 2007)

In the second study, an intensive green roof with a 12 inch (300 mm) course depth evaporated 68% of the total of annual rainfall plus supplemental irrigation it received.

Kolb (2004) cited his own past research as proving that the angle of the roof is not as significant a variable as once thought (Kolb, 1999); in fact runoff coefficients remain fairly constant for roofs with between 1.4 and 40 degrees of slope. However, he found that the type of substrate used did have a significant effect on the runoff coefficient. He also found that the “length of watercourse”, or distance water must travel to a drain, had a powerful effect on the runoff coefficient. Quadrupling the length of the watercourse resulted in a 25% to 70% reduction in the runoff coefficient depending upon the construction of the green roof. He called for future research in this area, which was not addressed in the most current *FLL Guideline* (2002).

There have been several studies conducted in North America documenting the ability of green roofs to reduce and slow roof runoff. A study conducted by Moran, Hunt and Jennings (2004) at North Carolina State University quantified storm water benefits of green roofs in terms of water retention and peak flow reduction. The two green roofs in the study retained, over a (non-consecutive in one case) study period from April to December 2003, 62% (Goldsboro, NC site) and 63% (Kinston, NC site) of the incident rainfall. The roofs reduced the average peak flow of

runoff, as compared to rainfall rate, by 78% (Goldsboro) and 87% (Kinston) (Moran et al., 2004). In a follow-up and continuation of this study, Moran, Hunt and Smith (2005) reported that from April 2003 to September 2004, the Goldsboro green roof retained 63% of the incident rainfall, while a new green roof in Raleigh, NC retained 55% over the period from July 2004 to September 2004. Average runoff peak flow reduction for these two roofs was 87% (Goldsboro) and 57% (Raleigh). The authors hypothesized that the discrepancy between these results was due to the differing study period lengths, the greater exposure to tropical storms at the Raleigh site, and the 7% slope of the Raleigh green roof as opposed to the nearly flat roof at Goldsboro. Runoff delays were experienced at 90% of the rain events at the Goldsboro site; 60% of these delays were 30 minutes or more. These data were not presented for the Raleigh site. Based on the results of runoff monitoring, the team established an approximate rational coefficient (Rational C) for green roofs. Ten storm events with rainfall over 1.5 inches (38 mm) at Goldsboro were used to calculate an averaged Rational C of 0.5. This was compared by the authors to a Rational C of 0.95 for traditional roofs, close to the theoretical maximum of 1 for a completely impervious surface.

Liu (2004) reported that a 6 inch (150 mm) test green roof in Ottawa, Canada retained an average of 54% of the rainfall that fell on the roof from April to September 2002. She indicated that green roofs' hydrological behavior is quite variable, however, and both retention and detention effects vary widely. According to Liu, detention can range from a few minutes to several hours, depending upon the intensity and length of each storm as well as the moisture content of the green roof medium prior to the storm.

One of the many aims of the Green Roof Infrastructure Technology Demonstration Project in Toronto was to determine the effects of the depth of a green roof on its efficacy as a storm water control system. Liu and Minor (2005) reported initial findings from the first year of the project, during which vegetation covered only about 5% of the project area. Average annual storm water volume reduction as compared to a control roof was 57% for both test green roofs, one of which had 4 inches (100 mm) of medium and the other 3 inches (75 mm) of medium. During the summer months, peak flow rates were reduced from 25% to 60% by the green roofs, and detention times ranged from 20 to 40 minutes. Liu and Minor reported that for some rain events with less than 0.6 inches (15 mm) of rainfall, the green roofs produced no runoff at all. This occurred when there had been no previous rainfall for six days. During the wetter spring and fall, when there were fewer days between storms, the added inch (25 mm) of medium on

one of the green roofs translated to a greater reduction in runoff. The thicker green roof continuously showed some reduction in runoff volume, while the thinner green roof occasionally became fully saturated and resulted in runoff volumes similar to that of the control roof. In late fall, for example, peak flow reduction ranged from 10% to 30% and detention times were less than those observed during the summer. Once again, the storm water control benefits of the green roofs were significant when viewed largely, but their performance on a per-storm basis was highly dependent upon pre-storm conditions and to some small degree on the thickness of their growing medium. The effects of the plants themselves were somewhat negligible in these results; it was anticipated that future reports on this study will comment on the effects of a fuller vegetative cover on runoff reduction.

DeNardo, Jarrett, Manbeck, Beattie and Berghage (2003) built six small structures at the Pennsylvania State University's Russell E. Larson Research Center in Centre County, Pennsylvania, three with green roofs and three with asphalt roofs, to determine the retention capacity of the green roofs. All of the roofs were constructed at a 1:12 slope with a gutter and downspout connected to a collector fitted with a pressure transducer to measure runoff quantities. The green roofs were constructed with a 0.5 inch (12 mm) drainage layer and 3.6 inches (89 mm) of growing medium topped by 1 inch (25 mm) of porous expanded polypropylene, and were planted with *Sedum sperium*. Rainfall and runoff were recorded from July to October 2002. DeNardo et al. found that the green roofs (values for the three green roofs were averaged in each case) retained 100% of the rainfall for storms less than 4 mm (0.16 inch), an average of 82% of the rainfall from one storm in August, and 70% of the rainfall from one storm in November. The green roofs retained⁴ between 20 and 33% of incident rainfall for the remaining seven of the thirteen storms recorded. Unlike in the Liu and Minor (2005) study, no correlation was found in this study between time between storms and percent of rainfall retained.

DeNardo et al. (2003) highlighted two October storms with similar cumulative rainfall quantities to illustrate detention times and related effects. Observations during a storm occurring on October 25 and 26, with a total rainfall of 0.96 inch (24 mm), showed a five hour delay between the start of the rain and the appearance of measurable quantities of runoff from the green roofs. During these five hours, the green roofs held 0.44 inch (11 mm) of rainfall, much more than their

⁴ The authors defined "retained" water as the difference between rainfall and runoff measured in the collection barrels for a given storm event.

ultimate retention capacity of 0.18 inch (4.6 mm), or 20% of the total rainfall for this storm. The authors indicated that 0.26 inch (6.4 mm) of rainwater⁵ was held in “temporary storage” on the green roofs. In a second example from October 16, the green roofs retained 23% of the 1.1 inches (28 mm) of cumulative rainfall. This storm began at a lower intensity than that of October 25 and 26. Interestingly, green roof runoff was first measured after 3 hours, during which only 0.12 inch (3 mm) of rain had fallen. The authors observed that during this less intense storm, water passed through the green roof assembly and ran to the drainage devices before the ultimate storage capacity of 0.26 inch (6.5 mm) for this storm was reached. From this observation they concluded that detention during periods of mild rainfall was minimal. However, the authors did not explain the vehicle whereby greater detention was achieved during the more intense initial rainfall on October 25 and 26. It should be noted that the rain on October 25 and 26 occurred 6 days after the previous storm, while the October 16 storm followed the previous storm by only 3 days. It is obvious from the somewhat unexpected findings of this study that the interaction between total rainfall, intensity of rainfall, length of time between storms and green roof retention and detention capacities is not always simple to predict. However, the study did prove that green roofs do provide both retention and detention benefits to a significant degree.

Monterusso, Rowe, Rugh and Russell (2004) presented the results of a pilot study at Michigan State University in East Lansing, MI, geared toward determining the effects of combinations of different green roof systems and different vegetation types on runoff reduction. Pollutant levels in green roof runoff from these combinations were also measured; these results are discussed in Section 3.1.2. The study included four different green roof types provided by American Hydrotech, Sarnafil, Siplast and Xeroflor. Three different plant mixes were tested on each of the four green roof system types: a sedum seed mix consisting of seven species, a sedum plug mix comprised of two species, and a plug mix of 17 native Michigan species. All four systems used the same growing medium, with 0.8 inch (20 mm) of depth in the Xeroflor sedum seed mix, 2.4 inches (60 mm) in the Xeroflor sedum plug mix and native plant mix, and 4 inches (100 mm) in the other nine combinations. The average runoff reduction from all twelve combinations over four monitored storm events was 49%. The only statistically significant difference between the combinations was seen in the fourth rainfall event, during which the Xeroflor system produced greater runoff in the plots planted with sedum plug and sedum seed mixes. The team

⁵ 0.43 inch (11 mm) of rain detained during the first five hours minus 0.18 inch (4.6 mm) net value of rain ultimately retained on the roof for this storm yielded 0.25 inch (6.4 mm) of “temporary storage”, or detention.

concluded that this result was likely due to the reduced substrate depth of these two systems rather than due to the effects of the vegetation. They also noted that despite this observation, the American Hydrotech, Sarnafil, and Siplast systems (all with 4 inches (100 mm) of medium) did not outperform the Xeroflor system (with 0.8 inches (20 mm) and 2.4 inches (60 mm) of medium) in any of the first three rain events. Results from the second storm, which occurred only two days after the first storm, support the hypothesis that a higher substrate moisture content prior to the storm event results in greater runoff quantities. The runoff volumes from this storm were greater than from those occurring after longer intervals of dry weather.

In summary, research to date has shown that temporal and climatic factors, such as the time of year, the interval between storms, the intensity and duration of storms, and the relative humidity have an effect on the capacity of green roofs to retain and delay storm water. Architectural factors such as the roof slope, the distance between drains, the type of green roof system selected, and more specifically the depth and makeup of the green roof medium and the variety of vegetation selected, also have a pronounced influence on the success of green roofs as storm water management devices. Efforts are ongoing, both abroad and in North America, to isolate the effects of these parameters and provide a reliable, useful measure of performance that may be used to quantify the action of green roofs in common storm water calculations. In the meantime, it would appear that green roofs are generally most appropriate when combined with additional storm water control measures, as their performance is not sufficiently consistent nor their capacity adequate to qualify them as complete storm water solutions in the majority of cases.

3.1.2. Storm Water Pollutant Removal

Pollutants commonly found in storm water runoff from conventional roof surfaces include those resulting from dry and wet atmospheric deposition and those deriving from leaching or breakdown of roof materials themselves. Pollutants resulting from atmospheric deposition include products of total and incomplete combustion (such as polycyclic aromatic hydrocarbons (PAHs)), heavy metals, pesticides, and polar compounds formed by atmospheric photochemical processes, such as halogenated acetic acids and nitrophenols (Bucheli, Müller, Heberle, & Schwarzenbach, 1998). Pollutants deriving from roofing itself vary greatly depending on the type of roofing used but consist mainly of trace elements.

The literature available in English on pollutant removal capacities of green roofs is relatively sparse. Katrin Scholz-Barth (2001) described how “plant roots, and their attached enzymes and micro-rhizal fungi, filter and treat rainwater as it percolates through the ground.” Köhler and Schmidt (1991) stated that green roofs are capable of removing more than 90% of the cadmium, lead, and copper and 16% of the zinc from rainwater, as well as reducing nitrogen levels while plants are active. While studies of runoff from traditional roofing focus on a wide range of pollutants, green roof studies tend to focus mainly on loadings and concentrations of nitrogen (N) and phosphorus (P) in runoff. This focus is due to regulatory requirements and the hope that green roofing will prove to be an effective storm water best management practice (BMP). Reduction of N and P is a top priority for storm water BMPs because of the adverse effect of these nutrients on downstream waterways through the process of eutrophication.

The ability of vegetated roofs to remove pollutants is a relatively new question in North America. A study conducted by Moran, Hunt, and Jennings (2004) evaluated two green roofs in eastern North Carolina for their ability to remove nitrogen and phosphorus originating in part from local animal production activities. Levels of total Kjeldahl nitrogen as nitrogen (TKN-N), nitrate/nitrite as nitrogen ($\text{NO}_3\text{-NO}_2\text{-N}$), ammonia nitrogen ($\text{NH}_3\text{-N}$), total nitrogen (TN), total phosphorus (TP), and orthophosphorus (OP) were measured. Contrary to their initial hypothesis, the researchers found no improvement in the quality of runoff from the green roofs when compared with runoff from the control roof and rainfall; in fact, the TN concentration in the green roof runoff was significantly higher than in the rainfall, and not significantly different than in the control roof runoff. The TP concentration was higher in the green roof runoff than in both the rainfall and the control roof runoff. The mass loading of TP was higher for the green roof runoff than for the rainfall and not significantly different than in the control roof runoff. Based on these results, the team deduced that the green roof growing medium was actually contributing to the nitrogen and phosphorus content of the green roof runoff. A side study was conducted to determine if the organic content in the growing medium affected the quantities of nitrogen and phosphorus in green roof runoff. Not surprisingly, media with a higher compost component leached more of both nutrients. It was hypothesized that if this initial nutrient contribution due to the medium were reduced, the mass loadings of nitrogen and phosphorus would also be reduced. It was also expected that over time, concentrations of TN would reduce as organic material is gradually washed out of the green roof medium. In a subsequent paper, Moran, Hunt, and Smith (2005) reported that after two and a half years of testing, there was no observed trend toward reduced TN or TP concentrations in green roof runoff at the Goldsboro site. This and

other studies point to the need to provide a low nutrient content soil medium where reduction of nutrient pollution is desired.

The Monterusso et al. (2004) study introduced in Section 3.1.1 included monitoring of nitrogen and phosphorus levels in green roof runoff. Runoff from four proprietary green roof systems, each planted with three different plant mixes, was tested for nitrate (NO_3) and phosphorus (P) concentrations at 140 days and 314 days following fertilization. Nitrate concentrations were higher on day 314 than on day 140 for eleven out of the twelve plots tested. The researchers assumed that decomposition of the organic materials present in the green roof medium were responsible for this increase, which ran counter to initial expectations. The largest concentration of nitrate was generally found in the Xeroflor system. This was hypothetically attributed to the reduced depth of growing medium in this system, which might have allowed more efficient leaching of nitrate. Phosphorus concentrations, on the other hand, were reduced for all twelve green roof plots. The plots planted with sedum seeds removed less phosphorus than the sedum plug mix or the native plant mix, which the authors assumed might be due to their relatively lower biomass at the time of runoff sampling. They also emphasized that further testing would be necessary to isolate the effects of different green roof system configurations on runoff volume and contaminant control.

The studies conducted by Moran, Hunt and Jennings (2004) and by Monterusso et al. (2004) reflect the notorious unpredictability of green roofs' pollutant removal performance. Köhler and Schmidt (2003) gave a long-term perspective on this problem based on observations of green roofs implemented in Germany:

The ability of Green Roofs to bind and retain contaminants is not sufficiently recognized at this time... Two contradictory processes are apparent in green roofs. On one hand, green roofs retain and bind contaminants which are introduced either as dry dust particles or suspended and dissolved in rain water. On the other hand, contaminants can be leached out of the substrate used in the green roof's construction, which can complicate the reuse of the runoff water. This is particularly noticeable immediately after installation... However, with the appropriate choice of substrate, mature green roofs can contribute to a significant reduction in the pollution of the receiving waters.

Köhler and Schmidt's (2003) study found that the ability of green roofs to retain nitrogen and phosphorus was dependent upon the organic content of the growing medium. Media with lower

organic content performed more effectively and phosphate removal was more successful after the vegetation was effectively established.

The *FLL Guideline* (2002) includes recommendations for the maximum organic content for green roof growing medium, as shown in Table 3.2.

Table 3.2 - Recommended organic content for green roof types (adapted from FLL, 2002, p. 49)

At intensive greening sites	
For substrates with an apparent density of $\leq 0.8^6$	$\leq 12\%$ by mass
For substrates with an apparent density of > 0.8	$\leq 6\%$ by mass
At extensive greening sites, multiple-course construction	
For substrates with an apparent density of ≤ 0.8	$\leq 8\%$ by mass
For substrates with an apparent density of > 0.8	$\leq 6\%$ by mass
At extensive greening sites, single-course construction	$\leq 4\%$ by mass

Per the *FLL Guideline*, "A greater proportion of organic matter may be required where special forms of vegetation, such as humus rooting plants, are used."

In a publication entitled *Green Roof Policies: Tools for Encouraging Sustainable Design*, Goya Ngan (2004a) credited the low organic contents recommended by the FLL as being responsible for the good quality of runoff from green roofs in Germany. According to Ngan, runoff from German green roofs can be used for gray water applications such as toilet flushing, as well as for washing and even drinking in some cases. Ngan (2004b) presented a case study of an office complex in Wiesbaden, Germany called the Soka-Bau (2004). Runoff water from the single-layer⁷ extensive green roofs at this site was tested and met quality standards for drinking water. Ngan attributed this finding to the absence of organic content in the growing medium, which consisted of lava rock, pumice and zeolite.

In a study presented at the Greening Rooftops for Sustainable Communities conference in Portland, Oregon, Livingston, Miller and Lohr (2004) also expressed a concern over elevated nitrogen and phosphorus levels in green roof runoff, and advocated using a growing medium

⁶ Apparent density is measured in g/cm^3 . 0.8 g/cm^3 is equal to 0.5 ounces per cubic inch.

⁷ The distinction between single-layer and multi-layer green roofs in the German literature and case studies refers to the common practice of combining the growing medium and the drainage layer into a single layer in ultra-extensive systems.

with a low organic content based on results from a test roof constructed in South Florida. A study underway at Michigan State University (2004) will also be evaluating nitrogen and phosphorus levels of green roof runoff.

Glenn MacMillan (2004) reported the results of water quality evaluations at a test green roof at York University in Ontario. The green roof runoff had higher concentrations of most measured pollutants than either the control roof runoff or the rainfall, particularly metals, cations, anions, bacteria, and some nutrients. Several pollutant concentrations exceeded Canadian and/or provincial guidelines: phenolics, TP, E. coli, cadmium, copper, lead, and fluoranthene. The green roof runoff exceeded the control roof runoff for loadings of phosphate, TP, most metals, cations, anions, and COD, but decreased the loadings of suspended solids, nitrogen (ammonia/ammonium, nitrite, and nitrite/nitrate), aluminum, copper, BOD, manganese, and most PAHs.

With conflicting and often disappointing results from North American studies, it appears that green roofs will require continued in-situ testing before reliable pollutant removal efficiencies can be determined. Despite the ambiguity surrounding green roofs' pollutant removal performance, some North American regulatory agencies have begun to consider green roofing's capacity to improve storm water quality in the effort to encourage the development of BMPs. Gehley and Rindlaub (2004) reported that at the Montgomery Park Business Center in Baltimore, Maryland, the 30,000 square feet of green roof was considered equivalent to at-grade grassed areas in terms of removal of phosphorus and was classified as an organic filter. The 2000 Maryland Stormwater Design Manual, Table D.4.7 indicates a TP removal rate of 50% for an organic filter (Center for Watershed Protection & The Maryland Department of the Environment, 2000).

To garner widespread acceptance for green roofs as filtration devices in North America, more empirical data are needed. The more rigorously and repeatedly proven ability of green roofs to reduce the rate and the quantity of roof runoff remains the most important proof of their promise as part of a holistic strategy to improve storm water quality. By reducing both of these parameters, green roofs provide slower flow and reduced volume to other, often overtaxed structural and non-structural storm water management devices. In practice, one way to deal with the possibility of low or perhaps even negative nutrient retention of a green roof is to route roof runoff into another, smaller storm water management system such as a bioretention area.

With this arrangement, the green roof provides some degree of volume and flow control, while the bioretention system removes nutrients not removed (or even contributed) by the green roof.

3.1.3. Runoff Warming

One less-frequently discussed ramification of green roofing installations is their potential effect on the water temperature of local streams. There are currently no published studies quantifying the specific impact of green roof runoff on stream temperature. However, the principles behind this impact are clear from the literature available on stream warming. Green roofs absorb and retain a significant portion of the rainwater incident on the surfaces they cover. There are five possible destinations for water that falls onto a green roof in the form of precipitation: uptake by plants in the root zone, uptake by pore spaces in the growing medium, evapotranspiration by plants, direct runoff (at the surface of the green roof assembly), and underflow (beneath the green roof assembly) to roof drainage systems or directly to the ground surface below, depending upon the configuration of the roof (Roofscapes, 2007). Liquid water exiting a green roof has either run off the surface of the growing medium, or passed through the green roof assembly on its way to the waterproof roof membrane below. In either instance, it has been in contact with the growing medium and therefore has conducted heat from this growing medium if the medium temperature is warmer than that of the rain incident upon it. Because incident rainwater tends to have a longer residence time on green roofs than on traditional roofs, this water has more time to conduct heat as it slowly seeps through the green roof assembly.

There is also a greater surface area for heat exchange afforded by the plants and pore spaces of green roof medium as compared with a traditional roof membrane. These two factors would tend to implicate green roofs as greater contributors to roof runoff warming than traditional roofs, where runoff usually, and ideally, is shed rapidly off the roof surface. However, the average reduced temperature of a green roof as compared with a traditional roof, and the overall reduction in volume of roof runoff as compared with that flowing off a traditional roof may serve to mitigate the impact of runoff warming by green roofs when viewed at a larger scale. It is clear that the degree and effects of roof runoff warming will depend upon the size, depth, and plant and medium properties of the green roof, as well as the characteristics of the site, watershed, and climatic region in which it is located. The case for investigating the potential effects of increased roof runoff temperature is made clear by the following discussion.

3.1.3.1. *How Streams are Warmed*

Johnson and Jones (2000) provided a list of transport mechanisms by which streams are warmed (see Figure 3.2). These include radiation, conduction, advection, evaporation, and convection.

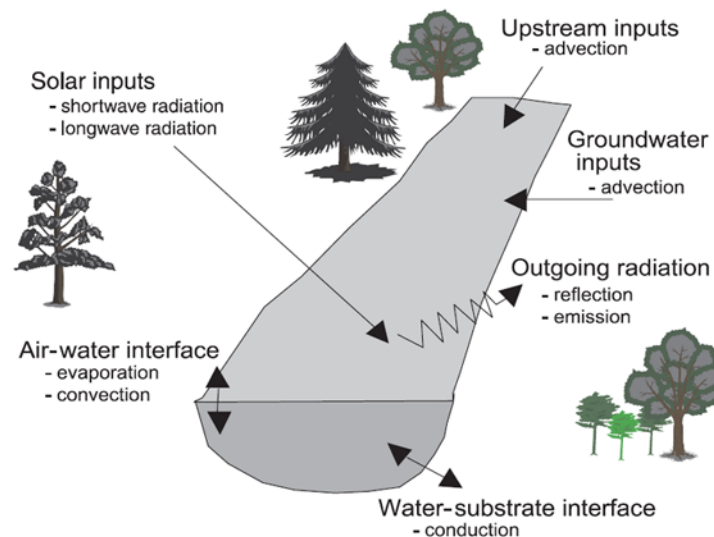


Figure 3.2 - Factors and mechanisms influencing stream temperature (Johnson & Jones, 2000, p. 31), permission to use granted by: Jason Charron, Business Manager, NRC Research Press (Jan. 11, 2007)

Johnson and Jones (2000) stated that short-wave solar radiation is the primary cause of stream warming. Their research focused on the significant impact of deforestation of riparian buffers, and the consequent loss of stream shading, on stream temperature increases. They also suggested that conduction between stream waters and stream beds significantly contributes to stream warming. When vegetation is absent, solar radiation warms stream banks and substrates, which then transfer heat directly to the water. Since the rate of soil-to-water exchange is more efficient than the rate of air-to-water exchange by three orders of magnitude, the authors concluded that this interface is perhaps second only to direct solar radiation in importance to stream warming.

Interestingly, both of these key mechanisms of stream warming are also present on green roofs, in varying degrees. Green roofs are inherently subject to direct solar radiation due to their location, though some may be partially shaded by adjacent buildings or trees. In most cases, the vegetation of the green roof itself provides shading for the layers beneath. The efficiency of this shading depends largely on the density, height, and other characteristics of the plants used.

As with riparian buffers, it can be anticipated that the degree to which these plants shade water running along the surface of a green roof will likely have an effect on the warming of that runoff water. And like stream beds, green roof media are subject to warming due to solar radiation. Because some percentage of incident water passes through the growing medium on its way off the roof, green roofs provide similar ideal conditions for water-to-substrate convective exchange seen in stream beds.

3.1.3.2. Biological Impacts of Stream Warming

In order to put the potential ramifications of runoff warming from green roofs in perspective, it is critical to understand why runoff warming is an important environmental concern. There is a large body of literature discussing the effects of elevated temperature in cold water streams on organisms that inhabit these streams. Due in part to the popularity of sport fishing, the effects of water temperature increase on fish have been studied extensively. Beitinger and Fitzpatrick (1979) explained that fish are more susceptible to thermal changes in their environment than land animals due to the great potential for heat exchange between their bodies and the water, and their inability to shed waste heat through radiation or evaporation. To thermoregulate, fish must seek waters of the appropriate temperature. Beschta et al. (1987) stated that because fish are cold-blooded (poikilothermic), their body temperature is dependent upon the temperature of their environment. Body temperature influences metabolic rate, which in turn influences biological processes, activity levels, reproduction and survival, and species competition. Becker and Fugihara's 1978 monograph linked increased mortality in fish exposed to *Flexibacter columnaris* (columnaris disease) to elevated water temperatures. Reeves et al. (1987) discussed the impact of water temperature on interspecies competition, stating that increased stream temperatures can both restrict the quantity of desirable habitat for salmonids (a family of fish including salmon, trout, and chars) and change the nature of competitive interactions between salmonids and other species.

A study by Wang and Kanehl (2003) investigated the effects of various parameters on macroinvertebrate (aquatic insect) assemblages in cold water streams in Wisconsin and eastern Minnesota. Characteristics of aquatic insect communities are often used as a convenient and relatively reliable indicator of stream water quality. For example, the abundance of pollution-tolerant species along with the absence of a variety of more sensitive species can indicate degraded water quality. Wang and Kanehl found that the percentage of urban land use and the stream temperature found in a particular watershed had the greatest effect on the diversity and

health of aquatic insect communities. There was significant degradation in many key macroinvertebrate parameters, and a concomitant decrease in water quality, in watersheds with over 7% effective impervious cover (defined as the total of streets, sidewalks, parking lots, rooftops connected with pavement driveways, and driveways). Increase in stream temperature, which is directly related to the degree of urbanization and impervious cover, was described as one of the main ways in which humans degrade stream quality. In their conclusions, they called for a limit to the impervious area in watersheds, particularly in cold water stream areas, and recommended that storm water best management practices (BMPs) such as detention ponds be designed to not only curb the peak flow of storm water, but also to minimize the effects on stream temperature.

Wang, Lyons and Kanehl (2003), using the same study area employed in the Wang and Kanehl (2003) study, found a similar negative exponential relationship between the percentage of connected impervious surface in a watershed and the health of its cold water fish communities. While the interplay of these two factors is complex, the study showed that the prevalence of desired species (in this case, trout) declines rapidly beyond 6% watershed imperviousness, and they are nearly nonexistent beyond 11% imperviousness. Wang et al. (2003) also found a statistical relationship whereby stream temperature was predicted to increase by 0.25 °C (0.5 °F) for every 1% increase in connected imperviousness. They pointed out that in America's Midwest, temperatures are naturally at a maximum threshold for particular cold water stream species, and even a slight increase in summer high stream temperatures can have a significant effect on their survival rates.

3.1.3.3. *Impacts of Urbanization on Stream Warming*

There are important implications to observations such as those of Wang and Kanehl (2003), who found a sharp drop-off in the water quality of cold water streams as the percentage of impervious area in watersheds approached approximately 7%. This infers that the most significant human impact on water quality can be found in relatively undeveloped watersheds, rather than in highly urbanized watersheds where water quality has already degraded significantly. Even more specifically, the effects of land cover in riparian buffer zones, defined in the Wang et al. (2003) study as areas within 100 feet (30 meters) of streams, represents 53% of the variation in values of fish health parameters when all other variables are excluded, making these areas particularly significant to cold water stream health.

A mathematical model predicting the effects of urbanization on stream water temperature developed by LeBlanc, Brown and FitzGibbon (1997) actually discounted the impact of all thermal discharges from point-sources such as industrial discharges and non point-sources such as agricultural and urban runoff, including roof runoff, as negligible in the calculation of water temperature increase in streams. The rationale for excluding these sources was based on the fact that the most critical condition for a stream's biota occurs during dry periods, when water volume and flow are at a minimum and stream temperatures are consequently at a maximum. By this logic, runoff reaching streams during and after storms actually mitigates this critical condition by providing a larger overall water volume in the stream, which then is less prone to thermal extremes. According to LeBlanc et al. (1997), changes in riparian vegetation, and the geometry and base flow of streams are the most critical parameters influencing stream temperature, while advection from overland flow was ignored in their model. Despite the exclusion of storm water in the model created by LeBlanc et al., there have been a number of studies which took into account the effects of storm water management strategies on stream warming both during base flow and storm flow conditions. These studies and their potential relevance to green roofs are discussed below.

3.1.3.4. *Impacts of Stormwater Management Best Management Practices (BMPs) on Stream Warming*

Green roofs are inherently effective heat exchangers which, due to their position atop buildings, are subject to potentially significant amounts of solar radiation. These two characteristics make them possible contributors to stream warming when employed, either formally or informally, as storm water management devices. Green roofs are a relatively new and experimental storm water management BMP. They have not yet been systematically evaluated for their potential contribution to stream warming. One way to predict this contribution is to evaluate them in light of principles currently being applied to more traditional BMPs.

Wang and Kanehl (2003) called for the avoidance of urban development in areas of substantial ground water recharge, and stated that detention ponds and other urban storm water management BMPs ought to be designed to increase stream baseflows, minimize peak flows, regulate ground water recharge, and minimize thermal impacts on streams. According to an extensive study by John Galli (1989) aimed at determining the impacts of various storm water management BMPs on aquatic life, all of the four representative BMPs tested exceeded Maryland Department of the Environment temperature standards during both base flow and

storm flow circumstances. Galli found that the infiltration-dry pond hybrid strategy had the smallest resulting temperature change and lowest maximum outflow temperature, while strategies with longer residence times of storm water, i.e. an artificial wetland, an extended-detention dry pond and a wet pond, had higher temperature changes and outflow temperatures. These results led him to conclude that BMP selection is critical in watersheds with 12% or less impervious area, where BMPs have a substantial effect on stream thermal regimes. In these areas, he suggested that storm water detention times be limited to 6 to 12 hours to prevent the temperature increases associated with longer residence times, and also recommended shading of storm water storage areas.

Because water is not, in a properly designed system, held for a substantial length of time in a green roof, it would appear that its impact on runoff warming is minimized in this regard.⁸ It is critical for green roofs to drain within a reasonable length of time to avoid drowning the roots of the plants forming their vegetated layers, as well as to prevent potential structural damage due to the weight of ponding water. While it is their capacity to delay runoff that makes green roofs attractive storm water flow control devices, the length of time water actually spends in such systems is relatively short. Karen Liu's (2004) study on a 6 inch (150 mm) deep extensive green roof with a 2% slope in Ottawa, Canada demonstrated a 95 minute delay in roof runoff after a light rain event of 0.76 inch (19 mm) occurring over 6.5 hours, and a mere 4 minute delay after a more intense storm of 0.84 inch (21 mm) over 21 minutes. Although green roofs tend to drain relatively quickly, they behave very differently from other typical storm water management BMPs. The different configuration, capacity, and location of green roofs relative to more traditional and better-understood BMPs makes useful comparisons to these systems difficult.

While there have been no published studies to date on the specific effects of green roof runoff on the warming of streams, the results of literature concerning stream warming carries great relevance for the use of green roofs as a storm water management BMP. Green roofs, particularly modern, extensive green roofs, have often been touted as an urban strategy for storm water management. It would appear from the stream warming literature that their greatest advantage might be found instead in more rural settings, where they could be used to keep the total impervious cover in the watershed below the critical threshold value.

⁸ One obvious exception to this rule would be the inclusion of a water feature such as a pond in an intensive green roof system.

It would seem prudent in the absence of data or models quantifying the specific effects of green roof runoff on stream temperature to consider the possible effects of this runoff on stream warming when green roofs are located in areas adjacent to riparian buffer zones, in cold water stream areas, in urbanizing rural watersheds such as new suburban developments, or in any combination of these areas where the risk of negative impact of warmed runoff is increased.

3.2. Energy

Geometry largely determines the degree to which the roof system will affect the overall energy balance of a building. The higher the ratio of roof area to building volume, the more significant heat transfer through the roof assembly becomes. The Oak Ridge National Laboratory (Griggs, Sharp, & MacDonald, 1989) stated that the roof can comprise 50 to 75% of the building's total envelope in a typical one-story building, making the roof's thermal properties critical to the building's energy performance. The faster heat transfer takes place, the more the building must rely on other systems to maintain temperatures within the comfort zone. Typically, this equilibration is achieved through the use of energy-consumptive heating and air conditioning systems, incurring considerable installation and operating costs to the building owner and environmental costs to local and global ecosystems.

Much research has been conducted documenting the detrimental, cumulative contribution of hot roof surfaces in cities to the urban heat island effect. To combat this effect, many roofing systems attempt to reduce the effect of solar radiation on roofs to mitigate overheating. Other systems employ strategies to slow unwanted heat transfer into the building's interior, such as insulation, radiant barriers, and air barriers. Reflective roofing, also known as "cool roofing", has been shown to be effective in reducing the energy balance of buildings, especially in cooling load dominated climates and building occupancies. The U.S. Department of Energy's Oak Ridge National Laboratory (2004) has created a "Cool Roof Calculator"⁹ that estimates energy savings based on roof system parameters (i.e. R-value, solar reflectance, and infrared emittance), energy costs and equipment efficiencies, and project location. Green roofs share many of the advantages of reflective roofs, while avoiding some of their pitfalls. A comparison of the significant thermal processes present on green roofs and reflective roofs is found in Section 3.2.4.

⁹ The Cool Roof Calculator may be accessed at <http://www.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>.

3.2.1. Vegetated Roof Thermal Processes

To structure a review of the literature on the thermal and energy performance of green roofs, it is necessary to begin with an understanding of the complex and interconnected processes present in these systems. In an oft-cited paper discussing the thermal role of green roofs on Greek buildings, Eumorfopoulou and Aravantinos (1998) summarized the thermal processes of green roofs, drawing heavily on the German literature. These processes include both functions of the plants and properties of the entire green roof assembly. Table 3.3 itemizes the processes discussed in the reviewed literature. These processes will be discussed in more detail in this section. They are grouped into the four main mechanisms of heat transfer to and from a building, namely evaporation, radiation, conduction and convection. The unique nature of green roofs necessitates the addition of a fifth category of processes affecting heat transfer, grouped here under the heading of “Other Biological Processes”.

Table 3.3 - Summary of green roof thermal processes

Green roof thermal processes	
Evaporation	Water removes latent heat energy absorbed by plants by evaporation off plant surfaces and soil ¹⁰ (Eggenberger, 1983), and by water transpired by the plants.
	Wet soil provides thermal resistance due to its latent thermal capacity (Minke & Witter, 1982).
Radiation	Plants reflect solar radiation back into the atmosphere (Eggenberger, 1983).
Convection	Energy absorbed by plants is transferred to air above the roof by convection (Eggenberger, 1983).
	Nearly still layers of air created by the plants provide thermal resistance, and the roughness of plant surfaces reduces wind forces (Eumorfopoulou & Aravantinos, 1998).
Conduction	Any solar energy not reflected or removed by evaporation or transpiration is conducted into the roof structure beneath the green roof (Eumorfopoulou & Aravantinos, 1998).

¹⁰ The term “soil” is used frequently in Section 3.2 in lieu of “growing medium” to reflect statements in the reviewed literature.

	The green roof itself provides increased thermal capacity due to its increased depth (Eumorfopoulou & Aravantinos, 1998).
	The thermal resistance of soil is inversely related to its moisture content in unfrozen soils (Alcazar & Bass, 2005).
Other Biological Processes	Plants absorb solar energy through photosynthesis (Alcazar & Bass, 2005).
	Plants maintain soil temperature above that of surrounding air to prevent roots from freezing in a process called “root respiration” (Eumorfopoulou & Aravantinos, 1998)

Vegetated roofing systems thermally protect the buildings they cover chiefly by consuming heat energy by converting liquid water into water vapor through the processes of evaporation and transpiration by plants. These two processes are difficult to isolate from one another and are therefore referred to commonly as evapotranspiration. Eumorfopoulou & Aravantinos (1998) stated that 27% of the incident solar radiation on a roof is reflected, while 60% is consumed in the process of evaporation, leaving 13% to pass into the soil. The moisture content of the soil also provides a source of liquid water that can be evaporated, consuming heat energy (Minke & Witter, 1982). Green roofs also radiate solar energy back into the atmosphere. Eggenberger (1983) assigned green roofs an absorption coefficient of approximately 0.3. Convection, or transfer of heat to or from air molecules passing over the roof surface, is affected by two processes. First, natural convection of warm air removes heat energy from green roof surfaces (Eggenberger, 1983). Second, the surface of the plant layer, the roughness of which depends largely on the type and density of the vegetation, creates a zone of nearly still air that serves to insulate the roof and protect it from the effects of wind forces (Eumorfopoulou & Aravantinos, 1998).

Solar energy that is neither reflected off the surface of the roof, nor consumed in the evaporation or transpiration processes, nor convected off the roof through air movement, finds its way into the building beneath the green roof assembly through the process of conduction. The increased depth of green roofs as compared with traditional roofs provides thermal mass properties that serve to dampen and delay the effects of outdoor temperature swings on the building’s internal temperature and provides a degree of effective thermal resistance. Actual thermal resistance is largely dependent upon the moisture content of the growing medium or “soil” making up much of this depth. Alcazar and Bass (2005) illustrate the direct relationship

between soil moisture content and thermal conductivity. The wetter soil is, the more easily heat energy will flow through it, as shown in the example in Figure 3.3.

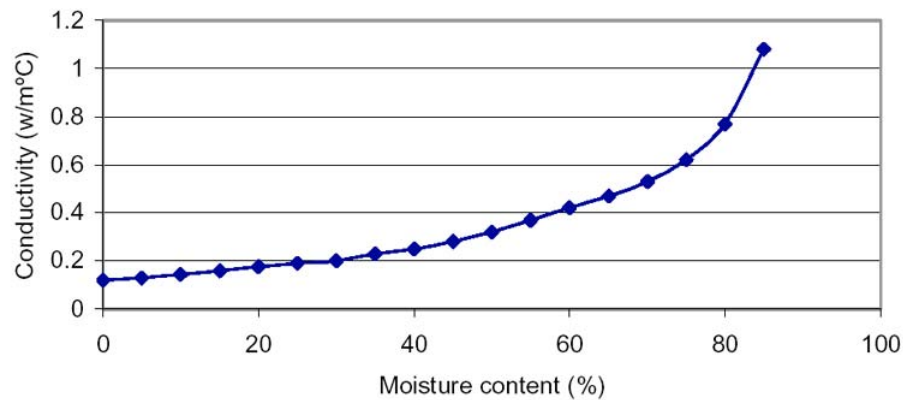


Figure 3.3 - Thermal conductivity of soil substrate used in the green roof. (Soil porosity = 0.86) (Alcazar & Bass, 2005, p. 576), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Jan. 25, 2007)

The insulating effect of the soil in winter is generally considered to be negligible (Eumorfopoulou & Aravantinos, 1998), since the soil has so little thermal resistance when wet. Karen Liu (2004) and Liu and Minor (2005) have also observed in Canadian studies that the thermally protective properties of growing medium diminish as it freezes. Some green roof studies (see Section 3.2.3) have shown that increased soil moisture content is directly related to increased roof thermal performance. While this may at first appear to be a contradiction to the statements above, these studies are referring to the latent thermal capacity of the moisture in the soil as opposed to its contribution to the soil's conductivity.

Several other processes contribute to the overall thermal effect of green roofs. These are biological in nature and as such are more difficult to quantify. Alcazar and Bass (2005), in their calculation of "equivalent absorbance" (discussed in Section 3.2.4) assigned a role to photosynthesis in the absorption of solar energy. Eumorfopoulou & Aravantinos (1998) described a biological process called "root respiration" which keeps soil temperatures slightly elevated to prevent the freezing of roots.

One must keep in mind that vegetated roof thermal processes do not function in isolation. They are profoundly affected by the variability of the weather, in terms of ambient temperature, solar

radiation, snow cover (Liu & Minor, 2005), rainfall, wind speed, and humidity. Green roof thermal processes are also dependent upon the characteristics of the building beneath the green roof, not only in terms of the building's physical makeup, but also in terms of its usage characteristics such as the differential between the set point temperature inside the building and the outside temperature (Liu & Minor, 2005). It is clear that any study of vegetated roof thermal processes must take these external physical, thermal, and temporal variables into account.

3.2.2. Effects of Vegetated Roof Thermal Processes

The combined effects of the relevant thermal processes result in lower temperatures above the roof membrane on hot days than those experienced above a typical roof. A study conducted by the National Research Council Canada (NRC) in Ottawa, Canada (Liu, 2004), showed a considerable reduction in roof temperature in a green roof system as compared with a light gray reference roof, as seen in Figure 3.4. The temperatures shown in the figure are dry-bulb temperatures.

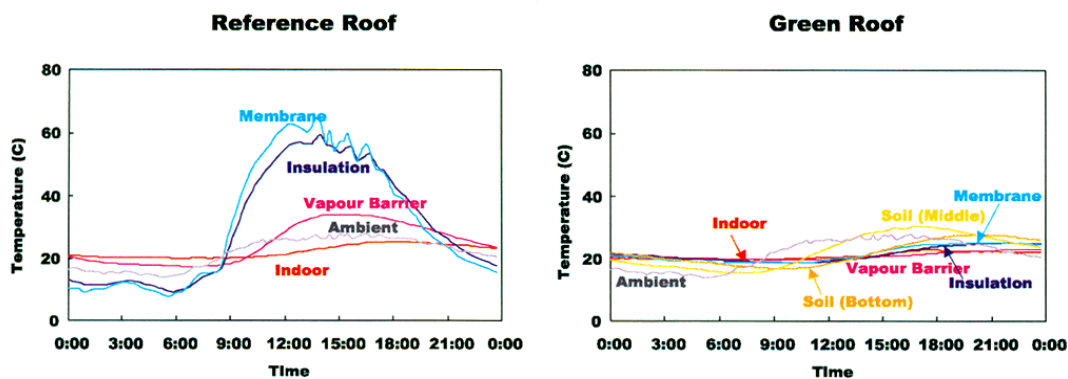


Figure 3.4 - Temperature profile within the roofing systems on a summer day (July 16, 2001) indicating that the green roof reduces the temperature fluctuations within the system (Liu, 2004, p. 7), permission to use granted by: Kristen Ammerman, Roof Consultants Institute, Inc. (Jan. 22, 2007)

When the effects of solar radiation, radiant exchange and convection are taken into account, the impact of the temperature difference between typical roofs and green roofs are more dramatic than temperature comparisons alone would indicate. These effects can be accounted for in heat transfer calculations by determining the sol-air temperature, defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (2001) as “the temperature of the outdoor air that in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with

the sky and other outdoor surroundings, and convective heat exchange with the outdoor air” (p. 29.15). The sol-air temperature is used to calculate the heat flux through a roof assembly. On warm, sunny days, the sol-air temperature at a green roof surface is considerably lower than the sol-air temperature of a typical roof surface subjected to the same conditions. Cooler roof surface temperatures translate to less heat gain to the building.

Maintaining cooler temperatures immediately above and within the roof assembly have additional benefits beyond reduction of heat flux into the building. Timothy Leonard and James Leonard (2005) pointed out that higher roof temperatures can reduce the cooling capacity and increase the electrical draw of air handling units, which are frequently located on roofs. They also cited the rapid decline in the R-value of polyisocyanurate and extruded polystyrene board, two types of insulation in common usage in North American roof assemblies, when roof assembly temperatures exceed 50°F (10°C). Green roofs, which moderate temperatures on and above the roof, can enhance the efficiency of mechanical cooling systems, reduce electrical loads, and maximize the efficacy of typical insulation materials.

In addition to providing passive cooling benefits, green roofs contribute to the success of active energy generation systems such as photovoltaic (PV) arrays. There is a trend developing in Germany, reported by Wolfgang Ansel, manager of the German Roof Gardener Association, or Deutscher Dachgärtner Verband (DDV) (Appl & Ansel, 2004), to exploit the synergistic relationship between green roofs and PV arrays. Green roofs moderate the temperature at the roof level, increasing the efficiency of PV arrays, which perform most effectively at roof temperatures near 77°F (25°C). The green roof serves as ballast for the supports of the PV array, avoiding penetrations through the roof membrane to anchor the system.



Figure 3.5 - Photovoltaic installation combined with extensive green roof on a school near Stuttgart (Appl & Ansel, 2004, p. 323), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Jan. 25, 2007)

The thermal benefits of green roofs extend even to the components of the roof assembly itself. Green roofs reduce both the maximum temperatures and the amplitude of temperature swings of the roof membranes they cover. Liu and Minor (2005) described how high temperatures accelerate the deterioration of roof membranes, and large fluctuations in temperature lead to interior stresses resulting from cycles of expansion and contraction. By generally lowering temperatures at the roof membrane, green roofs in effect extend the life of that membrane by slowing its heat-induced deterioration. Likewise, by dampening swings in temperature, green roofs reduce the likelihood of thermal stresses developing in roof membranes (Liu & Minor, 2005).

3.2.3. Studies Demonstrating Vegetated Roof Thermal Properties

Many recently published studies of green roof thermal properties were conducted in warm climates rather than in the cooler central-European birthplace of modern extensive green roofs. Summer performance of green roofs has long been intuitively viewed as a strategy for passive cooling, but little research has been conducted to support and quantify the effectiveness of this strategy. Scientists in Greece, France, India, Japan and Singapore are beginning to focus on the ability of green roofs to provide cooling, or at least insulation, of buildings in Mediterranean and tropical climates. Further, through in-situ monitoring, modeling, simulation, and sensitivity analysis, these scientists are interested in discovering the parameters that most affect green roof energy performance and in creating models to predict green roof behavior in cooling-load dominated climates. Beyond this, there is a desire to incorporate a simplified model of vegetated roofs' thermal performance into whole-building energy simulation packages. If this is accomplished, green roofs will be able to be evaluated as a passive cooling technique in standard energy analyses. The thermal complexity of green roofs, particularly with respect to the plant layer, has in the past prevented them from being modeled with accuracy. The research reviewed here is an important step towards clearing the way for green roofs to become one of the main tools in the architect's kit of passive cooling strategies.

Eumorfopoulou and Aravantinos (1998) conducted studies of green roofs with various vegetation heights, various types of drainage layers, and various amounts of roof insulation, comparing their thermal performance to one another and to a traditional bare roof. Despite the fact that green roofs always shortened the amplitude of both annual and daily temperature fluctuations, and reduced the amount of solar radiation transmitted into the building interior, they

found that only the deepest (intensive) green roof systems sufficiently obviated the need for insulation in the total roof assembly. Part of the study focused on the type of drainage material employed in the vegetated roof system; the researchers discovered that varying this layer had a negligible thermal effect in insulated green roof systems and a marginal effect in uninsulated systems.

In a study by Niachou, Papakonstantinou, Santamouris, Tsangrassoulis, and Mihalakakou (2001), the authors cited past empirical studies and theoretical models of earth-sheltered buildings that have focused on the winter thermal condition. They asserted the need to investigate the summer thermal properties of green roofs in an effort to reduce the increasing heat island problem in urban areas, particularly in warm climates. In an experimental study conducted in the Loutraki region near Athens, Greece, Niachou et al. (2001) found that the localized surface temperature of a green roof depended upon the type and density of vegetation, with thick green vegetation generating lower temperatures than sparser red vegetation or areas of bare growing medium. Researchers observed no significant difference between the average surface temperature of a green roof versus a traditional roof for insulated buildings. However, in insulated buildings, interior spaces beneath the green roof exhibited temperatures 3.6°F (2°C) cooler than those beneath the bare roof. For uninsulated buildings, the green roof surface temperature was about 18°F (10°C) cooler than that of a traditional “bare” roof. Interior temperatures were not monitored.

Based on the data collected from the experimental study, a mathematical model was proposed and several scenarios focused on thermal comfort of the building interior were tested. The most important findings from this simulation suggested that the effect of a green roof on the cooling of interior spaces, as well as its capacity to transfer heat between the building and the exterior year round, is highly dependent upon the degree of insulation present in the roof assembly. In well-insulated roof structures, the effect of the green roof on yearly energy savings was almost negligible (less than 2%), while in moderately insulated buildings the total energy savings ranged from 4% to 7% (with night ventilation) and in uninsulated buildings the yearly savings ranged from 37% to 48% (with night ventilation). Night ventilation was modeled due to the fact that the dampening effect of temperature swings exhibited by green roofs tends to result in higher nighttime temperatures. This property suggests that green roofs might be even more efficient when coupled with night ventilation, a theory that was borne out by the results of the simulation. In general, the green roof demonstrated an energy savings over the bare roof, even

in the winter months¹¹, but this savings was much more pronounced in buildings with less insulation.

Elena Palomo del Barrio (1998) has described a complex model of green roof performance based on the thermal properties of the support, soil, and canopy (plant) layers of a typical green roof. Her object in creating this model was to conduct sensitivity analysis in an effort to generate a simpler, more reasonable model and to determine the most relevant green roof parameters. This simplified model was then used to predict the thermal performance of green roofs and their potential as a cooling strategy, particularly in the Mediterranean region. Parametric sensitivity analysis was performed on the mathematical model using weather data from 10 days in August in Athens, Greece. One chief finding from this endeavor was that green roofs do not technically cool buildings in the summer, they instead act as highly efficient insulators. In other words, they reduce, but do not reverse, heat flux from the outside to the inside of buildings. The parametric analysis conducted on the model derived five significant parameters: leaf area index (LAI), foliage geometrical characteristics, and soil apparent density¹², thickness, and moisture content. The paper did not report the use of green roof data to test the presented model.

In summary, Palomo del Barrio suggested that a green roof optimized to reduce summer heat gain should include plants with a large amount of leaf surface area, which usually means a horizontal leaf distribution. The main function of leaves in a green roof, according to Palomo del Barrio, is to shade the growing medium below. The soil selected should be lightweight and capable of sustaining a high moisture content (called a large “field capacity”), as a high soil moisture content provides greater thermal conductivity and capacity thereby reducing heat flux through the soil.¹³ Deeper soils decrease heat flux into the building due to their insulating

¹¹ The authors stated that the green roof resulted in a greater energy savings in the winter than in the summer in the simulated study. It should be kept in mind, however, that winter weather conditions in Athens, Greece are quite mild and rarely drop below freezing.

¹² Soil apparent density was defined by the author as the “mass of the particles referred to the total volume of the disperse body, including pores” (Del Barrio, 1998, p. 181). In other words, it is the soil’s mass divided by its bulk volume, before the sample is dried.

¹³ Although Palomo del Barrio suggested peat as a promising green roof soil component based on her observations, a high organic content in growing media can lead to issues with the storm water pollutant control potential and long-term stability of a green roof assembly.

effects and their capacity to dampen diurnal temperature swings. Palomo del Barrio asserted that her model sufficiently addressed the modeling of the canopy layer, where, “shortwave radiation is the only process in the canopy which has an important effect on the green roof behaviour” (p. 191). She conceded, however, that the soil model needs more work, especially with respect to the soil moisture parameter. The complexity of this parameter remains one of the barriers to high-quality modeling of the winter performance of green roofs.

A later study performed by Theodosiou (2003) also addressed the summertime passive cooling potential of green roofs in the Mediterranean. A simulation model was validated using empirical data recorded over 20 summer days at a green roof site in Thessaloniki, Greece. As with the Palomo del Barrio (1998) study, which Theodosiou drew from and augmented in his own model, the intent was to develop a model that could be incorporated into building energy simulation models, and to determine the green roof parameters relevant to cooling. Seven parameters relating to the green roof assembly and climate were examined across their possible ranges: foliage height, foliage density (represented by LAI), soil layer thickness, planted roof type (ultra-extensive, extensive, or intensive), insulation layer (in this case, extruded expanded polystyrene) thickness, atmospheric relative humidity, and wind speed. A diagram showing the effects of each parameter’s maximum and minimum value on the total thermal flux is shown in Figure 3.6. In this study, total thermal flux was a measure of the cooling capacity of the green roof assembly; a positive heat flux indicated desirable heat flow from the inside to the outside of the building.

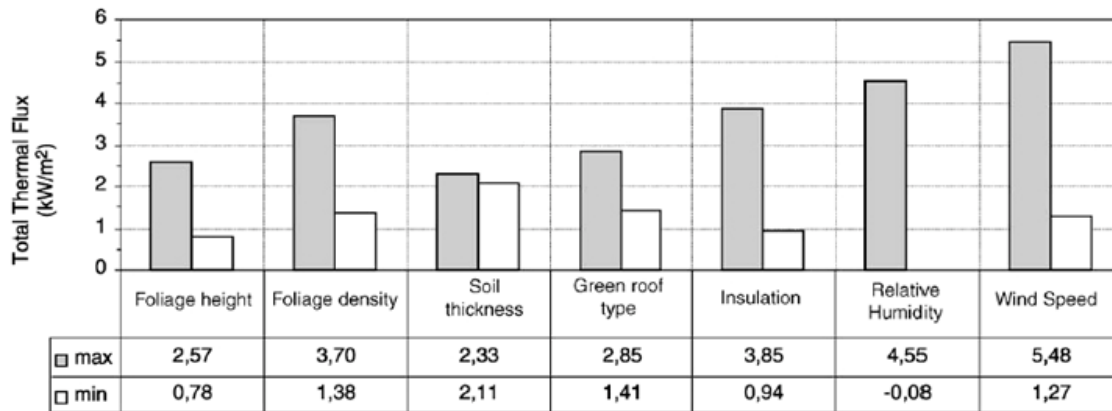


Figure 3.6 - Total thermal flux through planted roof for both extreme parameter values during the summer period (Theodosiou, 2003, p. 915)¹⁴

In brief, taller foliage led to greater heat flux, because it blocked solar radiation and created a cool thermal zone above the plant canopy. It was not a significant parameter on its own, but became important when coupled with foliage density. Foliage density was the most important vegetative parameter and was directly related to heat flux for the same reasons as foliage height, as well for the higher transpiration levels of dense foliage which were most impressive on dry days. Soil layer thickness did not have a significant effect on the overall heat flux, but it was noted that thicker soils always provided cooling while thinner soils did not cool the building during extremely high temperature swings. The planted roof type also did not substantially affect the overall summer heat flux, but as with thicker soils, deeper roof assemblies were capable of cooling even during the hottest periods when cooling was most critical. An increase in insulation thickness was shown to “strangle” the transport of heat flux from the building interior to the growing medium of the green roof, and the absence of roof insulation was seen as the most sensitive green roof system parameter of those studied. However, Theodosiou stated that since green roofs (excepting deep intensive systems) make almost no thermal contribution to the roof in winter, some degree of roof insulation is warranted for acceptable year-round performance. Of the two climatic parameters examined, relative humidity had a greater effect on heat flux than did wind speed. Low relative humidity resulted in higher heat flux due to the greater potential for evapotranspiration (ET), the main mechanism for heat removal, as opposed

¹⁴ Reprinted from *Energy and Buildings*, Vol. 35, Theodore G. Theodosiou, Summer period analysis of the performance of a planted roof as a passive cooling technique, Page 915, Copyright 2003, with permission from Elsevier.

to heat avoidance (shading). Higher wind speed had its most significant positive effect on heat flux during drier conditions, where it supported increased ET.

A study conducted by Kumar and Kaushik (2005) built on prior research in the creation of a model of green roof thermal performance coupled with building simulation models. The goals of the study were to isolate the effects of foliage characteristics such as LAI and height on green roof performance, to estimate thermal load reduction in buildings due to green roofs, and to determine the combined effects of green roofs and thermal shading on interior space conditioning. The authors adopted Palomo del Barrio's (1998) model separating green roofs into support, soil and canopy layers, and introduced a theoretical interior occupied space into the calculations to determine the effects of green roofs on interior temperatures. The model was validated using data collected in Yamuna Nagar, India. Findings supported the correlation between increased LAI and reduced temperature in the plant canopy, smaller temperature swings in the plant canopy, and reduced heat flux into the building.¹⁵ Degree and variation of heat flux were both reduced with increasing vegetation height. Modeling of the interior temperature in a 20-by-16-by-13-foot (6-by-5-by-4-meter) unconditioned room with four occupants and a 22-square-foot (2-square-meter) window demonstrated an average interior temperature reduction of 6°F (3.3°C) from the bare roof condition to the green roof condition, and a reduction in interior diurnal temperature variation of 9°F (5.1°C). A cooling effect of 3.02 kWh per day, or 1.08 kWh per square foot (0.1 kWh per square meter), was deemed attributable to the green roof and sufficient for the space in question. Further, the maximum temperature reduction between the ambient air and the room interior was found to occur between 12:00 and 15:00, the period during which maximum heat gain usually occurs. These results support the potential for cooling benefits of green roofs in tropical climates.

A study by Onmura, Matsumoto and Hokoi (2001) evaluated the evaporative cooling potential of planted roofs. In situ, wind tunnel, and mathematical studies were used to conduct this evaluation. The authors isolated five possible parameters influencing the reduction of the surface temperature of a concrete roof beneath a lawn garden: thermal resistance, thermal capacity, solar absorption, convective heat transfer at the sample surface, and latent heat transfer due to evaporative cooling. Field measurements at a test roof in Osaka indicated that the green roof had a solar absorptivity of 0.77, equal to or higher than that of concrete (0.6 to

¹⁵ In this study, positive heat flux indicates heat flow from outside to inside, an undesirable condition for cooling.

0.8). Since summer daytime temperatures dropped from 140°F (60°C) at the control concrete roof slab to 86°F (30°C) at the roof slab beneath the green roof, instead of rising as would be expected based solely on the solar absorptivity coefficient, solar absorption was discarded as a contributor to the green roof's cooling potential. In terms of thermal resistance and capacity, it was determined that increased moisture content in the green roof layer lead to increases in both of these parameters. However, varying these parameters in a mathematical model did not adequately predict the temperature drops experienced in the in-situ tests, therefore it was determined that the role of the remaining parameters, heat and moisture transport, was considerable.

A wind tunnel test was conducted to evaluate these remaining parameters, and results were used to generate a simultaneous transport model. Manipulation of this model indicated that both solar radiation and the moisture content of the lawn contributed significantly to the temperature distribution through its section. This temperature gradient was thought to support the evaporative cooling effect of the roof lawn garden through a complex process of heat and moisture transport. The authors called for future sensitivity analysis of the heat and moisture parameters to improve the model. Despite the complexity of modeling these effects, field measurements were encouraging: the 54°F (30°C) drop in temperature exhibited by the test roof translated into a 50% reduction in heat flux transmitted to the interior.

In a study in Singapore, Wong, Chen, Ong, and Sia (2003) attempted to quantify the thermal benefits of green roofs in a tropical climate by considering both the benefits to the building with the green roof and the wider effects on the microclimate surrounding the building. Vis-à-vis the direct effects of green roofs, Wong and colleagues obtained field study results similar to those of Onmura et al. (2001), with a maximum roof surface temperature decrease of 54°F (30°C) relative to a bare roof. They also established a relationship between increased LAI and reduced surface temperatures on green roofs. These reduced temperatures led to reduced heat transfer, and therefore lower heat gain, into interior spaces topped by a green roof, when compared to a bare roof and a roof with only soil (no vegetation). The effects of both the growing medium and plants were considered; the reduced heat gain was attributed largely to the shading effects of the plants and to the "insulation" effect of wet growing medium, likely due to evaporation of soil moisture.

To evaluate the indirect benefits of green roofs, a test apparatus was used to determine the effects of the green roof at points up to 40 inches (1 meter) above the roof surface, in terms of ambient, mean radiant and global temperatures, humidity, and reflected radiation. It was determined that while the roof surface heated the ambient air above both the green and bare roofs during the day, the planted surface actually cooled the ambient air during the night hours while the bare roof showed no such thermal reversal. The maximum ambient temperature difference between bare and green roofs of 7.6°F (4.2°C) occurred just 12 inches (300 mm) above the roof surface and became less significant as distance above the roof increased. Results of the humidity measurements did not show a significant difference between bare and green roofs, which was attributed to the short distance between the sensors; the authors suggested that ventilation might be a good strategy to reduce localized high humidity caused by evapotranspiration. Long-wave (heat) radiation into the atmosphere was significantly reduced at the green roof versus the bare roof, with the most significant differences ($\Delta 7.29^\circ\text{F}$ (4.05°C) global temperature, $\Delta 8.1^\circ\text{F}$ (4.5°C) mean radiant temperature) occurring at dusk. A maximum reduction of 34.6 British thermal units per hour per square foot (109 watts per square meter), a measurement of reflected solar radiation, occurred at midday at the green roof compared to the bare roof. The authors concluded that the results of these radiation tests indicate that green roofs are in fact a viable strategy to reduce the urban heat island effect.

A later study in Singapore, reported by Puay Yok Tan and Angelia Sia (2005) at the 2005 Greening Rooftops for Sustainable Communities conference, focused in part on the thermal properties and reflective characteristics of four green roof test plots installed atop a multi-story carpark. In this study, the green roofs were superimposed on an existing exposed white concrete slab roof, where pre-installation weather and temperature data had been previously collected.¹⁶ The researchers found that soil moisture level in the green roof systems was directly related to roof surface temperature reduction. While the green roofs reduced post-installation roof surface temperatures by up to 32°F (18°C) as compared to pre-installation temperatures, post-installation roof surface temperatures on these extensive systems occasionally exceeded corresponding pre-installation temperatures during periods of drought. The authors attributed this phenomenon to the reduced thermal capacity of the thin 2 to 4 inch (50 to 100 mm) growing medium layer as compared to that of the original exposed 10 inch (250

¹⁶ The pre-installation and post-installation data were recorded at different times of the year. The authors do not state how this discrepancy is accounted for in this comparison. However, the yearly temperature variation in tropical Singapore is not as significant as that found in temperate regions.

mm) thick concrete slab. They also observed that while concrete roof surface temperatures covered by the green roof systems were generally 27 to 36°F (15 to 20°C) cooler than adjacent bare concrete roof surfaces¹⁷ as observed by infrared thermography, the ambient air temperatures post-installation were only 3 to 5.4°F (1.7 to 3°C) lower than pre-installation temperatures. The researchers calculated that the green roof was responsible for a maximum 60% reduction in heat flux into the building through the roof assembly.

While the thermal findings were somewhat ambivalent, the researchers did witness a significant reduction in light levels (between 12% and 56%) experienced by adjacent housing complexes overlooking the carpark roof. These results were due to the reduced amount of reflected radiation off the green roof surfaces as compared to the original, uncovered concrete roof surface (a 32% to 50% reduction). This is an encouraging finding for promoters of green roofs in Singapore, who may assert that these systems are more “neighbor friendly” than their white concrete counterparts.

While the literature reporting results found in Asia and Europe is useful, more investigation in North America is needed. Karen Liu of the National Research Council of Canada has contributed to this effort with published reports from two green roof studies, the first conducted at an experimental facility in Ottawa (Liu, 2004) and the second at the Eastview Neighbourhood Community Centre in Toronto (Liu & Minor, 2005). Similar results were obtained at the two sites. In Ottawa, it was shown that a generic green roof system with 6 inches (150 mm) of depth significantly reduced temperatures and temperature fluctuations at the roof membrane, especially in the summer. There was a 75% reduction in energy demand based on the lower average daily heat flow, both positive and negative, through the green roof as compared to the generic roof over the 22 month study period (Liu, 2004). In Toronto, two green roof systems, one 3 inches (75 mm) and the other 4 inches (100 mm) deep, were compared to one another and to a reference roof. Because plant coverage was only around 5% during the period of study, the results largely reflected the performance of the growing medium rather than the action of the plants. Here again the green roofs reduced heat flow into the building, on the order of a daily average heat flow reduction of 70 to 90% in the summer and 10 to 30% in the winter, when compared to the reference roof. A comparison of the two systems evidenced marginally

¹⁷ The roofs in this study did not employ a waterproofing membrane as is common practice in North America. Instead, the concrete roof slab was variously exposed directly to the elements or covered with a green roof system.

superior performance for the slightly deeper system, i.e. approximately 3% less heat flow into the building in the warmest months, which Liu attributed to its greater thermal mass and thermal resistance, and to the larger capacity for latent heat removal due to evaporation from the larger amount of moisture retained in the deeper growing medium. Interestingly, the shallower system evidenced 10% less heat flow through the roof assembly than the deeper system in the winter months. This was attributed to the insulating properties of the shallower system's drainage layer, which was made of expanded polystyrene (Liu & Minor, 2005).

Jeff Sonne (2006) reported results from a comparison of a vegetated roof and a more typical membrane roof installed side by side on a two-story building at the University of Central Florida in Orlando. The green roof was additive to the conventional roof construction and consisted of 6 to 8 inches (150 to 200 mm) of green roof media topped by predominately native vegetation, which was irrigated twice weekly. For a study period of July 4, 2005 through September 1, 2005, Sonne reported a reduction in average maximum daily temperature from 130 °F (54 °C) at the conventional roof surface to 91 °F (33 °C) at the green roof surface. As was observed in other studies, the green roof's average minimum daily temperature, at 84 °F (29 °C), was higher than that of the conventional roof, at 71 °F (22 °C). This was due to the typical dampening of temperature swings exhibited by green roofs. Perhaps the most interesting finding, supporting the theory that roof insulation reduces the relative effectiveness of a green roof, was the difference in heat flux through the roof depending on the amount of insulation at the sensor location. The test roof, like many North American roofs, included tapered rigid insulation providing positive roof drainage. In this case, the roof surface was more heavily insulated at the east and west ends than at the central drain locations. Table 3.4 illustrates the more impressive calculated difference in heat gain values between the green roof and the conventional roof at the less-insulated locations, and the less-impressive differences seen at the well-insulated edge locations.

Table 3.4 - Average heat flux estimates for July 4, 2005, through Sept. 1, 2005. (adapted from Sonne, 2006, p. 61)

Location	Approx. R-Value	Avg. Green Roof Flux		Avg. Conventional Roof Flux	
		Btu/h · ft ²	W/m ²	Btu/h · ft ²	W/m ²
East	38	0.33	1.0	0.36	1.1
Middle	17	0.53	1.7	0.74	2.3
West	38	0.31	0.98	0.34	1.1

For the test period, Sonne reported an averaged decrease in heat gain of 18.3% for the green roof as compared to the conventional roof, and translated this to an estimated 700 watt-hours (2,500 megajoules) per day of air conditioning avoided during the test period if the entire 3,300-square-foot (310-square-meter) roof had been greened at this particular facility.

Based on the results of these studies, it appears that for overall thermal performance with respect to passive cooling, the density of foliage, the moisture capacity of the growing medium, and the amount of roof insulation that is coupled with the green roof system are the three most important roof system parameters. An increase in the thickness of the system has little overall effect, but positively affects its ability to respond to extremes of temperature. Of the climate variables investigated, relative humidity appears to have the greatest impact, with dry conditions being most conducive to higher ET rates, and therefore more efficient performance of the green roof. Green roofs have been proven to have a significant impact on passive cooling of interior spaces, and to effectively reduce the radiation of heat energy into the environment when compared with traditional roofs. While the thermal transport mechanisms of green roofs are difficult to model, it is clear that these mechanisms are among the most critical to their thermal performance, and that future research will need to focus on increasingly accurate predictive models, particularly those which may be integrated into whole-building simulation programs.

3.2.4. Green Roof Modeling

There have been attempts to quantify the thermal benefits of green roofs in a way that is easy not only for scientists to understand, but also for designers and owners to appreciate. In the building industry, there is a desire to define an R-value for green roofs. R-value, a measure of thermal resistance, i.e. the reciprocal of conductance, is frequently used as a convenient index for comparing the thermal properties of building materials in general. Christopher Wark of

Shade Consulting, LLC (2004) argued that assigning a heat transfer rate, or Q value, to green roofs would describe their thermal performance much more accurately than attempting to assign them an equivalent R-value. Unlike insulation which operates by resisting conductance of heat flow regardless of direction, the thermal behavior of green roofs depends upon a more complex combination of radiation, convection, evaporation, and conduction. Wark has written that the heat flow rate, or Q, is a more accurate term to describe the multifaceted action of green roofs. Q represents heat transfer rate in British thermal units per hour, or watts. Many studies of vegetated roofing thermal processes have presented results in terms of Q, or a related term, called heat flux, or Q". Q" represents heat transfer rate per unit area, or heat flux in Btu/hr-ft², or W/m².

These terms are related according to the following equation:

$$Q'' = Q/A$$

Equation 3.2 - Definition of heat flux (U.S. Department of Energy, 1992, p. 3)

where

Q" = heat flux (Btu/hr-ft² or W/m²)

Q = heat transfer rate (Btu/hr or W)

A = area (ft² or m²)

Wark also explained that green roofs behave similarly to "cool" roofs in their response to solar radiation, and that because of this they have a similar "winter penalty" whereby the green roof may be a liability during the heating season because it does not absorb as much heat as a dark-colored traditional roof. Gaffin, Rosenzweig, Parshall, Beattie, Berghage, O'Keeffe and Braman (2005) have capitalized on this similarity to cool roofing by developing a method to estimate green roof performance using an "equivalent albedo".

A team of researchers from Columbia University and the Pennsylvania State University have developed a method that compares the performance of green roofs with that of white reflective roofs, the energy benefits of which are widely appreciated (Gaffin, Rosenzweig, Parshall, Beattie, Berghage, O'Keeffe & Braman, 2005). By creating an energy balance model verified and calibrated with data from in-situ monitoring conducted at the Pennsylvania State University, this group developed an "equivalent albedo" for green roofs ranging from 0.7 to 0.85. This range means that green roofs are as thermally efficient as the brightest of white roofs. Because green roofs shed heat not simply as a result of their surface color, but largely through

evapotranspiration, their thermal performance is not dependent on the maintenance of a pristine white surface, as is the case with white reflective roofing. Green roofs also prevent the problem of creating glare for adjacent buildings by providing instead a more pleasant vegetated surface. The team illustrated how green roofs combine two key strategies for reducing the urban heat island effect, namely urban greening and increased reflectivity (or in this case, its thermal equivalent), into one self-sustaining roof treatment.

The Bowen ratio (β) is a coefficient used in climate modeling of land surfaces. It represents the ratio of sensible heat flow due to convection to latent heat flow, as shown in Equation 3.3.

$$\beta = \frac{Q_{convection}}{Q_{latent}}$$

Equation 3.3 - Bowen Ratio

Convective heat flow is equated to sensible heat flow in this equation. Generally, arid regions have high Bowen ratios, while densely vegetated, humid areas have low Bowen ratios. In their 2005 paper, Gaffin et al. accounted for the latent heat flow component of green roofs by artificially altering the convective heat flow of a white roof to represent the performance of a green roof. In so doing, they were able to assign an “equivalent albedo” to a non-vegetated roof to mimic the performance of a green roof. In an attempt to more closely model the actual behavior of green roofs, Gaffin, Rosenzweig, Parshall, Hillel, Eichenbaum-Pikser, Greenbaum, Blake, Beattie, and Berghage (2006) presented the results of experimental studies at the Pennsylvania State University where Bowen ratios from 0.12 to 0.35 were reported for sedum green roofs with approximately 4 inches (100 mm) of growing medium during the month of July 2003. Effectively, this means that the latent heat losses exceeded the sensible heat losses by 3 to 8 times for these roofs. The team hypothesized that the range of ratios represented the fact that the ratio changed along with soil moisture content. Because soil moisture content was not recorded in the experiment, average rainfall rate was used as a proxy for this variable. Gaffin et al. (2006) showed that more rainfall tends to bring more evapotranspiration and lower Bowen ratios, approaching a theoretical minimum of $\beta = 0.1$, the coefficient used for open water surfaces. The range of Bowen ratios in the experimental study were compared with moist, irrigated environments. It was noted that drier months would yield different results.

Susana Saiz Alcazar and Brad Bass (2005) used Environmental Systems Performance - research (ESPr) software to model a typical urban residential building in Madrid, Spain to compare the energy performance of a conventional roof to two types of extensive green roofs. The modeled building consisted of eight stories broken into sixteen zones for the purpose of analysis. The roof accounted for just 16% of the total building envelope.

The modeling of the plant layer and soil layer were discussed in detail. Alcazar and Bass incorporated a factor called “equivalent absorbance” into the optical parameters of the green roof’s plant layer. This factor accounted for the effects of evapotranspiration and photosynthesis on the net absorbance of the plant layer. These biological processes effectively decrease the amount of solar energy absorbed by this layer. Alcazar and Bass echoed Palomo del Barrio’s (1998) assertion that blocking of solar radiation is the only important parameter in the plant layer’s contribution to green roof performance (see Section 3.2.3). They therefore ignored the effects of convective heat flux in the plant layer due to its negligible effect and omitted the effects of conductive heat flux in the plant layer due to the lack of consensus on an appropriate value for this parameter in the literature. The most significant variable discussed with respect to the soil layer was the effect of moisture content. They described how moisture content of the soil is higher (a value of 80% was assigned) during heating (winter) conditions and lower (20%) during cooling (summer) conditions. In their model, the difference between these two values translated into an increase in the U value of the roof system of 8% when soil moisture increases from 0 to 20%, and an increase in the U value of the roof system of 20% when soil moisture increases from 0 to 80%. In simple terms, the wetter the soil (winter condition) the greater its conductivity, thus the less thermal insulation it provides. However, the authors asserted that in ultra-extensive systems such as the ones modeled, with only 2 inches (50 mm) of soil, the insulation value of the soil may be neglected altogether.

Alcazar and Bass’ conclusions from the modeling exercise pointed to the significance of considering peak loading conditions and building geometry in the potential for energy savings. They reported overall energy savings of less than 2% annually for the two green roof cases as compared with the traditional roof. In contrast, the green roofs accounted for a 12% reduction in energy use on a peak cooling day. Interestingly, they discovered that on a peak cooling day, 25% of the energy benefit attributable to the green roof was experienced by the building’s uppermost zone, located immediately beneath the roof. These savings quickly degraded for zones located increasingly far beneath the roof, with only negligible energy savings achieved on

stories four or more stories beneath the roof, as shown in Figure 3.7. These observations have important implications for the use of green roofs as load-shaving devices, and for strategizing their use on buildings where the roof constitutes a relatively large portion of the building envelope. The authors observed a trend of diminishing returns below a roof-to-envelope ratio of 0.5, at which there would theoretically be a 30% reduction in building energy use as extrapolated from the model employed in the study. While this study was designed to investigate the effects of green roof implementation in Spain's urban residential sector, the conclusions made have relevance for North America as well. The results of the study would tend to support the efficacy of employing green roofs in suburban and smaller urban centers, where buildings do not often exceed four stories in height, as opposed to categorizing them solely as strategies for highly urbanized areas.

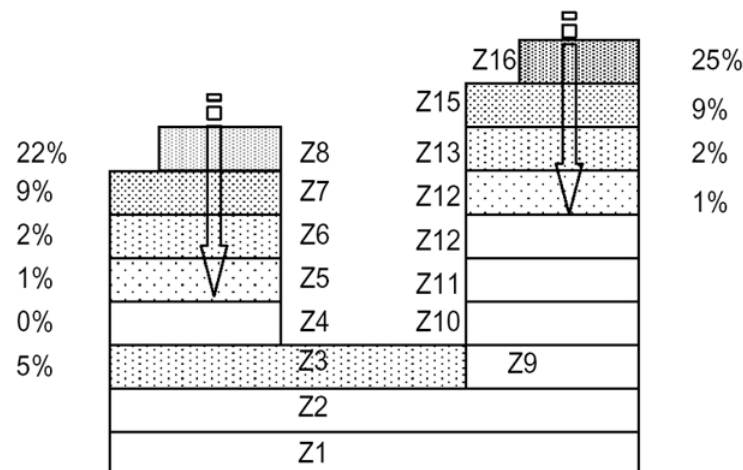


Figure 3.7 - Peak cooling energy reductions achieved in the zones of the building (Alcazar & Bass, 2005, p. 579), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Jan. 25, 2007)

Martens and Bass (2006) modeled warehouse buildings with green roofs using climate data for Toronto in July in an attempt to isolate the impact of roof-to-envelope area ratio on energy performance. Incorporating the energy balance model designed by Gaffin et al. (2005) for green roofs, they assumed a Bowen ratio of 0.12, which is on the low end of the ratios found by Gaffin et al. (2006) at the Pennsylvania State University test site. This means that the Martens and Bass study assumed a relatively moist environment with relatively high rates of evapotranspiration, and consequently, lower rooftop temperatures at the green roof. The effects of thermal mass and thermal capacitance were ignored. Using ESP-r software developed at the University of Strathclyde in Glasgow, Scotland, Martens and Bass (2006) found that for a 820-

by-820-foot (250-by-250-meter) building with a green roof and an internal loading of 50,000 W, energy savings over a conventional roof of 73%, 29%, and 18% were achievable for one, two and three story buildings, respectively. These simulated buildings had roof-to-envelope area ratios of 0.95, 0.91, and 0.87 respectively, all relatively high numbers. Clearly, potential energy savings are dependent upon building construction and internal loading, and the climate and the Bowen ratio assumed for the study period. The Martens and Bass study did show that building geometry, as quantified by roof-to-envelope area ratio, floor area, and number of stories, has a significant effect on expected thermal performance. Bass and colleagues are currently working on a tool to group green roof energy benefits according to building type, roof type (including extensive and intensive green roofs), Canadian city, and time step (seasonal or annual) (Bass, 2006).

3.2.5 Embodied Energy and Environmental Impact

Embodied energy was defined by Treloar (1994) as

The quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e. direct energy plus indirect energy.

Milne and Readon (2004) claimed that the embodied energy of materials constituting buildings is more important than previously thought in comparison with the energy used to operate buildings. They discussed the use of Life Cycle Assessment (LCA) as a tool to determine the true energy costs of building products.

Analyses of embodied energy are often coupled with other measures of negative environmental impact, such as the potential of a product or system to consume scarce resources, to pollute the environment, or to contribute to the waste stream, for the purpose of developing a more complete picture of the product's overall environmental influence (Milne and Readon, 2004). Measures of the environmental suitability of building products based on single and multiple attributes have been developed worldwide, but such guidelines have yet to be developed for green roofs in particular. An analysis of the embodied energy and environmental impact of various vegetated roofing systems is beyond the scope of this dissertation. This discussion will highlight some of the challenges encountered in the process of computing embodied energy and environmental impact for building products in general, and will present a brief overview of proposed attributes used to guide the selection of vegetated roofing materials in particular.

In an article in *Environmental Building News*, Malin (2003) outlined the process of determining environmental suitability as it relates to building products. A product's "upstream" conditions are considered, such as acquisition, manufacturing and transport, along with its "use-phase" impacts, such as the amount of energy the building consumes as a consequence of including the product, and its "downstream" effects, such as eventual reuse, disposal, or recycling.

Tools used to measure embodied energy and environmental impact in building products are in their infancy in North America, and those specific to green roofing have yet to be developed. Malin (2003) described difficulties with the creation of rating systems, standards, or endorsements defining building components as "environmentally preferable products" (EPPs). Malin (2003) listed several organizations involved in tackling development of EPP standards. The International Organization for Standardization (ISO) has prescribed a methodology for Life Cycle Assessment, a tool widely used to evaluate the environmental impact of products or systems, but Malin argued that inconsistency in the quality and depth of data used in these analyses often renders them difficult to compare with one another. The National Renewable Energy Laboratory (NREL) and its partners, including the Canadian Athena Sustainable Materials Institute, have created a U. S. Lifecycle Inventory (LCI) database with publicly accessible information on which to base such analyses. Modules within the Building and Construction Products category are currently limited to wood products (NREL, 2006). The U. S. Environmental Protection Agency (EPA) has developed an Environmentally Preferable Purchasing program in cooperation with the U.S. Departments of Energy and Agriculture, and the American Society for Testing and Materials is now developing a "Standard for EPP Standards". The National Institute of Standards and Technology (NIST), in cooperation with the EPA and the private sector, has created a tool called Building for Environmental and Economic Sustainability (BEES) that helps designers and other stakeholders select building products using a weighted analysis of environmental and economic performance measures (NIST, 2003). This tool currently incorporates several traditional roof systems, but does not include vegetated roofing.

Private organizations are also devising their own methodologies for product assessment. Where such standards have been developed, problems with consensus among industry representatives, market acceptance, reliability and transparency of data used in the analysis, relevance to the product's actual mode of use in the built environment, certification and labeling

of products, and overlapping or conflicting standards abound (Malin, 2003). Logically, standards for green roofs in general must precede the development of EPP standards, which aim to distinguish products from one another, assigning greater value to those that exceed basic requirements. Hopefully, lessons learned from the development of EPP guidelines for more widely used building materials will be carried over to green roofing as EPP standards and other measures of environmental impact are developed for this growing sector of the building market.

Goya Ngan (2004) reported that guidelines for determining the ecological impact of green roofs have begun to be outlined by the Deutscher Dachgärtner Verband (DDV), or German Roof Garden Association. She translated this organization's "Ecological Guidelines for Roof Greening" as follows:

Production: Use of recycled materials, consideration of the energy balance for materials, new or recycled.

Manufacturing: Reduced environmental impact of manufacturing through resource and energy savings.

Transport: Minimizing the transportation distances by building and/or extending a logistics system.

Application: Sustainable use of materials through long lifespan (durability).

Waste disposal: Disposal safeguard through re-utilization (Ngan, 2004, p. 28).

Ngan also cited a list of considerations raised by Krupka (2001), which included the energy required to manufacture green roof media products such as expanded clay and slate, the energy expended to transport materials such as lava rock from source to site, the use of non-recyclable plastic drainage mats and filter cloth, and the presence of potentially harmful chemicals in waterproofing membranes used in some green roof systems, such as PVC and root-repellant agents.

Ngan (2004) called for future research in the area of recyclable green roof system elements, and related that German green roof systems frequently include reclaimed crushed brick in drainage and growing media layers. She concluded that using local materials will not only reduce the embodied energy of green roof systems but will also help develop the green roof industry in Canada, and pointed to the use of non-proprietary material specifications as one strategy to encourage this practice.

3.3. Acoustics

Besides providing the hydrological and energy benefits mentioned above, green roofs also possess certain acoustical properties that may be favorable. Several green roofs have been implemented in the vicinity of airports to protect against noise infiltration. A report by Roofscapes, Inc. (2003), a Philadelphia-based green roof provider, described the use of green roofs on structures lying in the flight path of airplanes as a measure to moderate the effects of growth at the expanding Frankfurt airport in Germany. Similarly, the Gap 901 Cherry project in San Bruno, California, designed by William McDonough + Partners, was claimed in the Green Roof Awards of Excellence (Green Roofs for Healthy Cities, 2003) to attenuate noise from the nearby San Francisco airport by up to 50 decibels, by virtue of the mass of its growing medium. Peck, Callaghan, Kuhn and Bass (1999) cited a German study by Minke and Witter (1983) demonstrating that a green roof with a 4.8 inch (120 mm) substrate layer can decrease noise transmission by 40 decibels, while a 8 inch (200 mm) substrate layer can decrease noise transmission by 46 decibels.¹⁸ Peck et al. (1999) also stated that the growing medium dampens the effect of low-frequency noise while the plants themselves block high-frequency noise.

A few studies have been conducted to determine the acoustical properties of soils and other granular media. These tend to be extremely technical in nature and are thus largely inaccessible to architects or other design professionals who generally possess only rudimentary training in acoustics. They are also difficult to translate directly to green roofing, because of their inherent complexity coupled with the lack of modeling of components below or above the growing medium. However, two such studies make important observations that may, through further study and more direct application to green roofing systems, become cogent to the framework for green roof system selection.

In a paper by Martens, van der Heijden, Walthaus and van Rens (1985) the authors considered existing acoustical models of soils that are based on the single parameter of flow resistivity. Generally, flow resistivity is directly proportional to acoustic impedance, the ability of a material to resist the flow of acoustic energy (Cowan, 1994). Martens et al. (1985) pointed out the inadequacies of single-parameter flow resistivity models, which are based on assumptions regarding the porosity and homogeneity of soils that do not reflect the true characteristics of

¹⁸ The sources cited did not provide the acoustic frequency of the noises for which the stated attenuation is claimed.

natural soils. Testing of forest soils, grass-covered soils, and bare sandy soils conducted by Martens et al. supported more complex acoustical models which account for the stratified nature of soils. Certain general conclusions regarding specific soil parameters were drawn from these tests. Though no clear relationship between porosity of soils and flow resistivity was drawn, there was a distinct correlation between higher water content and higher flow resistivity. Additionally, the researchers found that plants and their roots significantly affect the structure of soil, and therefore its acoustic performance. Further research was called for by the authors in this area.

Voronina and Horoshenkov (2003) have developed a theoretical model for the acoustic performance of loose granular media, validated by experimental tests conducted by two independent laboratories in Moscow, Russia and Bradford, England. The authors stated that these media are currently being used in both interior and exterior applications for acoustical control due to their high absorption, high mechanical strength, and relatively low cost compared to other acoustic absorbers. Granular media tested in this study included vermiculite, rubber crumb, perlite, and nitrile foam granulate. Voronina and Horoshenkov (2003) derived a model that predicts the acoustic properties of these media with respect to characteristic particle dimension, porosity, tortuosity, and specific density. Using this model, they were able to classify granular media according to characteristic particle dimension and specific density, and to predict that these classifications will be useful to acoustical engineers in designing appropriate systems. While this research is promising, it is not yet directly applicable to green roofing. While both perlite and vermiculite are frequently used as base materials for green roof media (Dunnett & Kingsbury, 2004), the effects of organic content and the plants themselves on the acoustic performance of green roof media remains to be tested.

In the absence of a sufficient body of empirical evidence needed to construct a model predicting green roof acoustical performance, a proxy measurement is necessary. The most direct of these is found in the application of the mass law, “a relationship that relates a doubling in mass or frequency to a 6-dB increase in transmission loss for a homogeneous partition over a specific frequency range” (Cowan, 1994, p. 274). Figure 3.8 shows the effect of mass on the attenuation of transmitted sound due to the effects of the mass law. The x-axis indicates surface mass multiplied by the frequency of a sound. The y-axis indicates transmission loss in dB. Doubling the mass (or the frequency of the sound) will cause a theoretical 6 dB increase in transmission loss, with field results closer to 4 dB (Stein & Reynolds, 1992). When applied to

green roofing, this means that deeper growing medium will provide more mass and therefore better noise attenuation benefits.

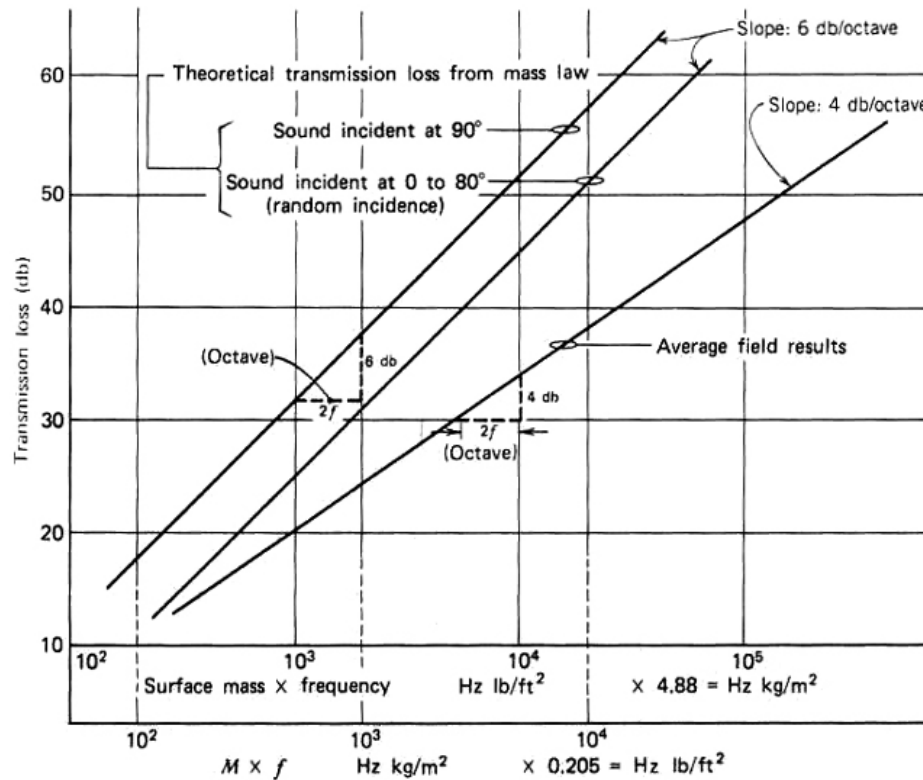


Figure 3.8 - Graphic representation of mass law action in attenuation of transmitted sound. (Stein & Reynolds, 1992, p. 1383)¹⁹

Based on a rule of thumb derived from the mass law, it is possible to rate various green roof systems based on their ability to block sound transmission into interior spaces.

Atop the roof itself, greening dampens the reflections and reverberations of sound common in urban settings. Theodore Osmundson (1999) listed this sound attenuation property as a public benefit of urban roof gardens. Porsche and Köhler (2003) quoted a study by Koch and Seitz (1998) that quantified this noise reduction capacity at approximately 2 to 3 dB when compared with a traditional gravel ballast roof. Again, in the absence of widespread testing, there is no reliable way to differentiate between green roof systems in terms of their dampening effects on

¹⁹Stein, B., & Reynolds, J.S.. *Mechanical and electrical equipment for buildings* (8th ed.). Copyright © 1992 by John Wiley and Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

ambient noise. A placeholder will be incorporated into the framework for green roof system selection in anticipation of possible future quantification of this parameter.

3.4. Structure

Structural loads frequently are controlling factors in green roof design. In retrofit applications, the existing roof structure must be carefully evaluated and reinforced if necessary prior to installing a green roof. As in the case of Chicago City Hall's roof, the green roof can be designed to take advantage of the greater load-bearing capacity of the roof structure above columns by placing deeper medium and larger plants only at these locations.

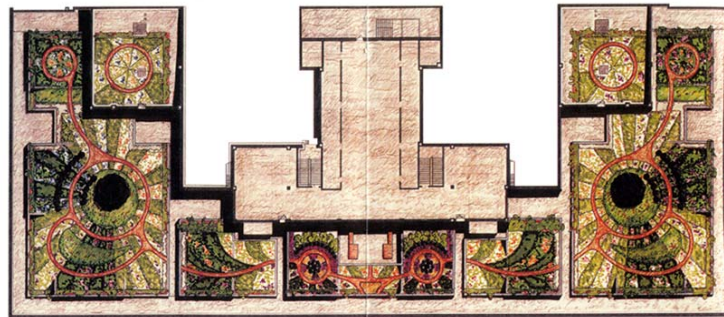


Figure 3.9 - Roof of Chicago City Hall with trees and deeper plantings located above building columns, image courtesy of City of Chicago, Department of Environment

To minimize green roof weights while providing sufficient depth to sustain plant life, a variety of lightweight manufactured growing media have been developed. In Germany, extensive green roofs often weigh no more than the typical gravel ballast roofs they replace, making them viable in re-roofing applications (Dunnett & Kingsbury, 2004). With intensive systems, plant weights also must be taken into consideration when determining green roof system loads.

In addition to conforming to weight restrictions, green roof systems must also resist the wind loads present at the roof surface. Strategies for wind resistance include parapet walls and photodegradable mesh, such as that used at the Life Expression Chiropractic Center in Hazleton, Pennsylvania, to protect the plants and growing medium from wind scour until the plants are fully established (Miller, 2002). Vertical structural loads are fairly easy to quantify; lighter green roof systems are generally preferred over heavier systems due to their compatibility with typical roof construction in North America. However, any index of performance must also take into account the effects of wind on plants and the potential for roof

membrane uplift. More robust, heavier systems or systems with protective meshes or other devices will likely perform better, especially during the critical plant establishment phase. However, degree of wind resistance is not a factor suitable for differentiating among alternatives; it is rather a binary factor. The designer need only determine whether or not a contemplated system meets or does not meet the wind resistance requirements for a particular project. This question will be incorporated into the framework as a criterion potentially limiting the range of alternatives from which the designer may select.

3.5. Compliance

The policy issues surrounding the implementation of green roofing are complex and largely beyond the purview of this investigation. However, when considering the viability of green roofing in North America, governmental incentives and regulatory requirements frequently become an important factor in the decision to employ vegetated roofing on a particular building. Therefore, this research will address the ability of green roofs to effectively satisfy or take advantage of the various regulatory requirements or policy incentives currently in place in various locales.

For example, the Code of Maryland Regulations stipulate that

(2) Unless otherwise specified by watershed management plans developed according to §E of this regulation, all redevelopment projects shall reduce existing site impervious area by at least 20 percent.

(3) Where site conditions prevent the reduction of impervious area, stormwater management practices shall be implemented to provide water quality control for at least 20 percent of the site's impervious area.

(4) When a combination of impervious area reduction and stormwater management practice implementation is used for redevelopment projects, the combination of impervious area reduction and the area controlled by a stormwater management practice shall equal or exceed 20 percent (Maryland Secretary of State, 2005)

Green roofs are a key method used to reduce a site's impervious area (MDE, 2004a), and were used at the Montgomery Park Business Center, which houses the offices of the Maryland Department of the Environment. Chicago, Portland and Toronto have also implemented policies encouraging roof greening, which in part explains the popularity of green roofing in those cities.

Examples of policy initiatives with some impact on green roof system selection are discussed in Section 3.5.1.

Because green roofs are relatively new phenomena in North America, their capacity to comply with building code issues such as roof access, life safety and fall protection also must be considered when assessing their feasibility. For instance, some jurisdictions are concerned with the potential flammability of plant materials and require a fire sprinkler system at the roof surface. Depending upon its design and maintenance requirements, a green roof can sometimes be considered as an occupied floor of a building by code officials. In these cases, the roof area factors into the allowable area calculation for the structure, and a minimum of two means of egress from the roof are required. These and other code stipulations can affect not only the type of green roof selected but can frequently affect the decision whether to implement a green roof or not. Because of the great variability of the codes in effect throughout North America, it is not feasible to evaluate green roof system types for code compliance. However, the framework should include some means of alerting designers to the possible ramifications of green roofs, to aid them in their project-specific code reviews. This topic is discussed in more detail in Section 3.5.2.

The U. S. Green Building Council's Leadership in Energy and Environmental Design (LEED) program has also catalyzed the use of green roofs on projects seeking certification. Green roofing enables designers to garner LEED points in several categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials & Resources (depending upon the green roof system components used), Innovation & Design Process, and potentially even Indoor Environmental Quality. As a growing number of governmental organizations adopt the use of LEED certification as a requirement of facility design, the green roofing industry stands to benefit. In fact, at a Roof Consultants Institute meeting held in Richmond, Virginia on May 6, 2004, Peter D'Antonio of Sarnafil, Inc., a leading thermoplastic PVC roof and waterproofing membrane manufacturer, claimed that the earning of LEED credits is the main catalyst for the green roofing industry in the United States. LEED is a numerical tool that can be used to rank project alternatives, but in this framework, LEED point ratings will be incorporated into a constructed attribute scale that will measure the capacity of green roofing to meet the criteria measured by the LEED rating system. Construction of attribute scales in general is discussed in Section 4.4.2, and the applicability of LEED to green roofing is explicated in Section 3.5.3.

3.5.1. Green Roof Policy Types and Examples

The main goal of policies related to green roofing is to encourage the widespread implementation of vegetated roofs so that their public benefits might be realized (Ngan, 2004). While a review of the history of green roofs in North America shows that they have often been implemented for private pleasure or gain, without the development of policies to support them, green roofs will likely not be built in sufficient numbers to provide appreciable benefits in terms of storm water abatement, heat island reduction, and other improvements to communities and ecosystems. This sub-section will sort green roof policy types into categories and introduce some specific, illustrative examples. While by no means comprehensive, this discussion will attempt to discover the patterns in the approach of various jurisdictions to valuing, rating, or otherwise encouraging the use of green roofs. A strategy for including these policy standards as decision-making criteria in the framework for green roof system selection will be proposed.

Goya Ngan (2004), in her investigation entitled *Green Roof Policies: Tools for Encouraging Sustainable Design*, divided green roof policies used in Germany into four broad categories. These are “direct financial incentives, indirect financial incentives, ecological compensation measures, and integration into development regulations” (p. 9). The following discussion is structured around these distinctions. In each policy category, Ngan provided specific examples of each type of policy as it is manifested in Germany. Following the German examples, a paper by Steven Peck and Dayna Goucher (2005) is referenced to demonstrate the degree to which green roof policy has gained a foothold in North America. Peck and Goucher conducted a survey of ten cities along with a review of the literature to identify existing green roof policies. They estimated that over 15 local governments have launched green roof policies in North America.

3.5.1.1. Direct Financial Incentives

In Germany, direct financial incentives are often offered by communities or city governments as subsidies to private citizens and developers for the construction of green roofs. These are frequently calculated in terms of a sum of money per square unit of area, or as a percentage of construction, or design and construction, cost. There are often limits to the amount funded, and restrictions on the types of systems that qualify for subsidies. Ngan (2004) related that minimum runoff coefficient (typically ≤ 0.3), minimum substrate thickness (differs according to locale), and provision of a long-term maintenance plan (typically 10 years) are usual qualifications, while less common requirements include disconnection from storm sewer

systems, maximum roof slope, PVC-free roof membranes, and specific types and minimum height of vegetation. Other direct financial incentives are aimed specifically at particular urban areas in need of greening.

While direct financial incentives to employ green roofs are rare in North America, there are examples of states and municipalities that provide tax credits for the use of green technologies in general. Most often, these tax credits are tied to requirements for buildings to meet criteria for Leadership in Energy and Environmental Design (LEED) certification. For example, in Oregon, the Business Energy Tax Credit offers a refund of 35% of the premium cost of environmentally responsible activities including the construction of “sustainable buildings”. The credit requires that the building achieve a minimum of LEED Silver certification and specific additional requirements. The credit is granted according to the building’s square footage, its LEED category (New commercial construction and major renovation projects, Core and shell projects, and Commercial interiors projects), and its LEED rating (Oregon Department of Energy, 2006). Similarly, Maryland uses LEED criteria, without requiring official LEED certification, to determine eligibility for its Green Building Tax Credit. This credit offsets 6 to 8% of “green” construction costs for buildings over 20,000 square feet (2,000 square meters) in priority funding areas (Maryland Energy Administration, 2006).

Green roofs are also eligible for another type of direct financial incentive based on their energy-conserving properties. Quebec’s Energy Board has pioneered a Green Roof Financial Incentive Program in an effort to control the demand for natural gas and promote energy-efficient technologies. As of September 26, 2003, one Canadian dollar (CND) per square foot of green roof area may be earned by clients of Gaz Metropolitain, the local supplier of natural gas. To be eligible, the green roof must cover over 60% of the project’s roof area and feature a minimum of 6 inches (150 mm) of growing medium (The Green Roof Infrastructure Monitor, 2003). At the national scale, the Commercial Building Incentive Program (CBIP) offered by the Office of Energy Efficiency, Natural Resources Canada, grants up to \$60,000 CND for new construction, addition, or renovation projects incorporating energy-saving systems or upgrades to the building envelope. A \$80,000 CND incentive is offered by the Industrial Buildings Incentive Program (IBIP) for new buildings representing a 25% savings in energy over a reference building, as calculated according to the Model National Energy Code for Buildings. (Mishra, 2004). While neither of these programs are focused on green roofs exclusively, according to Peck and Goucher (2005), four projects incorporating green roofs have been approved under the CBIP,

and green roofs have been officially acknowledged as an “energy efficiency measure” within the program. Mishra (2004) also described a governmental incentive called the Green Municipal Enabling Fund that supports feasibility studies for new environmental technologies, and Environment Canada’s EcoAction program that supports efforts of non-profit organizations that seek to provide positive environmental influences in their communities.

Various municipalities, non-profit organizations, and private organizations support green roofing as part of a wider environmental, fiscal, or social agenda. Peck and Goucher (2005) cited Chicago’s Urban Heat Island Initiative, which seeks to reduce heating and cooling loads by supporting the implementation of green roofs and other strategies, Earth Pledge’s funding of green roofing on affordable housing in New York, the Trillium Foundation’s contribution to green roofing on cooperative housing in Toronto, and the Chesapeake Bay Foundation’s support of green roof projects in the Anacostia watershed. Financial support of green roofs often comes in the form of donated materials in addition to cash contributions. For example, in a life cycle cost analysis of the green roof at Portland’s Multnomah County headquarters, Lee (2004) showed that combined financial and material contributions caused the green roof to be less costly than a conventional roof over a 60 year life cycle, while without the contributions, the conventional roof was less expensive. In an atypical case of involuntary direct funding, the green roofs at Chicago City Hall and the Chicago Center for Green Technology were subsidized by the city’s legal settlement with the electrical utility Commonwealth Edison (Kevin Laberge, personal communication, July 16, 2004). The wide range shown in these few examples shows that the nature of direct funding sources can be as diverse as the character of green roof projects themselves.

3.5.1.2. *Indirect Financial Incentives*

Indirect financial incentives in Germany are most often found in the form of split wastewater fees. Rather than pay for sanitary and storm sewer infrastructure costs simply by charging land owners a fee based on potable water supplied to the site, some municipalities in Germany charge two fees: a fee for disposal of sanitary waste based on water consumption, and a separate storm water fee based on the quantity of impervious area on a site. This approach is taken in an effort to make land owners more accountable for the amount of storm water flowing off of their sites, and to encourage control of storm water on site where possible. The benefits of this system are social, economic and environmental. Dwellers of multi-family residential buildings where land use per capita is small are not forced to bear an unfair share of the public

cost of storm water management, and land owners seeking to reduce their storm water fees are induced to use methods that reduce both peak flow and volume of storm water. Where this occurs, infrastructure and flood control needs are reduced, and pollution from combined sewer overflows is less likely (Ngan, 2004). Those who implement storm water control strategies often pay discounted storm water fees, and those who are able to disconnect from the public storm sewer system may avoid the storm water fee altogether. Green roofs are sometimes eligible for a storm water fee discount for the portion of the site they cover. The thickness of the green roof substrate, or the runoff coefficient of the green roof, discussed in Section 3.1.1, often impacts the degree of discount for which the roof qualifies, with a typical extensive green roof achieving a discount of 50%.

Such transparent financial accountability for individual contribution to storm water loads is rare in North America. Ngan (2004) cited Moffatt's (2001) description of the main economic barrier in Canada to implementation of policies such as split wastewater fees:

The very substantial capital outlays that have been dedicated to existing infrastructure can eliminate the potential for cost savings from Green infrastructure. Sometimes property taxes are already predicated on paying for larger, centralized systems, and thus anyone who invests more money to reduce reliance on upon such systems ends up paying twice.

Despite this barrier, there are examples of municipalities working toward implementation of storm water fee reduction incentives. Peck and Goucher (2005) pointed to Minneapolis and Portland as cities with recently introduced and currently developing storm water utility credit programs, respectively. Green roofs are eligible for credits in these programs due to their status as accepted storm water best management practices in these cities (Moffatt, 2001, p. 36).

3.5.1.3. *Ecological Compensation Measures*

An integrated collection of German federal laws known as the "Intervention Rule" requires municipalities to adopt a decision-making process for both land use and development that deals with the environmental impact of a constructed "intervention". Interventions are defined as "any changes affecting the appearance or use of areas which lead to considerable or lasting impairment of the efficiency of the balance of nature or the natural scenery" (BNatSchG §8 (1), as translated by Ngan, 2004). The rule leads the decision-maker through a series of questions

which, when answered affirmatively, point to the required solution to resolve the negative impact of any intervention.

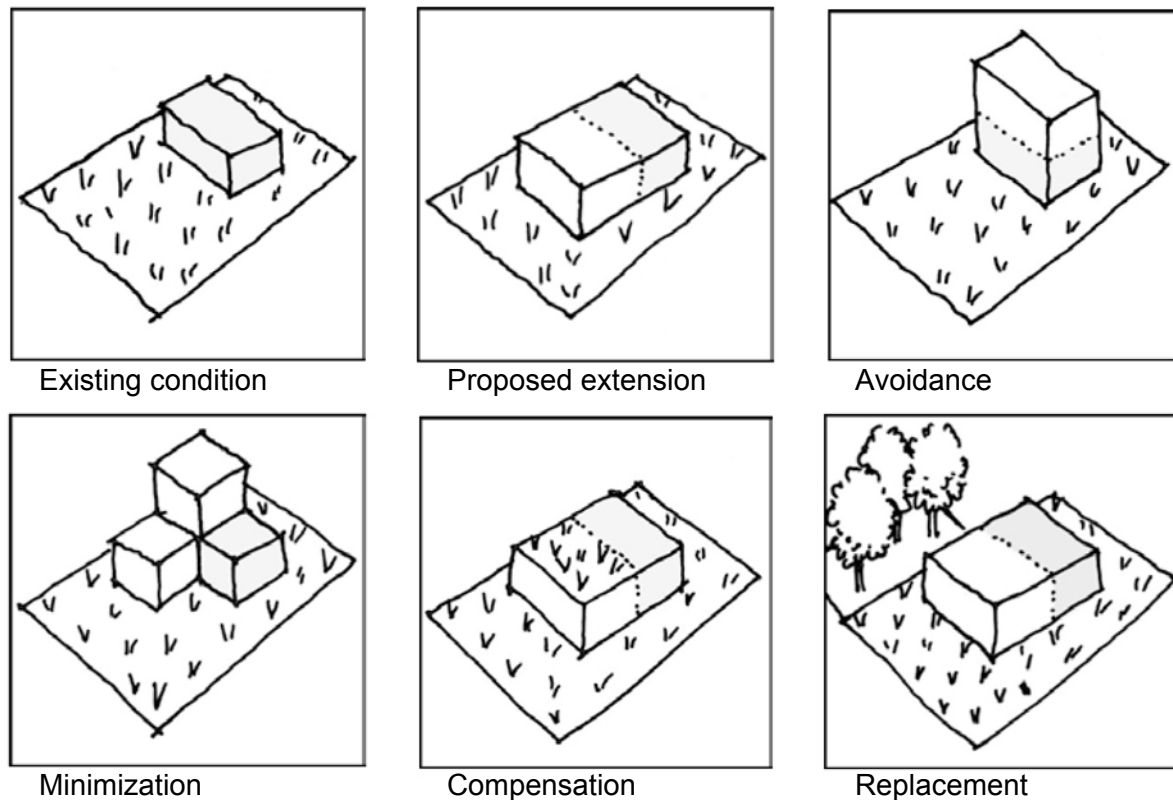


Figure 3.10 - Responses to environmental intervention (Ngan, 2004, pp. 24-35), permission to use granted by: Goya Ngan (Feb. 10, 2007)

In the diagrams in Figure 3.10, Ngan succinctly portrayed the preferred series of approved solutions to an environmental intervention as laid out in the Intervention Rule. A generic existing structure is shown at the top left, with a hypothetical proposed extension shown at the top center. First, it must be determined whether the intervention can be avoided, as shown in the top right diagram. If this is not possible, the designer must attempt to minimize the intervention, as seen at the bottom left. Again, if this is not possible, the designer must consider ways to compensate for the intervention on site, as show in the bottom center drawing, or replace in some way the natural environment that is lost as a result of the project going forward. This often takes the form of off-site nature restoration projects or financial contributions to such efforts. If none of the aforementioned solutions are viable, the project will not be approved.

Green roofs fit into the “compensation” category of the Intervention Rule. The FLL performance rating system discussed in Section 4.4.5 has been proposed as a method for determining whether or not a particular green roof can be expected to compensate for a particular intervention, not only in the short term, but over an extended period. Ngan (2004) observed that this compensation is often difficult to prove. Additionally, only certain municipalities in Germany, not the federal government, officially consider green roofs ecological compensation measures. However, the Intervention Rule, like the split wastewater fee system, does provide a legal climate supporting accountability for environmental impacts of construction projects and other disturbances.

In North America, formal acknowledgement of green roofs as ecological compensation measures is virtually non-existent. In one attempt to remedy this situation, the City of Waterloo, Ontario, has conducted a feasibility study to, among other objectives, determine if green roofs might qualify as “green spaces” (Moyer, 2005). A minimum of 5% green space is required on all development projects in Ontario (Peck & Goucher, 2005). Karen Moyer (2005) argued that since green spaces have traditionally been defined as public park area, green roofs might be considered viable green spaces only if they provide a visual amenity to the public. The highest potential for this situation is in urban areas where green roofs may be viewed by surrounding high-rise buildings. Obviously, the amenity value would be greater if the roofs were also physically accessible to the public; the City of Waterloo has also undertaken an investigation of the accessibility of green roofs in the attempt to draw meaningful conclusions about their potential use as green space.

3.5.1.4. *Integration into Development Regulations*

The final category of policy initiatives in Germany discussed by Ngan (2004) is the incorporation of green roofs or similar strategies into local laws governing development. She stated that, of the four strategies, this is the only one that is compulsory rather than voluntary, and that it is often combined with voluntary incentive programs. Green roofs are included in development regulations in a variety of ways. They may be specified as a part of legally binding development plans or required as compensation for high density land-use types. In some municipalities, the roofs of certain types of buildings are required to be greened, for example, buildings with roof slopes under a certain maximum pitch, public buildings, and buildings located on the urban fringe. Where these requirements exist, they generally are accompanied by performance

requirements for the green roof, with the *FLL Guideline* (2002) often invoked as a design standard.

Similar strategies are in their infancy in North America. Structured in a similar fashion to the mandatory German development regulations, one popular North American strategy called “density bonusing” is offered as an incentive for developers to maximize the earning potential of new construction in specific areas, and to offset the higher first costs of green roof technologies (Peck & Goucher, 2005). Often density bonusing is granted in the form of floor area ratio (FAR) increases. Floor Area Ratio is generally defined as the total floor area of a building divided by the area of its site. Essentially, these FAR bonuses allow property developers who meet certain requirements to exceed the maximum amount of floor area that may be built in a particular area.

Marie Johnson (2004), Senior Planner with the City of Portland, reported that in December 2000, the Portland City Council began to grant a density bonus for the use of eco-roofs in the Central City Plan District area. According to Portland’s zoning code, eco-roofs are considered “a rooftop stormwater facility”. The incentive, known as the Eco-Roof Bonus, is structured as follows:

Where the total area of the green roof is at least 10 percent but less than 30 percent of the building’s footprint, each square foot of green roof earns one square foot of additional floor area.

Where the total area of the green roof is at least 30 percent but less than 60 percent of the building’s footprint, each square foot of green roof earns two square feet of additional floor area.

Where the total green roof area is 60 percent or more of the building’s footprint, each square foot of green roof earns three square feet of additional floor area (The Green Roof Infrastructure Monitor, 2001, pp. 1-2).

Johnson (2004) also stated that parties taking advantage of the incentive must sign a covenant with the City of Portland to properly construct and maintain a viable green roof on the property in question, and that the eco-roof design must be approved by the Portland Bureau of Environmental Services. The measure is the first of its kind in North America, and its success as an incentive to construct green roofs is based largely on the market value of real estate in the affected area (GRIM, 2001).

The City of Chicago also provides developers with a floor area ratio (FAR) increase when they include green roofs on their projects. The Zoning Ordinance reads as follows:

17-4-1015-A Eligibility and Standards

Buildings with green roofs are eligible for floor area bonuses, provided they meet the following minimum standards:

1. The site for which the floor area bonus is requested must be located in a dash 12 or dash 16 “D” district.
2. To be eligible for floor area bonus, a green roof must cover more than 50 percent of the net roof area (i.e., the total gross area of the roof minus any roof area covered by mechanical equipment) or 2,000 square feet of contiguous roof area, whichever is greater.
3. Documentation must be submitted demonstrating that the roof can support the additional load of plants, soil, and retained water, and that an adequate soil depth will be provided for plants to thrive.
4. The roof area must contain sufficient space for future installations (e.g., mechanical equipment) that will prevent adverse impacts (e.g., removal of or damage to plants or reduction in area) on the green roof.
5. Plant varieties, soil depths and soil content must comply with Chicago Department of Environment guidelines.
6. Vegetation must be maintained for the life of the building.
7. Green roofs are subject to periodic inspection by the Department of Zoning to ensure that the amenity is properly maintained.
8. Private decks or terraces associated with individual *dwelling units* may [sic] do not qualify for floor area bonuses.

17-4-1015-B Bonus Formula

The floor area bonus for qualifying green roofs is calculated as follows: Bonus FAR = (area of roof landscaping in excess of 50 percent of net roof area / lot area) X 0.30 X Base FAR (City of Chicago, 2006a).

The maximum bonus achievable with this formula is 2 FAR (City of Chicago, 2006b), which is added to the Base FAR for the building. The first criterion limits the application of the bonus to the densest districts in the city, those with a maximum FAR of 12 and 16, respectively. As with Portland’s Eco-Roof Bonus, the remaining criteria of the bonus seek to ensure that the green roofs meet certain minimum standards and remain viable throughout the building’s life span.

Certain federal agencies in the United States, along with many state and local governments in both the U.S. and Canada, have begun requiring LEED certification for buildings meeting specific criteria (Peck and Goucher, 2005). While achieving LEED certification does not necessarily require the incorporation of a green roof, green roofs are viewed by many in the design community as an efficient way to satisfy some LEED requirements, as discussed in Section 3.5.3.

Another regulation with an impact on development is the Clean Water Act implemented by the United States Environmental Protection Agency (EPA). The Clean Water Act is the 1977 amended form of the 1972 Federal Water Pollution Control Act Amendments (EPA, 2006). Extensively revised and expanded with the 1987 Amendments, the law's far-reaching implications include efforts to control the release of both point and nonpoint source pollutants into U. S. and Canadian waters. The law is relevant to the implementation of green roofs insofar as they may be considered storm water best management practices. Green roofs, by reducing roof runoff volume, have the capacity to mitigate point source pollution by reducing the occurrence of combined sewer overflows (CSOs). They also have the potential to limit nonpoint source pollution by reducing pollutant loads into waters receiving roof runoff. These properties are discussed more fully in Section 3.1.

3.5.1.5. *Additional Strategies and Tools*

Ngan concluded her discussion of green roof policy in Germany with a list of miscellaneous additional strategies and tools used to encourage the implementation of green roofs, including design competitions, strategic media coverage of roof greening, greening of government buildings as examples, investigations into the embodied energy of green roof systems, and the development of performance rating systems. As discussed in Section 4.4.5, while not consistent or universal in application, performance rating systems have been important in determining whether or not green roofs meet the requirements of green roof policy initiatives, and if they do, to what degree.

Some of these strategies and tools have also been used in North America. Green Roofs for Healthy Cities selects green roof design projects for distinction in an annual awards ceremony. The green roof on the Ford Rouge plant in Dearborn, Michigan has received extensive media coverage, and is a feature of the popular factory tour of the truck plant. The Chicago City Hall, the Multnomah County building in Portland, Oregon, the Toronto City Hall, the Atlanta City Hall,

and other municipal buildings incorporate green roofs in an attempt to both demonstrate and encourage this technology. Although ecological impacts of green roof systems have not been specifically determined, nor have official performance guidelines for these systems been set, there is a great deal of interest in these topics. While organizations like ASTM work toward development of official green roof requirements in North America, the German *FLL Guideline* (2002) is frequently referenced as the best existing resource for green roof design and implementation. As of summer 2007, ASTM has approved and released five standards related to green roof technologies: E2396, Standard Test Method for Saturated Water Permeability of Granular Drainage Media [Falling-Head Method] for Green Roof Systems; E2397, Standard Practice for Determination of Dead Loads and Live Loads associated with Green Roof Systems; E2398, Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Green Roof Systems; E2399, Standard Test Method for Maximum Media Density for Dead Load Analysis of Green Roof Systems; and E2400, Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems. Future standards addressing the “Selection, Installation and Maintenance of Plants”, “Use of Expanded Shale, Clay or Slate as a mineral component in growing media”, and a standard for assessing green roofs are currently in various stages of creation and revision (Berghage, 2005).

In addition to the strategies outlined by Ngan, Peck and Goucher (2005) discussed the fast-tracking of government approvals for projects including green features in Chicago, and the adoption of LEED standards as both a procurement and tax credit incentive in federal, state, provincial and municipal jurisdictions, as catalysts for the green roofing industry. Michael Berkshire (2005) of Chicago’s Department of Planning reported that projects meeting “green” criteria will be evaluated by a team of building officials familiar with green technology, using the city’s new green building code which permits certain elements banned by the regular code. As an additional incentive, these projects will ideally be shunted through the approval process in under 30 days. This process has been introduced, but its success is not yet known. More common and widely accepted is the role that LEED has played in supporting green roof implementation. This topic is discussed in Section 3.5.3.

3.5.1.6. Summary

While the range of policy initiatives supporting vegetated roofing is diverse and specific to both location and project, there are several attributes of green roof systems that are repeated in the language of many such policies. These tend to reward the use of certain systems over others,

and to reward green roofs over traditional roofs. These attributes include the depth of the growing medium and the area or the percentage of total roof area a green roof occupies on the roof. Before these attributes are examined, it is productive to introduce a checklist of questions that, if answered affirmatively, make this analysis worthwhile. If no green roof incentives or other policies are relevant to the project in question, this parameter of the framework can be circumvented, saving the designer time and energy. Examples of such binary questions drawn from this section's discussion include:

Do the building's size and use category make it eligible for a tax credit involving green roofs?

Where LEED certification is anticipated, can the green roof contribute to LEED certification requirements?

Is the project located in a priority area where financial incentives for green roofs are offered?

Can the green roof's energy benefits be demonstrated to the satisfaction of the local building officials?

Are there any organizations who might financially support the installation of a green roof on this project?

Is there a storm water utility credit program in the project's jurisdiction?

Will the green roof as proposed qualify for a FAR bonus useful to the developer or owner of the building?

Are green roofs considered a storm water BMP in the project's jurisdiction?

Will the developer or owner gain prestige or credibility if a green roof is used?

Will inclusion of a green roof save time or avoid obstacles in permitting?

Negative responses to these questions do not necessarily mitigate against employing vegetated roofing, they merely negate the influence of certain policy questions on the decision of which type of roof system to use. Where LEED certification is deemed important, the user of the framework will be directed to a separate parameter where these issues are addressed more fully (see Section 3.5.3).

3.5.2. Code Review

The influence of building codes on vegetated roofing system selection is highly project-specific. Because roofs can never be considered in complete isolation from the buildings they cover, it is difficult to isolate factors which might influence the decision to employ a green roof, or to help decide which type of green roof might most effectively meet code requirements. Despite this

difficulty, there are a few case studies within the existing literature that point to issues which should at least be considered during the process of green roof design. These are reviewed below, with allusions to the relevant sections of the 2006 International Building Code (IBC) and the 2006 International Plumbing Code (IPC) authored by the International Code Council (ICC). These codes are adopted widely by jurisdictions within North America, often with addenda or modifications to account for local conditions. While it is impossible to account for all the possible code variations in different locales and projects, the following discussion aims to alert the designer to some of the relevant issues raised by the building code, and determine their effects, if any, on the design of green roofs.

3.5.2.1. *Structural Requirements*

Charlie Miller, P.E. (2006), a widely recognized green roof expert and president of Roofscapes, Inc., asserted that green roofs must often meet the requirements of ballasted roofs, and stated that roof gardens are recognized by the ICC with sections that address the dead and live loads incurred with the use of these systems. According to the IBC:

1607.11.2.3 Landscaped roofs. Where roofs are to be landscaped, the uniform design live load in the landscaped area shall be 20 psf (0.958 kN/m²). The weight of the landscaping materials shall be considered as dead load and shall be computed on the basis of saturation of the soil. (ICC, 2006a, p. 288)

IBC's Table 1607.1, Minimum Uniformly Distributed Live Loads and Minimum Concentrated Live Loads, assigns a uniform live load of 100 pounds per square foot to "Roofs used for roof gardens or assembly purposes" (p. 285).

Additionally, all "roofs subject to maintenance workers" (p. 285) must support a concentrated load of 300 pounds (140 kilograms).

3.5.2.2. *Edge Protection*

Miller (2006) also mentioned requirements for parapets and guards. Whether or not a parapet is required by the IBC at a roof edge, and the height and makeup of that parapet when required, are functions of the area of a building, the degree of fire resistance of its various elements, its separation distance from other structures, and the location of roof openings where relevant.

The requirements for guards are also complex:

1013.1 Where required. Guards shall be located along open-sided walking surfaces, mezzanines, industrial equipment platforms, stairways, ramps and landings that are

located more than 30 inches (762 mm) above the floor or grade below (ICC, 2006a, p. 217).

While there are some exceptions, guards in general must be 42 inches (1076 mm) high, with strict requirements governing the permissible size of openings in the guard depending upon their use and the occupancy of the building or area in which they are employed.

1013.3 Opening limitations. Open guards shall have balusters or ornamental patterns such that a 4-inch-diameter (102 mm) sphere cannot pass through any opening up to a height of 34 inches (864 mm). From a height of 34 inches (864 mm) to 42 inches (1067 mm) above the adjacent walking surfaces, a sphere 8 inches (203 mm) in diameter shall not pass (ICC, 2006a, p. 217).

There are separate, specific requirements for mechanical equipment and roof access, as follows:

1013.5 Mechanical equipment. Guards shall be provided where appliances, equipment, fans, roof hatch openings or other components that require service are located within 10 feet (3048 mm) of a roof edge or open side of a walking surface and such edge or walking surface is located more than 30 inches (762 mm) above the floor, roof, or grade below. The guard shall be constructed so as to prevent the passage of a 21-inch-diameter (533 mm) sphere. The guard shall extend not less than 30 inches (762 mm) beyond each end of such appliance, equipment, fan or component.

1013.6 Roof access. Guards shall be provided where the roof hatch opening is located within 10 feet (3048) of a roof edge or open side of a walking surface... (ICC, 2006a, p. 218).

While roof gardens or other types of green roofs are not expressly mentioned, it is implied that roofs designed to be occupied for activities other than service functions must be fitted with guards to protect the occupants. Osmundson (1999) discussed the need for 42 inch (1076 mm) high guards at the edges of roof gardens, with openings designed to protect children. These requirements are more stringent than those for areas only trafficked by maintenance personnel. The decision to make a roof habitable or not may have a significant impact on the cost required to protect the edges of the roof.

3.5.2.3. **Occupancy Classification, Egress Requirements, and Accessibility**

Kathy Bash (2004) alluded to another requirement of the IBC that is somewhat dependent upon local interpretation and the size of the green roof contemplated. In a case study of the Brewery Block 4 Ecoroof in Portland, Oregon, the original intent to provide an accessible ecoroof was abandoned due to the local interpretation of an ecoroof as an assembly area, which would have required two means of egress. The roof was reconceived as a visual amenity for occupants of overlooking floors. The IBC provides the following:

1015.1 Exit or exit access doorways required. Two exits or exit access doorways from any space shall be provided where one of the following conditions exists:

1. The occupant load of the space exceeds the values in Table 1015.1.
2. The common path of egress travel exceeds the limitations of Section 1014.3.²⁰
3. Where required by Sections 1015.3, 1015.4 and 1015.5.²¹

Exception: Group I-2 occupancies shall comply with Section 1014.2.2 (ICC, 2006a, p. 220).

Table 3.5 - Table 1015.1 Spaces with one means of egress (ICC, 2006a, p. 220), permission to use granted by: Carol Petry-Johnson, International Code Council (Feb. 20, 2007)

OCCUPANCY	MAXIMUM OCCUPANT LOAD
A, B, E ^a , F, M, U	49
H-1, H-2, H-3	3
H-4, H-5, I-1, I-3, I-4, R	10
S	29

a. Day care maximum occupant load is 10.

Determining occupancy type of a given space is not always a straightforward procedure; for example, the IBC states:

1004.8 Outdoor areas. Yards, patios, courts and similar outdoor areas accessible to and usable by the building occupants shall be provided with means of egress as required by this chapter. The occupant load of such outdoor areas shall be assigned by the building official in accordance with the anticipated use....

²⁰ Essentially, the “common path of egress travel” is the distance one must travel before “two separate and distinct paths of egress travel to two exits are available” (ICC, 2006a, p. 201). This varies by occupancy type and whether or not the space is fitted with automatic fire sprinklers.

²¹ These sections do not apply to roofs.

Exceptions:

1. Outdoor areas used exclusively for service of the building need only have one means of egress.
2. Both outdoor areas associated with Group R-3 and individual dwelling units of Group R-2 (ICC, 2006a, p. 204).

Often the building official will determine which occupancy classification to assign to a space. This decision determines the maximum occupant load, and therefore the number of means of egress required. In cases such as the Brewery Block 4 Ecoroof, where the green roof was a retrofit, the complications of adding additional means of egress to an existing building may simply preclude providing an occupied roof garden. Even in new construction, requiring two or even one code-compliant means of egress from an occupied roof may prove cost-prohibitive.

Access to an unoccupied roof is less demanding:

1009.1 Stairway to roof. In buildings located four or more stories in height above grade plane, one stairway shall extend to the roof surface, unless the roof has a slope steeper than four units vertical in 12 units horizontal (33-percent slope). In buildings without an occupied roof, access to the roof from the top story shall be permitted to be by an alternating tread device.

1009.11.1 Roof access. Where a stairway is provided to a roof, access to the roof shall be provided through a penthouse complying with Section 1509.2.

Exception: In buildings without an occupied roof, access to the roof shall be permitted to be a roof hatch or trap door not less than 16 square foot (1.5 m²) in area and having a minimum dimension of 2 feet (610 mm) (ICC, 2006a, p. 214).

Local codes may also impact the number of means of egress required; in a case study of the green roof at Bank One Center (BOC) in Chicago, architect Matthew W. Kuhl (2004) related that although BOC is a 'green roof' and not a 'rooftop garden', with access limited to the public, city planning code required two means of egress in the form of stair towers from the area. Due to separation distance requirements for means of egress, both stairs had to be a considerable distance apart, requiring two distinct penthouse elements (p. 212).

In many of the case study projects examined in this dissertation, egress and edge protection requirements prevented the green roof from being occupied. Theodore Osmundson (1999), whose text largely considered intensive vegetated roofs in lieu of contemporary extensive systems, warned that in his experience, local codes almost always require two means of egress from roof gardens.

Two potential code-related complications presented themselves in the green roof project at Chicago City Hall, impeding the permitting process. These were circumvented by the project team when they asserted that the roof would be closed to the public. First, the city's code would have required extension of 31 plumbing vents to a height of 6'-6" (2.0 meters) above the roof surface (Kevin Laberge, personal communication, July 16, 2004). A similar requirement can be found in the International Plumbing Code (IPC):

904.1 Roof extension. All open vent pipes that extend through a roof shall be terminated at least [NUMBER]²² inches (mm) above the roof, except that where a roof is to be used for any purpose other than weather protection, the vent extensions shall be run at least 7 feet (2134 mm) above the roof (ICC, 2006b, p. 69).

The extended vents would have greatly detracted from the roof's aesthetic value.

Second, the roof garden would have needed to meet accessibility requirements of the Americans with Disabilities Act, which would have likely meant radical changes to the proposed design. Declaring the roof unoccupied avoided a host of monetary and semantic problems for this retrofit project.

3.5.2.4. Roof Gardens As An Additional Story

Steven L. Cantor (2005) specifically and minutely addressed the residential, urban green roof market in his analysis of traditional versus modern green roofs in New York City. He raised the issue of highly articulated green roofs, such as those incorporating pergolas, being viewed as penthouses by local code officials. If sufficient in area, such spaces need to be treated as an additional story of the building, rarely a desirable situation since the number of stories a building comprises affects many requirements regarding required fire resistance ratings, allowable floor areas, and construction types. In new construction, if the roof is considered a story in a building where height restrictions are critical, the potential rentable space may be reduced by including a vegetated roof. According to Section 1509.2 of the IBC:

The aggregate area of penthouses and other rooftop structures shall not exceed one-third the area of the supporting roof. A penthouse, bulkhead or other similar projection above the roof shall not be used for purposes other than shelter of mechanical equipment or shelter of vertical shaft openings.... Penthouses or bulkheads used for

²²The IPC provides a sample ordinance for its adoption by a jurisdiction. This ordinance specifically requires the jurisdiction to name the number of inches vent pipes must extend. This number varies by geographical location (Woodson, 2004).

purposes other than permitted by this section shall conform to the requirements of this code for an additional story (ICC, 2006a, p. 275).

Osmundson (1999) warned that despite the fact that roof gardens are not conditioned, nor enclosed, nor separately accessed spaces, many are considered a separate story by building officials. He cautioned roof designers to investigate local requirements.

3.5.2.5. Fire Risk

Cantor (2005) discussed local regulations in New York City that limit the amount of combustible materials on a roof, because roofs must be accessible to emergency rescue workers.

Osmundson (1999) stated that no wood construction is permitted in roof gardens, which is true for construction types employed on most large buildings. The IBC (ICC, 2006a) states that roofs, with a few exceptions, must be classified as Class A, B, or C, defined as effective against severe fire, moderate or light fire-test exposure, respectively. These classifications are determined by testing the roofing assembly with methods described in ASTM E 108 or UL 790. At present, there are no test methods in North America applicable to vegetated roofing. There have been a range of responses to the potential flammability of green roof systems by building officials, who in the absence of roof classifications find themselves in the position of determining whether or not such systems shall be permitted within their jurisdictions. In their *Design Guidelines for Green Roofs*, Peck and Kuhn (2000) related that European manufacturers provide some data indicating that green roofs are fire retardant when saturated. However, since drought conditions must also be considered, German codes require non-combustible fire breaks such as gravel or concrete paver paths at 130-foot (40-meter) intervals and at roof perimeters and penetrations. John White (2001) of the Garland Company contributed that the German codes require lightning rods atop roofs, and that it is common to combine sedums or other plants that have a high moisture content with native grasses that are more flammable. White (2001) claimed that North American insurance companies have not identified green roofs as posing a high fire risk, but he suggested adopting the German strategies where minimizing fire risk is particularly critical. He called for additional research on the fire-retardant capacities of various green roof plants, and suggested the use of a fire sprinkler system to limit the spread of fires should they occur.

Kevin Burke (2003) of William McDonough + Partners related the process of convincing local officials to permit the construction of the native grassland roof atop GAP's 901 Cherry headquarters. The main concern was the possibility of fireworks igniting the vegetation. To

satisfy the fire department's need for rooftop access, ladders and roof hatches along with fire hoses were spaced throughout the field of the roof to assure adequate coverage in the event of a fire. An irrigation system was included and provisions were made to trim the grass just prior to each Fourth of July celebration as an additional preventative measure.

3.5.2.6. Roof Drainage

The layout and sizing of roof drainage systems are governed by plumbing codes. As stated in the International Plumbing Code (2006b),

1106.1 General. The size of the vertical conductors and leaders, building storm drains, building storm sewers, and any horizontal branches of such drains or sewers shall be based on the 100-year hourly rainfall rate indicated in Figure 1106.1 or on other rainfall rates determined from approved local weather data²³ (ICC, 2006b, p. 82).

Green roofs significantly reduce the average volume of roof runoff and frequently the velocity of such runoff as compared to traditional roofs. However, during a lengthy or intense storm, green roofs may become saturated, allowing a high percentage of incident rain to flow through the green roof assembly to the waterproofing beneath. Because drainage systems must be designed to avoid structural failure due to ponding water, reductions usually cannot be made to the required size and positioning of these drainage elements. Even if a green roof system were proven to consistently and reliably reduce the volume and rate of roof runoff, designers must consider the possibility of future changes to the roof's function within the lifespan of the building. Kuhl (2004) explained that possible, though unlikely, future removal of the green roof at the Bank One Center in Chicago was the reason for designing roof drainage to the standards required of a traditional roof.

In certain cases, however, the cost of roof drainage systems can be reduced if runoff is permitted to flow off of roof edges to the ground below. There is provision in the IPC for such a scenario,

1101.2 Where required. All roofs, paved areas, yards, courts and courtyards shall drain into a separate storm sewer system, or a combined sewer system, or to an approved place of disposal. For one- and two-family dwellings, and where approved,

²³ Appendix B of the International Plumbing Code gives specific 100-year, 1-hour rainfall in inches for certain U.S. cities as derived from Figure 1106.1, which is a series of maps depicting contour lines that establish rainfall in various areas.

storm water is permitted to discharge onto flat areas, such as streets or lawns, provided that the storm water flows away from the building (ICC, 2006b, p. 81).

At the Life Expression Chiropractic Center in Hazleton, PA, roof runoff flows through gapped fascias at the eaves in an intentional celebration of natural processes that aligns with the building's program (Earth Pledge, 2005). The Satellite Operations Facility for the U. S. National Oceanic and Atmospheric Administration uses the same strategy at a much larger scale. The project incorporates a 146,000-square-foot (13,560-square-meter) green roof. At its north and east perimeter, runoff flows off the domed roof onto earth berms and is captured by underground perforated pipe. At the southern perimeter, a system of scuppers discharging into gravel pits more dramatically highlights runoff events. Through the use of these edge strategies, the number of internal roof drains needed in the project is greatly reduced (Gehley & Rindlaub, 2004). While some means of dealing with roof drainage must always be provided, these projects demonstrate how expensive internal roof drainage systems can be minimized or eliminated when the green roof is coupled with strategies for storm water management at or below grade.

3.5.2.7. Reroofing

Kevin Laberge (2003), an engineer with the Chicago Department of Environment, discussed code-related issues that added cost and potential permitting difficulty to the green roof project at Chicago City Hall. The first of these was the unforeseen cost of removing the existing roof membrane before installing the green roof on this historic building. Laberge reports that this was necessitated by Chicago's Building Code, but the requirement to remove existing roof membranes is quite common on retrofit projects and must be considered as part of the initial cost of a green roof where applicable. The IBC states:

1510.3 Recovering versus replacement. New roof coverings shall not be installed without first removing all existing layers of roof coverings where any of the following conditions occur:

1. Where the existing roof or roof covering is water soaked or has deteriorated to the point that the existing roof or roof covering is not adequate as a base for additional roofing.
2. Where the existing roof covering is wood shake, slate, clay, cement or asbestos-cement tile.
3. Where the existing roof has two or more applications of any type of roof covering (ICC, 2006a, p. 276).

There are three exceptions to Section 1510.3, but these refer to roofing systems that cannot be construed to include any vegetated roof system currently available.

There is some relief offered by the code for reroofing applications; according to the exception to IBC Section 1510.1, “Reroofing shall not be required to meet the minimum design slope requirement of one-quarter unit vertical in 12 units horizontal (2-percent slope) in Section 1507 for roofs that provide positive drainage” (p. 276). Positive roof drainage is defined in the IBC as “the drainage condition in which consideration has been made for all loading deflections of the roof deck, and additional slope has been provided to ensure drainage of the roof within 48 hours of precipitation” (p. 263). Anecdotal evidence would suggest that green roofs can suffer from the effects of ponding water, as in the case of the Brewery Block 4 Ecoroof in Portland, Oregon presented by Bash (2004). In this project, the flanges of roof drains, which were set one inch (25 mm) above the surface of the roof membrane as a result of a coordination error, allowed water to pool in the areas surrounding the drains. As a remedy, the media and plant layers of the ecoroof were elevated above these areas of ponding with spaced rigid insulation and a specialized drainage layers. Despite this correction, portions of the green roof near the drains remained saturated for extended periods of time and suffered plant loss and growth of moss and algae. This circumstance led to a design revision on subsequent projects and serves as a caution to designers to minimize temporary ponding, even when it is permitted by code on reroofing projects.

3.5.2.8. *Other Considerations*

Cantor (2005) related that in urban areas, co-op boards play an additional regulatory role. These groups may have their own set of requirements intended to protect the tenants of a building at large, most of whom will not enjoy the benefits of the proposed green roof. These regulations tend to limit any new roof penetrations and added weight represented by a roof garden, and may require arguably superfluous additional protection to the roof. While urban residential roof gardens are a small segment of the overall modern green roof market, the difficulties encountered with their implementation serve as red flags alerting green roof designers to potential issues they may encounter depending upon the type of green roof proposed.

3.5.2.9. Summary

As seen in the preceding discussion, many of the code-related issues in green roofing design center around structural soundness, life safety and fire safety. These issues in turn often depend on whether or not, and to what degree, a roof is accessible. Cantor (2005) summarized the conundrum faced by designers and owners when deciding whether to include an extensive, uninhabited roof or an intensive, occupied roof in a project. He submitted that in areas such as Manhattan, the additional difficulties concomitant with true roof gardens are outweighed by the amenity value they afford. In his view, green roofs in general would be more readily supported, and funds for their upkeep, whether public or private, would be more easily raised if they were accessible to the public. Others considering green roofs of a different nature, or in a different locale, may reach other conclusions.

Rather than attempt to quantify attributes of particular vegetated roofing system types as they relate to code compliance, a list of applicable topics to be researched as part of the code review process undertaken during building design is presented as an influence diagram, shown in Figure 3.11. Because most code requirements center around design issues rather than issues of roof system selection, this diagram is not currently tied to the framework described in Chapter 5. Instead, it may be used as a checklist of related questions to be used during the process of green roof design.

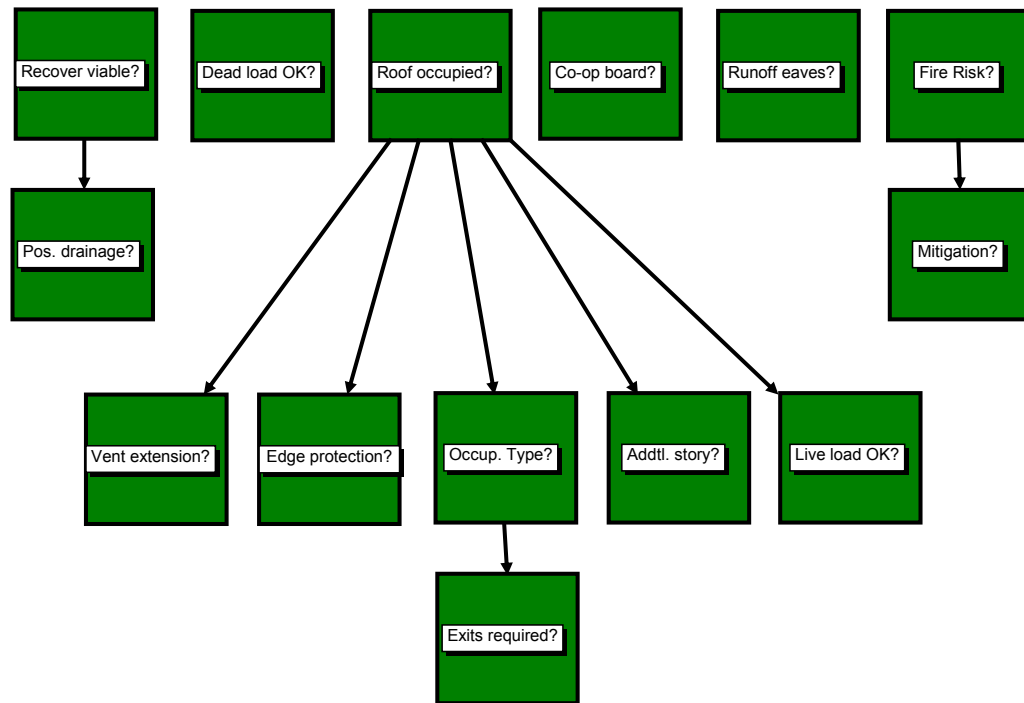


Figure 3.11 - Influence diagram of code considerations for green roofing

The relationships between the decisions depicted in Figure 3.11 are drawn as value influence arcs. Beginning at the top left of the diagram, if it is determined that a recover is viable for a re-roofing project, a next logical step is to determine whether or not the existing roof has positive drainage. If it does not, a recover may be ill-advised. Next, the dead load of the proposed roof needs to be estimated to ensure the roof structure can support it. As discussed previously, the decision to allow building occupants regular access to a green roof potentially affects a range of other considerations. These include the need to extend plumbing vents and provide roof edge protection to prevent falls, the occupancy type assigned to the roof space and, by extension, any exits required to satisfy this occupant load, the possibility that the roof garden will be considered an additional story by code officials, and the need to account for the live load occupants will generate. The presence of co-op boards introduces a group of issues not elaborated in this diagram. The code must also be researched to determine if water may run off of roof eaves, if this is a desired method of dealing with roof drainage. Finally, the fire risk of green roof vegetation must be considered, and any efforts to mitigate this risk must also be evaluated for its acceptability to code officials.

3.5.3. Relevance of LEED to Green Roofing

The U. S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) Green Building Rating Systems are described by their authors as “voluntary, consensus-based, market-driven, based on accepted energy and environmental principles, and they strike a balance between established practices and emerging concepts” (USGBC, 2005). Created by USGBC committees, the LEED portfolio of Green Building Rating Systems are in essence a set of elaborated checklists of potential credits to be earned by a proposed building project. The total number of credits, determined during the certification review process conducted by the USGBC, establishes the level of the project as certified, silver, gold or platinum. The LEED Rating System Product Portfolio includes rating systems for new construction and major renovations, existing buildings, commercial interiors, and a growing array of new standards currently under development. LEED has been criticized for its checklist approach which gives static weights to a wide range of building strategies, but despite its shortcomings, it is being referenced and often required by an increasing number of governmental organizations.

LEED credits can potentially be earned when a building design incorporates a vegetated roof. Whether or not, and in which categories, these credits are earned is a project-specific question, since every building, and by extension every vegetated roofing project, is to some degree unique. The strategy adopted here is to examine two case study projects presented in the literature to glean the important characteristics of green roofs that will likely lead to the earning of credits within the LEED system. While this process is inexact, it gives a reasonable idea of the relative potential of various green roof systems to satisfy specific LEED criteria and to contribute to the LEED rating assigned to the project at large.

The LEED system used in this analysis is LEED-NC, the Green Building Rating System For New Construction & Major Renovations, Version 2.2, released in October 2005. While certain green roofing projects might fall under the umbrella of other versions of LEED, the LEED-NC system will be applied in a significant number of cases and can therefore be considered representative.

Richard Kula (2005a) claimed that green roofs can directly contribute to earning points within each of the following credits. The corresponding credits under LEED-NC Version 2.2 are given in parentheses, and are used in the following discussion.

Reduced Site Disturbance, Protect or Restore Open Space (SS Credit 5.1: Site Development: Protect or Restore Habitat and SS Credit 5.2: Site Development: Maximize Open Space)

Landscape Design that Reduces Urban Heat Islands, Roof (SS Credit 7.2: Heat Island Effect: Roof)

Storm Water Management (SS Credit 6.1: Stormwater Design: Quantity Control and SS Credit 6.2: Stormwater Design: Quality Control)

Water Efficient Landscaping (WE Credit 1.1: Water Efficient Landscaping: Reduce by 50 percent and WE Credit 1.2: Water Efficient Landscaping: No Potable Water Use or No Irrigation)

Innovative Wastewater Technologies (WE Credit 2: Innovative Wastewater Technologies)

Innovation in Design (ID Credit 1-1.4 Innovation in Design)

Kula based his analysis largely on his experiences with the Winnipeg Mountain Co-op, a retail facility with a green roof of approximately 3,000 square feet (279 square meters) planted with native prairie vegetation. This project earned a LEED Gold certification in 2004 (Kula, 2005b).

The intent of the Protect or Restore Habitat credit is to “conserve existing natural areas and restore damaged areas to provide habitat and promote biodiversity” (USGBC, 2005, p. 18). The requirements dictate that:

on previously developed or graded sites, restore or protect a minimum of 50 percent of the site area (excluding the building footprint) with native or adapted vegetation.

Native/adapted plants are plants indigenous to a locality or cultivars of native plants that are adapted to the local climate and are not considered invasive species or noxious weeds. Projects earning SS Credit 2²⁴ and using vegetated roofing surfaces may apply the vegetated roof surface to this calculation if the plants meet the definition of native/adapted (p. 18).

The intent of the Maximize Open Space credit is to “provide a high ratio of open space to development footprint to promote biodiversity” (USGBC, 2005, p. 19). The requirements list three options for providing vegetated open space on the site, depending upon the local zoning

²⁴ SS Credit 2 is Development Density & Community Connectivity, which intends to “channel development to urban areas with existing infrastructure, protect greenfields and preserve habitat and natural resources” (USGBC, 2006, p. 12).

requirements or lack thereof. Under all three options, “for projects located in urban areas that earn SS Credit 2, vegetated roof areas can contribute to credit compliance” (p. 19). Clearly, these two credits are geared toward urban green roofs, with the first further requiring that the roof sustain native or adapted vegetation for the purpose of simulating natural habitat as closely as possible.

The intent of the Heat Island Effect: Roof credit is to “reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impact on microclimate and human and wildlife habitat” (USGBC, 2005, p. 23). Two of the three options for meeting this intent reference vegetated roofs:

Option 1

Use roofing materials having a Solar Reflectance Index (SRI) equal to or greater than the values in the table below for a minimum of 75 percent of the roof surface.

Option 2

Install a vegetated roof for at least 50 percent of the roof area

Option 3

Install high albedo and vegetated roof surfaces that, in combination, meet the following criteria:

$$(\text{Area of SRI Roof} / 0.75) + \text{Area of vegetated roof} / 0.5 \geq \text{Total Roof Area} \text{ (p. 23)}$$

Table 3.6 - SRI Requirements for SS Credit 7.2 (USGBC, 2005, p. 23), permission to use granted by: Taryn M. Holowka, United States Green Building Council (May 29, 2007)

Roof Type	Slope	SRI
Low-Sloped Roof	≤2:12	78
Steep-Sloped Roof	>2:12	29

The Stormwater Design Quantity Control credit intends to “limit disruption of natural water hydrology by reducing impervious cover, increasing on-site infiltration, reducing or eliminating pollution from stormwater runoff, and eliminating contaminants” (USGBC, 2005, p. 20).

Requirements differ depending on the existing imperviousness of the project site. The Stormwater Design Quality Control credit rewards designs that “limit disruption and pollution of natural water flows by managing stormwater runoff” (USGBC, 2005, p. 21). 90% of the average annual rainfall (within watersheds categorized as humid, semi-arid or arid) must be treated by acceptable best management practices (BMPs); these BMPs must remove 80 of the average

annual post-development total suspended solids. For both credits, vegetated roofs are listed among the “potential technologies and strategies” to encourage infiltration of stormwater by minimizing impervious surfaces. There is no mention of the ostensible capacity of green roofs to filter pollutants. Rather, vegetated roofing is listed as one of several “alternative surfaces” used to maximize pervious surfaces on a site to effectively minimize pollutant loadings.

One or both of the Water Efficient Landscaping credits are earned by projects that “limit or eliminate the use of potable water, or other natural surface or subsurface water resources available on or near the project site, for landscape irrigation” (USGBC, 2005, p. 26). While no reference is made to green roofs in the wording of the credits, if a green roof is incorporated into a project, provision should be made to irrigate the roof, along with any other site landscaping, with stored rainwater or some form of non-potable water meeting the credits’ requirements. If a green roof is irrigated with potable water, it may actually be a liability, possibly preventing the overall project from earning one or both of the credits. Green roofs with no irrigation requirements will not encounter this complication.

Kula (2005b) argued that green roofs can directly contribute to the Innovative Wastewater Technologies credit if they can be designed to directly treat wastewater, or can be fertilized with compost tea from composting toilets. He cited the Winnipeg Mountain Co-op project, where solid waste from the composting toilet was used as a green roof soil amendment, and compost tea was included in irrigation water. He explained that compost tea contains large quantities of nitrogen, which shifts the green roof to a phosphorus-limited environment. When so affected, the green roof removes phosphorus from incident rainfall, helping to condition the water that filters through the green roof and is eventually discharged on site or to stormwater facilities. While the opportunity for this synergy is exciting, such an arrangement requires a relatively high level of building systems integration and is more intricate and maintenance intensive than the typical extensive green roof or roof garden.

The Innovation in Design credits (up to four per project) reward designers for developing unique solutions that defy categorization under the current LEED System, or for achieving exceptional performance in one or more of the established categories. Kula argued that green roofing has great potential to contribute toward the earning of these credits, especially when integrated into whole-building systems.

Kula claimed that green roofs can contribute, either directly or indirectly, to up to 15 credits in the LEED system. In his discussion at the Greening Rooftops for Sustainable Communities conference in Washington D.C., Kula (2005b) listed additional credits to which green roofs can indirectly contribute (LEED NC Version 2.2 credit names are in parentheses):

Water Use Reduction (WE Credit 3.1: Water Use Reduction: 20 percent Reduction and WE Credit 3.2: Water Use Reduction: 30 percent Reduction)

Optimise Energy Performance (EA Credit 1: Optimize Energy Performance)

Renewable Energy (EA Credit 2: On-Site Renewable Energy)

CFC and Ozone Depleting Substance Reduction (EA Prerequisite 3: Fundamental Refrigerant Management and EA Credit 4: Enhanced Refrigerant Management)

Storage and Collection of Recyclables (MR Prerequisite 1: Storage & Collection of Recyclables)

Carbon Dioxide Monitoring (EQ Credit 1: Outdoor Air Delivery Monitoring)

According to Kula (2005), some credits can be gained indirectly when green roofs are part of a set of integrated systems. The Water Use Reduction credits apply only if some type of storm water capture system is coupled with the green roof project, reducing the amount of potable water consumed within the building. Likewise, the On-Site Renewable Energy credit is indirectly supported by green roofs when they are combined with photovoltaic cells, a synergy elaborated in Section 3.2.2 of this dissertation. Other credits account for properties more integral to the performance of the green roof itself, such as the Optimize Energy Performance credit. This credit is considered indirect because the energy benefits of green roofs are, at present, difficult to calculate.

The relationship of green roofing to some of the indirect credits is clear only when a project is viewed in the most holistic sense. For example, the Outdoor Air Delivery Monitoring credit will not be affected by the presence or absence of a green roof, but Kula (2005) argued that green roofs can provide a more oxygen-rich environment near fresh air inlets, minimizing the quantity of ventilation air needed. The credit's intent is to reduce carbon dioxide concentrations in occupied spaces using a minimum of ventilation air, which in turn minimizes the amount of energy consumed to condition this air. While quite distant from the letter of the credit, the green roof does contribute to its underlying spirit. Similarly, while the cooling properties of green roofs are difficult to quantify, they have been repeatedly proven to help reduce or obviate the need for mechanical refrigeration, a goal rewarded by the Fundamental and Enhanced Refrigerant

Management credits. Likewise, the Storage & Collection of Recyclables credit will apply to green roofing projects where organic wastes such as paper and foods are composted on site and reused as fertilizer on the green roof. It is often productive to “think outside the box” where LEED credits are concerned, in this case, to rethink the everyday concept of recycling to embrace the idea of a self-sustaining rooftop garden, fed by building wastes. While such strategies may not be accepted for LEED credit, they certainly contribute to the goals LEED seeks to encourage.

Logan Cravens (2004) provided a similar analysis of how green roofs help earn LEED credits with a very different project, an earth-sheltered, unoccupied barrel aging cellar southeast of Portland that was certified with a LEED Silver rating. He asserted that the green roof contributed directly to earning three LEED credits, and indirectly to three more. The three direct credits (LEED NC Version 2.2 credits shown in parentheses) echoed those discussed by Kula: the Sustainable Sites Credit 7.2: Heat Island Effect at Roof, (SS Credit 7.2) worth one point, and Water Efficiency Credit 1: Water Efficient Landscaping, worth two points (WE Credits 1.1: and 1.2). The heat island effect credit was earned because the vegetated roof, aside from three skylights and a vent, covered the entire structure, and the water efficiency credits were earned by using a non-irrigated, two-foot- (600-mm-) deep system planted with drought-resistant wildflowers and grasses. The three credits to which the green roof lent indirect support were Sustainable Sites Credit 5: Reduced Site Disturbance (now SS Credits 5.1 and 5.2), Sustainable Sites Credit 6: Storm water Management (SS Credit 6.1), and Energy and Atmosphere Credit 1: Optimize Energy Performance (EA Credit 1). Because the roof simulated and extended the natural prairie and effectively covered the entire building, it both sustained natural habitat and effectively negated the building footprint. Cravens stated that the roof “slows storm water runoff” (p. 196). The green roof likely assisted in the earning of the stormwater management credits because it was considered a pervious surface. Finally, while the green roof’s two feet (600 mm) of soil garnered an R rating of only 7.5 according to energy calculations measuring its performance when fully saturated, and therefore needed to be supplemented with 4 inches (100 mm) of expanded polystyrene, the synergistic effects of burying a building in the ground and covering its roof with backfill and vegetation were clear. The most dramatic of these was the avoidance of mechanical refrigeration in the building.

3.5.3.1. Summary

There is obviously some room for interpretation when deciding the value of a green roof system in terms of LEED credits earned, either directly or indirectly. However, there are sufficient references to vegetated roofing within the LEED guidelines to make its contributions undeniable. Green roofs are valued most for their widely publicized and defensible benefits, namely their capacity to maximize pervious surface, to reduce the heat island effect, and in some cases, to preserve native habitat. Green roofs that either use recycled irrigation water or do not require irrigation are given an advantage within the system. A provisional rating scale based on the concepts raised by Kula and Cravens and tied to the particular characteristics of specific green roof systems will be generated and included as a value function within the framework. As the implementation of green roofing becomes more widespread, and as more designers of LEED certified buildings can isolate the effects of the vegetated roof on the outcome of the certification process, this value function may be improved.

3.6. Cost

As might be expected, the price of green roofing varies widely depending upon the system selected, the local availability of material and labor, the accessibility of the project to the green roof installer, and so on. Green roofs that are touted as economically competitive are proved to be so when subjected to a life cycle cost analysis that takes into account the expected longer life of the green roof when compared with a traditional system as well as the avoided costs of energy and storm water management and any other financial incentives. Because various building owners are concerned with different aspects of a green roof's estimated cost depending upon the nature and degree of their investment in the project, projected initial costs and maintenance costs will be included in the design of the framework along with a more comprehensive life cycle cost analysis.

Experts claim that the life of roof membranes in vegetated roofing systems may be extended up to three times when compared with a system that places the membrane in direct exposure to the elements. This extended life is achieved because the vegetated layer protects the membrane from degradation caused by ultraviolet radiation, internal stresses caused by thermal cycling (Scholz-Barth, 2001), and external mechanical damage caused by foot traffic and other impacts. Because the history of modern green roofs is relatively short and no accelerated aging tests that simulate green roof conditions have been performed on roof membranes, further observation and research is required to quantify the extended life benefit afforded by green roof

systems.

Jeff Sties, an architect and green roof designer based in Charlottesville, Virginia, presented economic data on green roofing during a presentation given at Virginia Tech's physical plant on November 21, 2003. He estimated that the first cost of extensive green roof systems is between \$10 and \$15 per square foot (\$110 and \$160 per square meter), and the first cost of intensive systems is between \$15 and \$20 per square foot (\$160 and \$220 per square meter), not including the cost of any structural upgrades required to support the roof. He defined intensive systems as any green roof deeper than 4 inches (100 mm). Likewise, at the Green Roof Design 101 Course held by Green Roofs for Healthy Cities (GRHC, 2004a) a cost of \$10 to \$15 per square foot (\$110 and \$160 per square meter) was used as a general rule of thumb for pricing extensive green roofs in North America. These numbers included only the green roof components, not the underlying waterproofing system. This cost range can be used to estimate the cost of a green roof in isolation from the cost of a traditional roof system.

Dunnett and Kingsbury (2004) gave a rule-of-thumb cost estimate of \$10 to \$20 per square foot (\$110 and \$220 per square meter) for extensive green roofs, and \$20 to \$40 per square foot (\$220 to \$430 per square meter) for intensive green roofs. They contrasted this with a typical cost of \$4.00 to \$8.50 per square foot (\$43 to \$91 per square meter) for traditional roofing systems in the United States at 2002 prices, with the \$4.00 (\$43) price representing a roof estimated to last 15 to 20 years, and \$8.50 (\$91) representing a 30 to 50 year roof.

The U.S. Environmental Protection Agency (2006), in a web publication addressing the heat island effect, compared the low-end prices of green, traditional and white reflective "cool" roofs, including preparation, materials, and installation. The publication cited a low-end cost for extensive green roofs in the U.S. at \$8.00 per square foot (\$86.10 per square meter) compared to \$1.25 per square foot (\$13.50 per square meter) for low-end traditional roofing and \$1.50 per square foot (\$16.10 per square meter) for cool roofs.

Green roof costs are difficult to pin down, especially in the early stages of design. However, it is often necessary to construct broad-brush estimates for budgeting and deciding between alternatives. Two organizations have provided general outlines of factors to be considered in generating cost estimates for green roofing. Tables 3.7 and 3.8 were presented by Green Roofs for Healthy Cities in the *Green Roof Design 101 Course Participant Manual* (2004a).

Table 3.7 - Cost ranges and factors: extensive roofs (GRHC, 2004a, p. 48), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Jan. 25, 2007)

(Please note that the costs may vary by region and that this should be used only as a general guide. A cost of \$0.00 indicates that the element may not be required in the design.)

Element	Price Range \$USD	Factors
Design	4-8% of project cost	Size and complexity of project
Project Admin./Site Review	6-12% of project cost	Size and complexity of project and no.of professions involved
Initial Structural Evaluation	\$0-\$1000	Existing building. Quality of documentation.
Re-roofing	\$0-12 / ft ²	Depends on components, accessibility and other issues
Drainage	\$1-\$5.50 / ft ²	Type of drainage layer, size of project
Filter Cloth	\$0 -\$0.50 / ft ²	
Growing Medium	\$2 - \$12 / ft ³	Volum / type of growing medium, shipping and how placed on roof
Vegetation	\$0.20 - \$5.00 / ft ²	Type and size of plants, time of year, seeds, cuttings, plugs, mats and or pots.
Installation	\$2.40 - \$6.40 / ft ²	Size of project, sophistication of design, type of planting approach etc.
Curbing/Borders	\$0 - \$20 per linear foot	Pre-cast concrete, aluminum edging, timber borders, recycled etc.
Walkways	\$0 - \$10.20 / ft ²	Pre-cast concrete unit pavers, natural stone, wood decking, recycled products etc.
Maintenance	\$0.25 - \$4.10 / ft ² for the first two years	Size of roof, types of plants.
Irrigation System	\$0.0 - \$3.20 per linear foot	Type of irrigation system used and size of project.

Table 3.8 - Cost ranges and factors: intensive roofs (GRHC, 2004a, p. 49), permission to use granted by:
Jennifer Sprout, Green Roofs for Healthy Cities (Jan. 25, 2007)

Element	Price Range \$USD	Factors
Design	4-8% of project cost	Varies on size of project
Project Admin. / Site review	6-12% of project cost	Depends on size and complexity of project, number of professions involved.
Initial Structural Evaluation	\$0-\$1000	Existing building. Quality of documentation.
Re-roofing	\$0-12 / ft ²	Roof type, access, penetrations, flashing etc.
Drainage	\$1-\$5.50 / ft ²	Volume, type of medium
Filter Cloth	\$0.0-\$0.50 / ft ²	
Growing Medium	\$2 - \$20 / ft ³	Volume / type of growing medium, shipping and how placed on roof
Vegetation	\$1.25 - \$10.00 / ft ² and up	Type and size of plants/shrubs/trees, may require containers or anchorage.
Installation	\$6.40 – \$14.40 / ft ² (100 to 200% of material costs)	Size of project, sophistication of design, type of planting approach, access etc.
Curbing/Borders	\$0 - \$20 per linear foot	Pre-cast concrete, aluminum edging, timber borders, gravel, recycled etc.
Walkways	\$0 - \$10.20 / ft ²	Pre-cast concrete unit pavers, natural stone, wood decking, recycled products etc.
Maintenance	\$1.00- \$4.10 / ft ²	Size of roof, types of plants.
Irrigation System	\$0.0 - \$3.20 per linear foot	Type of irrigation system used and size of project.

Roofscapes, Inc. (2004), rather than give general cost estimates on its website, requests designers to respond to a Green Roof Work Sheet (Roofscapes, Inc., 2006) to help the company's engineers recommend a system and create a tailored cost estimate. Designers are asked to provide the following information.

Project location (i.e. city and state; and urban, suburban or rural)

Stage of design

Project description (i.e. building function)

New or retrofit construction

Time of construction

Height of roof above grade

Accessibility by crane

Area of green roof in square feet

Type of roof deck

Structural capacity of roof deck

Slope of roof

Location and type of roof drainage

Type of waterproofing

Special conditions including exceptionally high heat, wind, rainfall, drought conditions, or foot traffic

Whether or not union labor rates apply

Objectives of the designer (i.e. ecological, aesthetic, economic, educational, stormwater management or other)

Visibility and use of the green roof

Specific features desired (i.e. deck, pavers, trees, turf, other)

3.6.1. Site Utilization and Storm Water Management Cost Considerations

Chris Scott (personal communication, October 8, 2004), president of GreenTech, a supplier of modular green roof systems, related three major cost incentives he found most compelling to his clients. The first related to the possibility of providing usable space in the form of a roof garden to take advantage of otherwise underutilized roof area. Roof gardens can in certain cases become a source of occupied square footage, offsetting the need to provide similar areas elsewhere in the project. Historically, intensive green roof systems have been used in combination with plaza decks to satisfy a wide variety of recreational needs. The second incentive related to the avoided costs of providing an alternate form of storm water volume and

peak flow management. The third involved the potential of the green roof to avoid water contamination in a protected water area, permitting building to occur on a wider range of potential sites as well as encouraging more cost-effective land use. This third consideration assumes that the green roof employed possesses pollutant-removal capabilities, a claim that still largely remains to be substantiated with a body of experimental data and more widely accepted by authorities having jurisdiction over green roof projects.

From a cost perspective, it is clear that minimizing land use is a major benefit of green roofing as compared with many other more traditional forms of storm water management. For example, on an expensive urban site a green roof, which takes up no additional space on a site, would likely be economically preferable to a typical storm water management practice. For example, a dry extended detention pond, one of the least expensive storm water treatment methods, takes up 2 to 3% of the drainage area it serves, according to the United States Environmental Protection Agency (2005b). In the determination of potential costs, it is also important to consider the perception of the storm water management system by the users of the facility and the surrounding community. Using the same example, in order for a dry extended detention pond to effectively remove pollutants, water must be detained in it for over 24 hours (USEPA, 2005a). However, if the pond remains wet longer than three days, mosquitoes can be a problem (USEPA, 2005a). The damp, unusable ground can be a liability to the property owner. A study by Emmerling-Dinovo (1995) as cited by the USEPA (2005a) suggested that dry ponds can have a negative impact on surrounding real estate values. By contrast, green roofs, particularly extensive systems, are generally perceived as a new and exciting technology. Especially if the development is speculative, it may behoove the developer to consider the use of such a system.

3.6.2. Life Cycle Cost Analysis

Studies have been conducted in several locales to determine the viability of green roofs from a fiscal perspective. Obviously, the economic context of the place in which the study is centered has a major impact on the findings, but the basic elements of each life cycle cost (L.C.C.) analysis are fairly constant and predictable. These elements often include the higher first costs, the longer expected life, the avoided costs of energy and storm water management, the possible financial incentives, and the maintenance costs associated with green roofs.

A study by Porsche and Köhler (2003) compared the L.C.C.s of green roofs in Germany, the United States, and Brazil, focusing on five main benefits of green roofing: the extended life span of the roof membrane beneath the green roof, the reduction of rooftop runoff, the increase in thermal insulation, the reduction in noise transmission and reflection, and the increase in property values. Interestingly, despite the great popularity of extensive green roofs in Germany, the authors argued that their cost is approximately the same there as it is in the U.S., \$7.90 per square foot (\$85 per square meter). It is notable that this figure included the underlying roof membrane, while most figures quoted in the U.S. are in the \$10 to \$15 per square foot (\$110 to \$160 per square meter) range (see Section 3.6) and do not include the underlying waterproofing system. Regardless of this discrepancy, green roof systems are about three times as expensive as low-end roofing in both countries. The building lifespan used in this analysis was 90 years, which is typical in Germany. The green roof was expected by the authors to last between 50 and 90 years, an assumption that strongly favored green roofs in the life cycle cost analysis, especially when disposal and recycling costs of traditional roofing were included. In this study, the annual maintenance costs of an extensive green roof were estimated to exceed that of a traditional roof by five times, which tended to devalue green roofs in the analysis. However, Porsche and Köhler (2003) argued that the minimum labor rates in the U.S. are roughly half of what they are in Germany, which would possibly reduce the negative impact of maintenance costs in the U.S. as compared with German examples.

The remaining benefits of green roofs listed by Porsche and Köhler (2003) are largely viewed as qualitative in the United States: storm water reduction, thermal insulation, noise reduction and increase in property value. By contrast, in Germany there are financial bonuses, or fee offsets, associated with some of these benefits. The *FLL Guideline* (2002) assigns a coefficient of discharge to various green roofs according to their thickness and slope (see Table 3.1). A typical 4 inch (100 mm) low slope green roof is assigned a coefficient of discharge of 0.50, meaning it retains half of its incident rainfall on average. In the Porsche and Köhler analysis, the avoided cost of fees for storm water represented by an extensive roof was estimated at \$8.38 per square foot (\$90.2 per square meter) over the 90 year lifespan, which entirely offset its first costs. Both thermal and noise insulation were acknowledged as having value, but they were not accounted for in the L.C.C. analysis. However, in Germany, an increase in property value is manifested as an allowable 25% increase in the rental rate of terraces and roof gardens. Using average German rental rates, this translates to \$250 per square foot (\$2,700 per square meter) over the life cycle, greatly contributing to the viability of intensive roof

gardens. The outcome of this L.C.C. analysis of German green roofs strongly favored intensive green roofs, with extensive green roofs also outperforming traditional bitumen and gravel roofs, as shown in Table 3.9 and Figure 3.12.

Table 3.9 - Total cost-benefit overview of the estimated lifespan of 90 years in \$ per m² (Porsche & Kohler, 2003, p. 466), permission to use granted by: Dr. Stefan Krauter, Rio Solar Ltd. (Jan 22, 2007)²⁵

Type of roof	Construction, inspection and disposal/recycling costs (from Table 1, \$)	Total maintenance (from Table 3, \$)	Financial benefits / increased rental income (Table 5 + Table 2, \$)	Total costs (-) or total profit (+) per m ² (Column 2 + 3 -5, \$)
Bitumen roof	320	18	- -	338,00 -
Gravel roof	295	18	- -	313,00 -
Extensive green roof without PVC products	170	90	90,2	169,80 -
Extensive green roof with PVC products	185	90	90,2 -	184,80 -
Intensive green roof without PVC products	860	720	90,2 + 2.700,00	1.210,20 +
Intensive green roof with PVC-Products	820	720	90,2 + 2.700,00	1250,00 +

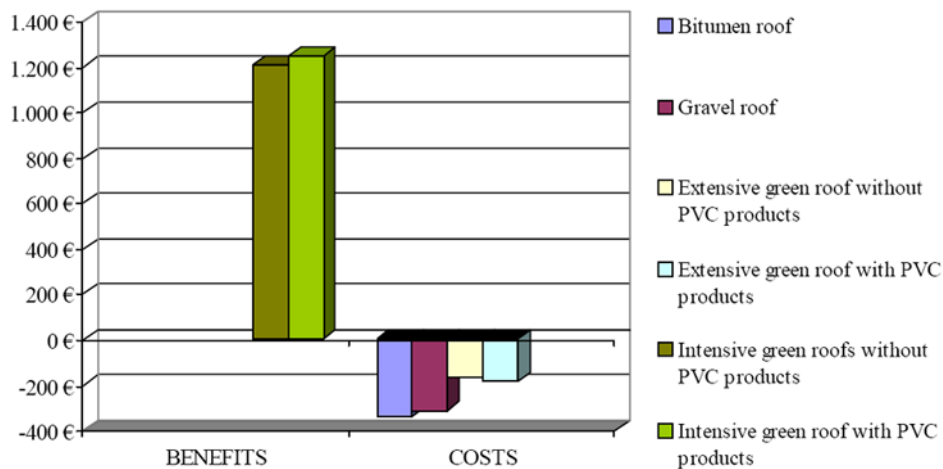


Figure 3.12 - A first total cost – benefit overview of the estimated lifespan of 90 years in \$ per m² (Porsche & Kohler, 2003, p. 467), permission to use granted by: Dr. Stefan Krauter, Rio Solar Ltd. (Jan. 22, 2007)

On the other side of the world, Wong, Tay, Wong, Ong and Sia (2003) evaluated the first costs and life cycle costs of extensive and intensive green roofs as compared with traditional exposed

²⁵ The dollar signs refer to U.S. dollars.

(inaccessible) and inverted membrane (accessible) roofs in Singapore. This study specifically took into account the cost implications of the energy benefits offered by green roofs in a tropical climate by simulating the energy costs for a medium-rise commercial conditioned building. In this example, the green roof components were defined as including the roof deck as well as all layers above it, but did not include the roof structure. Cost elements of the analysis comprised initial costs including structural costs, maintenance and replacement costs. In contrast to the Porsche and Köhler (2003) study, here a traditional exposed membrane PVC roof was expected to be replaced initially after 10 years, and subsequently after only 5 years. An inverted membrane traditional roof was assigned a replacement schedule of 20 years, while both extensive and intensive roofs were assumed to be replaced after 40 years, which is also the length of the analysis period.

A constant dollars approach was used in the L.C.C. analysis, with a discount rate of 5.15%. When comparing initial costs for inaccessible and accessible roofs, the researchers found that for the inaccessible case, an extensive green roof was about 82.5% more expensive than a typical exposed membrane roof, while for the accessible case, the intensive green roof was from 36 to 50% more expensive than the inverted membrane roof, depending on the type of plantings employed. When comparing life cycle costs, in the inaccessible case, the green roof was only 2.4% more expensive than the traditional roof, while in the accessible case, the difference between green and traditional roofs ranged from 50.3 to 93.3%. These results lead the authors to rule intensive green roofs out as a cost-effective option in Singapore. When assumed net energy cost savings of 14.6% were included in the analysis with a discount rate of 6.15%, the extensive green roof actually proved to be 8.5% cheaper than the traditional inaccessible roof over the 40 year analysis period, with payback occurring at 10 years, as shown in Figure 3.13.

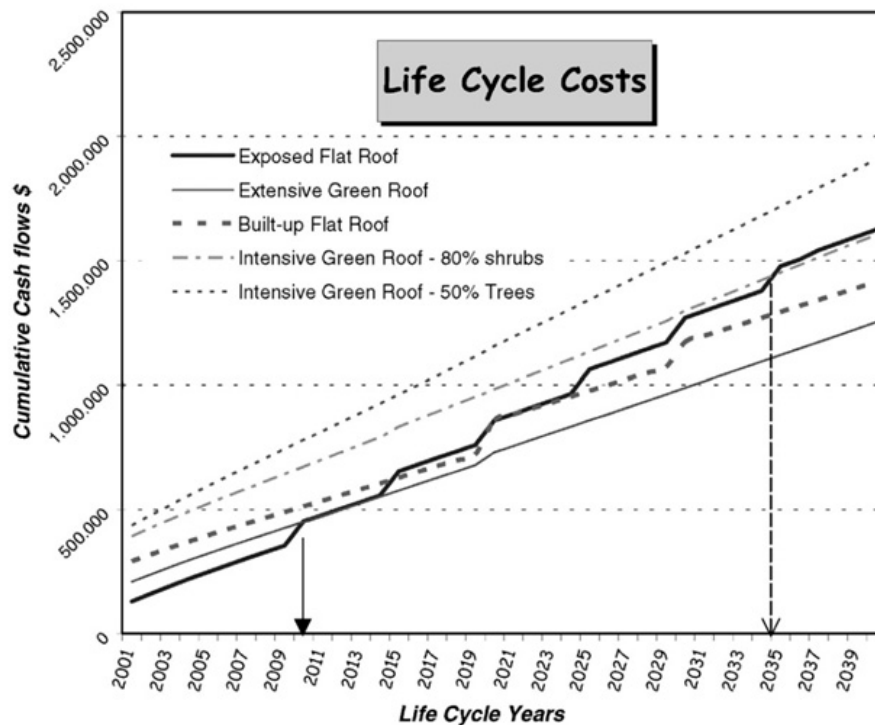


Figure 3.13 - Life cycle costs (including energy costs) at 6.15 percent discount rate (Wong et al., 2003, p. 507). Reprinted from *Building and Environment*, Vol. 38, N.H. Wong, S.F. Tay, R. Wong, C.L. Ong, A. Sia, Life cycle cost analysis of rooftop gardens, pp. 499-509, Copyright (2003), with permission from Elsevier.

A life cycle cost analysis of the green roof atop the Multnomah County headquarters in Portland Oregon, conducted by Quantec, LLC and presented by Allen Lee (2004), provided a series of perspectives from North America that can be compared and contrasted with those in Europe and Asia. Lee first made the distinction between the relatively narrowly focused life cycle cost analysis tool used in the study and a wider life cycle cost assessment which takes into account the entire lifecycle of all components of a system from cradle to grave. While acknowledging its limitations, especially with regards to including qualitative valuations, he pointed to the relative ease of use of the L.C.C. analysis and its widespread adoption by a range of organizations as an appropriate metric of financial impact over time for a given building system. In the case of the Multnomah County building, an extensive green roof was compared with a conventional roof over a study period of 60 years. This life cycle period was typical for analyses of this nature requested by the county. The replacement frequency of the conventional roof was set at 20 years, while the green roof replacement was set at 40 years. The outcome of the L.C.C. analysis showed the green roof costing an additional 7% over the capital cost of the

conventional roof. When real-world grant monies and donated materials were accounted for, the green roof was 34% less expensive than the conventional roof's capital cost. The economic factors accounted for in the study were summarized in the following equation:

$$LCC = FC + RC + O \& M + EC + SWC - RV$$

Equation 3.4 - LCC calculation (Lee, 2004, p. 132)

Where:

FC = first cost

RC= replacement cost

O&M = operations and maintenance cost

EC = energy costs associated with the roof

SWC = stormwater costs

RV = residual value

Perhaps more important than the methodology used to determine values for each of these parameters, which were somewhat project- and site- specific, was the sensitivity analysis performed on key input variables contributing to these parameters. Four such variables were evaluated for their sensitivity to a 30% increase or decrease in their values. The result on the net change in LCC was reflected in a chart reproduced in Figure 3.14.

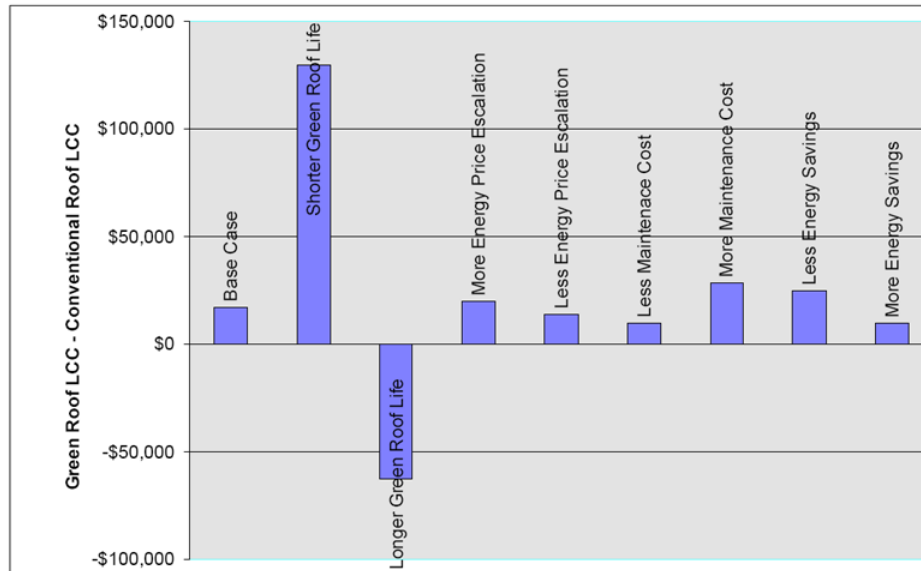


Figure 3.14 - Sensitivity of LCC Analysis to 30 percent changes in key inputs (Lee, 2004, p. 140), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Jan. 25, 2007)

The most sensitive input variable by far in this analysis was green roof life. Lee showed that if the green roof expected life were changed from 40 years to 52 years, the green roof would be no more expensive than a conventional roof, even without financial offsets. It is interesting to contrast the study length and green roof expected life in this study with that of the German and Singaporean studies discussed above. The study period and green roof life were both set at 90 years in the German study, and at 40 years in the Singaporean study. The other three parameters in Lee's study, in decreasing order of sensitivity, were maintenance cost, energy savings, and energy price escalation rate. The uncertainty of the inputs and the conservative nature of the L.C.C. analysis led Lee to conclude that it is likely that a green roof will be financially comparable to a conventional roof in Portland over a 60 year life cycle. He posited that the green roof financial benefits would be greater in a location with a longer cooling season and more expensive utility rates.

It is clear that the assumptions made in a life cycle cost analysis have a great deal of impact on the results. In the German study, the quantification of property value made a strong case for intensive green roofs, while in Singapore, the energy savings afforded by the extensive green roof coupled with its protection of the roof membrane from the elements made use of these roofs a cost-effective option. In Portland, the green roof's lifespan as compared with that of a traditional roof was the parameter upon which the analysis hinged. Project-specific financial

offsets also had a significant effect on the outcome of the L.C.C. study in Portland, and are in fact the deciding financial factor permitting implementation of many experimental green roofs in North America.

3.6.3. Summary

Some of the questions raised in Section 3.6 concern the design rather than the cost of a green roof, but the majority contribute to both design and cost considerations. Those related to cost are included in a detailed influence diagram found in Section 5.8.

4. FRAMEWORK METHODOLOGY

This chapter explores various ways of approaching the decision-making process in design, and applies these to the specific case of vegetated roofing system selection. First, an explanation of case study methodology is presented and a summary of the findings from six case study projects as they relate to each evaluative category found in Chapter 3 is provided. Next, several methods of defining a decision context are reviewed. Finally, the organization and development of the framework for green roof system selection are described, and approaches for accommodating uncertainty and tests for acceptability are discussed.

4.1. The Case Study as a Research Method

In the preface to *Case Study Research*, Robert K. Yin (1994) asserted that “empirical research advances only when it is accompanied by logical thinking, and not when treated as a mechanistic endeavor. This lesson turns out to be a basic theme of the case study method” (p. xv). He defined the case study as “an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” (p. 13). Robert E. Stake (1995), in *The Art of Case Study Research*, identified two main types of case studies, those he termed “intrinsic”, where an understanding of the case or cases themselves is of primary importance, and those he called “instrumental”, where the case study or studies are undertaken in the service of an overriding research agenda. The six case studies included in this dissertation were envisioned as an instrumental method to unearth the process and issues inherent to green roof design and to refine the research questions. The case studies were conducted to answer the question, “What are the factors relevant to the selection of green roof systems?”

In *Architectural Research Methods*, Groat and Wang (2002) identified five key properties of case studies. These, along with their attendant strengths and weaknesses, are explained in relation to the green roof case studies in the discussion that follows.

- 1) a focus on either single or multiple cases, studied in their real life contexts;
- 2) the capacity to explain causal links;
- 3) the importance of theory development in the research phase;
- 4) a reliance on multiple sources of evidence, with data needing to converge in a triangulating fashion; and
- 5) the power to generalize to theory (p. 346)

The first property refers to the richness gained through investigating a case in context, where interacting factors can be examined. A corollary weakness of case study research is that the studies can become too intricate to be useful. One of the main purposes of including case study research in the beginning phases of this dissertation was to allow the author to physically visit selected roofs for the purpose of acquainting herself more fully with the general political and physical climates in which green roof projects are situated. But because the case studies were instrumental, not intrinsic (using Stake's terms), in-depth descriptions of each of their contexts were not deemed critical, which prevented them from becoming overly complicated.

The second property, the explanation of causal links between research variables, can be difficult to defend due to the many uncontrolled variables present in case study research. For this reason, not all case studies attempt to define causal links. Yin (1994) classified case studies according to the type of research questions they answer. Exploratory case studies typically answer questions to determine "what" is responsible for a given phenomenon, descriptive case studies answer questions of "who, where, how many, or how much", and explanatory case studies venture to answer "how or why" something occurs (pp. 5-6). Because the case study component of this research occurred early in the process of problem definition, the case studies are exploratory and descriptive, rather than explanatory in nature. Their function was to develop hypotheses regarding factors important to green roof system selection rather than to establish causal links between such factors.

The third property alludes to the importance of basing research design on a theoretical framework. In this dissertation, the case studies were embarked upon with a preliminary understanding of the factors important to green roof design. The studies themselves helped to elaborate these factors and supported ongoing efforts to review the literature and develop the framework for green roof system selection.

The fourth property points to another strength of the case study, its ability to provide a convenient container for a range of information relevant to a project. Its weakness is the level of skill necessary to integrate this range of information effectively. As stated, the main purpose of considering case study research in this dissertation was to allow the incorporation of contextual data that are best attained by physically experiencing a built project. The site visit process naturally lent itself, in most cases, to a series of informal interviews of the persons responsible

for the inception, design, execution, or ongoing care of the green roof in question. Where such interviews proved impractical, or when information garnered therefrom was incomplete, these gaps were filled by published articles or case studies of these particular roofs prepared by other persons or organizations reviewing and evaluating built green roof projects.

The fifth property, the power to generalize case study findings to theory, partially counters a noted weakness of case study research, the lack of power to generalize case study findings to a wider study population. Yin (1994) stated that observations from case study research may often be generalized to theory through the process of “analytic generalization”. In this method, each case study is envisioned as a separate scientific experiment, the results of which may be used to support or refute a pre-existing theory. Multiple cases must support the same theory in order to achieve replication (Yin, 1994, Groat & Wang, 2002). In this dissertation, the green roof case studies served to direct the establishment of green roof evaluative categories hypothesized to be important to system selection. Future testing of the framework will provide the necessary validation of theory generalized from the case studies.

Groat and Wang (2002) concluded that their capacity to capture context and complexity make case studies appropriate for architectural research but, in the absence of rigorous procedural rules common to other research methods, they must be designed carefully to assure meaningful results.

4.1.1. Selection of Case Studies

Stake (1995) and Yin (1994) acknowledged that case studies do not provide a statistically representative sample of a population. There are often too many variables and too wide a range within each of these variables to make representing each possible combination a practical goal. This obstacle was encountered in the selection of green roof case study projects. A list of well-documented and well-known modern green roofs was compiled in a chart to determine patterns of classification. The number and range of the variables rapidly grew unwieldy. Table 4.1, which includes only the six case study projects eventually selected, shows just a small part of this complexity. To address this problem, Stake (1995) suggested that researchers select cases based on their contribution to the understanding of a particular research question rather than their capacity to represent the full range of possible situations. Following are the criteria used for the selection of the six green roof case studies presented in this research.

Table 4.1 - Matrix of case study characteristics

Project Name	Project Location	USDA Climate Zone	Urban, Suburban or Rural	Project Area (square feet)	Project area (square meters)	Green Roof Classification	Media Depth (inches)	Media Depth (mm)	Public or Private	Year
Montgomery Park Business Center	Baltimore, MD	7a	Urban	30,000	3,000	Extensive	2.0 to 3.0 ¹	50 to 75	Private, rented by public agency	2001
Life Expression Chiropractic Center	Hazleton, PA	5b	Rural	6,000	600	Intensive	5.0 (Miller, 2002)	130	Private	2001
Chicago City Hall	Chicago, IL	5b	Urban	20,300	1,890	Extensive, Semi-intensive, and Intensive	3.0 to 18 ²	75 to 450	Public	2001
Ford Dearborn Truck Assembly Plant	Dearborn, MI	6a	Suburban	475,000	44,100	Extensive	2.5 to 3.0 (Russell, 2004)	63 to 75	Private	2002
Toronto MEC	Toronto, ON	5b	Urban	10,000	900	Extensive	5.0 (Johnson, 2003)	130	Private	1998
Woodward Academy	Atlanta, GA	7b	Urban	4,000	400	Semi-intensive	6.5 ³	160	Private	2004

¹ Stewart Comstock, personal communication, April 12, 2004

² Kevin Laberge, personal communication, July 16, 2004

³ R. Alfred Vick, personal communication, September 23, 2004

The Ford Dearborn Truck Plant's green roof was one of the first selected for study because, at the time of selection, it was the largest green roof in the world.⁴ It is also one of the best-known green roofs in North America, recognized not only by the green roofing community, but by many in the public at large. This fame is due in part to Ford's inclusion of an observation platform overlooking the green roof, which exposes a projected 300,000 visitors per year (Kurth, 2004) to the roof as a chief feature of Ford's Rouge Factory Tour.

The roofs at Chicago City Hall and Montgomery Park Business Center were chosen in part because they are examples of government entities' direct support green roof initiatives through incorporation of green roofs at their own facilities. While Montgomery Park is a privately-owned building, it houses the rented offices of the Maryland Department of the Environment, the agency responsible for codifying storm water best management practices in that state. Additionally, the Chicago City Hall is somewhat unique in its incorporation of a range of depths of green roofs in one integrated design.

The Hazleton Chiropractic Center's roof was selected for its unusual curved profile, its rural location, and its relatively small size. The green roof at the Woodward Academy is also a small, privately owned roof, with the distinction of being the only roof among the six case studies to incorporate a modular, semi-intensive system. It is also the only roof of the six located in the south, a comparatively uncharted territory for green roof development.

Finally, the Toronto Mountain Equipment Cooperative's green roof was selected because it has a longer tenure than the other roofs studied, and because it is located in Toronto, a city that has lead the effort toward green roof research, implementation, and policy development in North America.

The clustering of the case studies generally in the Mid-Atlantic and Midwestern regions of North America is a function both of their greater prevalence there, and of financial and time constraints on the case study portion of the research. One positive consequence of these constraints is the similarity of the weather patterns at the case study locations, which permits a meaningful comparison of the storm water mitigation and thermal performance of the green roofs. Notably

⁴ The green roof at Chicago's Millennium Park held that distinction at the time of this writing, with 24.5 acres, or 1.07 million square feet (99,100 square meters) of green roof (GRHC, 2006).

and regrettably omitted are green roofs in the Pacific Northwest and Northern California, areas where green roofing (or eco-roofing, as it is known there) has gained a considerable foothold, and where the weather is quite different from that of the study area. It is hoped that this gap and others may be filled by future study.

It is acknowledged that these six cases by no means fully represent the range of possible green roof designs, nor are they necessarily the most commendable, though several of them have won green roof design awards.⁵ What is deemed most important in their selection is their capacity to demonstrate a diverse set of examples of green roof projects in context and, through these examples, to assist in the determination of relevant environmental categories that warrant deeper examination in the available literature.

4.2. Summary of Case Study Findings

The six case study projects listed in Table 4.1 were evaluated to determine key design factors for inclusion in the framework for vegetated roofing system design. The case study projects were selected to represent a range of building types, locations, and design considerations. The following is a brief discussion of how the green roof evaluative categories selected for analysis were manifested in the examined case study projects. More complete descriptions of each of the six projects discussed in this section are found in Appendix A.

4.2.1. Storm Water

Green roofs are frequently used as a component of storm water management systems. The two green roofs at Montgomery Park were designed primarily as storm water mitigation devices that reduce the impermeable area of the existing site. The same was true on a smaller scale at the Life Expression Chiropractic Center, seen in Figure 4.1, where the green roof intercepts and delays the flow of incident rainfall, allowing it to flow through a gapped fascia at the eaves. The green roof on Ford's truck assembly plant at the Rouge complex was also part of a comprehensive plan to mitigate storm water. According to Green Roofs for Healthy Cities, "it is anticipated that the green roof will retain 447,000 gallons per year, amounting to 50% of the

⁵ Montgomery Park Business Center received a Green Roof Award of Excellence from Green Roofs for Healthy Cities (GRHC) in the category of retrofit extensive roofs in 2003; the Ford Dearborn Truck Assembly Plant and the Life Expression Chiropractic Center received a Green Roof Award of Excellence in 2004 in the categories of Extensive Industrial Commercial and Extensive Institutional, respectively.

annual rainfall in Wayne County over the green roof area, or approximately one gallon/square foot/year” (GRHC, 2004b). The modular green roof installed atop the middle school art building at the Woodward Academy contributes to storm water management on the site. The green roof slows the rate and reduces the volume of runoff to be held in a concrete tank located beneath the parking lot before it is slowly released to the city’s storm drainage system.



Figure 4.1 - Life Expression Chiropractic Center

4.2.2. Energy

The potential for energy savings also often motivates owners to install green roofs. At both the Life Expression Chiropractic Center and at the Toronto MEC store seen in Figure 4.2, the green roof was expected to generally lower temperatures at the roof surface as compared with traditional roofing, thus potentially lowering temperatures at the roof membrane and inside the building. Unfortunately, it is often impossible to isolate the thermal effects of the green roof from the thermal effects of insulation incorporated into the roof assembly. Additionally, both temperature and heat flow reduction are difficult to quantify in the absence of monitoring equipment, which was the case for most of the case study projects. The green roof atop Chicago City Hall, however, was fitted with thermal data collection equipment; the roof garden there was projected to save the city \$3,600 in heating and cooling per year (Weston, 1999), or \$0.18 per square foot (\$1.90 per square meter) of green roof per year. Vegetative solar shading at the roof and walls of Ford’s truck plant minimizes heat gain. According to Green Roofs for Healthy Cities, the project’s engineers expected the green roof to reduce energy use by seven% (GRHC, 2004b). To help verify these claims, Ford has recruited experts from governmental organizations and the University of Michigan to collect and interpret building performance data (Litt, 2004). Daniel Bedard, construction manager at the Woodward Academy, expected the thermal benefits of the green roof on the Art Building to offset, at least in part, the higher cost of

green power purchased by the school in the form of renewable energy certificates (personal communication, September 23, 2004). These certificates support the use of wind, landfill natural gas, and solar energy sources. In all cases, further study is needed to determine the energy benefits to be derived from green roofs.



Figure 4.2 - MEC Toronto

4.2.3. Acoustics

Acoustical concerns did not feature prominently in any of the case study projects evaluated to date. As mentioned in Section 3.3, noise attenuation is a driving design consideration in structures located near airports.

4.2.4. Structure

Structure can be viewed as a controlling factor in most of the case studies, limiting the weight of the green roof system and therefore the depth of medium and type of plants selected. At Montgomery Park, because the 20,000-square-foot (2,000-square-meter) green roof was installed over an existing train shed, weight considerations controlled the design and required the existing steel roof framing to be structurally augmented. The green roof system used had a saturated weight of only 18 pounds per square foot (psf) (88 kilograms per square meter (kg/m^2)) (MDE, 2004b). The design of the roof garden at Chicago City Hall, seen in Figure 4.3, reflected the structure of the existing roof deck. According to Kevin Laberge, environmental engineer with the City of Chicago (personal communication, July 16, 2004), the trees located in the intensive planting areas (18 inches (450 mm) deep) were centered over building columns, while semi-intensive planting areas (4 to 8 inches (100 to 200 mm) deep) were situated in raised beds that coincided with former skylights. The remainder of the roof garden was an extensive design (3 to 4 inches (75 to 100 mm) deep). According to project specifications, the maximum

allowable structural weight of these planting areas was 90 psf (440 kg/m²), 75 psf (370 kg/m²), and 30 psf (150 kg/m²), respectively. To avoid overloading the existing structure, polystyrene insulation above the roof membrane was used to create the contours of the garden.



Figure 4.3 - Chicago City Hall

At the Woodward Academy's new art building, seen in Figure 4.4, load constraints on the roof structure limited the green roof load to 35 psf (170 kg/m²), according to R. Alfred Vick (personal communication, September 23, 2004), the project's landscape architect. The growing medium was saturated with water and subjected to a load test to determine the maximum allowable depth of 6½ inches (160 mm). The green roof modules were installed above 3 inches (75 mm) of gravel ballast to prevent roof membrane uplift, which was especially critical in the absence of a parapet wall at the roof perimeter.



Figure 4.4 - Woodward Academy

Table 4.2 - Saturated weight of case study green roof systems

Case Study Project	Saturated Weight of Green Roof System
Montgomery Park Business Center	18 psf (88 kg/m ²) (MDE, 2004b)
Life Expression Chiropractic Center	28 psf (140 kg/m ²) (Miller, 2002)
Chicago City Hall	30 to 90 psf (150 to 440 kg/m ²) (per project specifications)
Ford Dearborn Truck Assembly Plant	11 psf (54 kg/m ²) (Russell, 2004)
Mountain Equipment Cooperative (MEC)	38 psf (190 kg/m ²) (Johnson, 2003)
Jordan N. Carlos Middle School Art Building	35 psf (170 kg/m ²) (R. Alfred Vick, personal communication, September 23, 2004)

4.2.5. Compliance

Frequently, a green roof is implemented to satisfy a company or governmental policy or to demonstrate a new technology, rather than due to economic benefits expected over its life cycle. Code requirements often support the use of green roofing as a measure to improve the quality of the urban environment. The Montgomery Park Business Center's green roof, seen in Figure 4.5, was part of a larger set of strategies that led to the project winning the U.S. Environmental Protection Agency's Phoenix award for excellence in brownfields redevelopment. The green roof contributed to satisfying the Code of Maryland Regulations for redevelopment projects by reducing the site's imperviousness (MDE, 2004a). The green roof atop Chicago City Hall was the initial demonstration project of the Chicago Department of Environment's Urban Heat Island Initiative (Weston, 1999). Results of the project included guidelines for future green roof projects in Chicago, a performance specification for green roofs, and data demonstrating environmental benefits. Building codes also limit the use of green roofs as occupied space in some cases. Access to both Chicago City Hall's green roof and the modular green roof system on the art building at the Woodward Academy in Atlanta was limited to maintenance personnel and escorted visitors due to liability considerations in the absence of a parapet or railing at the roof edge of both projects.



Figure 4.5 - Montgomery Park

4.2.6. Cost

Cost was perhaps the most complex parameter, and was often tied to compliance with governmental or other incentives. The Ford Motor Company hired William McDonough + Partners to assist in the revitalization of the Ford Rouge complex, seen in Figure 4.6, a project slated to take 20 years and \$2 billion. McDonough estimated that the green roof alone saved the company \$5 million by avoiding the construction of a new storm water treatment plant, which would have otherwise been required (Litt, 2004). In many of the projects, cost was intertwined with other factors, such as the desired thermal benefits of the system or the need to upgrade the roof structure to support a green roof. Performance goals for the green roof were often balanced with the need to specify a system that would meet budget constraints. Further investigation is needed to derive meaningful relationships between cost and other parameters.



Figure 4.6 - Ford Rouge Plant

Information gleaned from the case studies supports and informs the analytical processes described within the green roof evaluative categories outlined in Sections 3.1 through 3.6.

Although an effort was made to select case study projects representing a variety of different project locations, building sizes and green roof types, the case studies do not fully represent the possible range of green roof system types and project characteristics to be evaluated by the framework. The literature review and analysis of additional green roof projects found in Chapter 3 provide a more comprehensive picture of the factors affecting green roof system design.

4.3. The Systems Approach

The systems approach was defined by Thomas K. Jewell (1986) in *A Systems Approach to Civil Engineering Planning and Design* as “a framework for analysis and decision-making” (p. 13). The text made explicit the rational skeleton behind effective design and planning processes that lead to optimal or near-optimal solutions. The systems approach, according to Jewell, should result in affirmative answers to the following questions:

1. Did the systems approach make the debate over the best choice of alternatives more rational and informed?
2. Did the systems approach introduce competitive alternatives that might not otherwise have been considered?

Systems analysis was viewed as a kit of mathematical tools that may be applied judiciously in support of the systems approach, but which do not constitute the process itself, as shown in Figure 4.7.

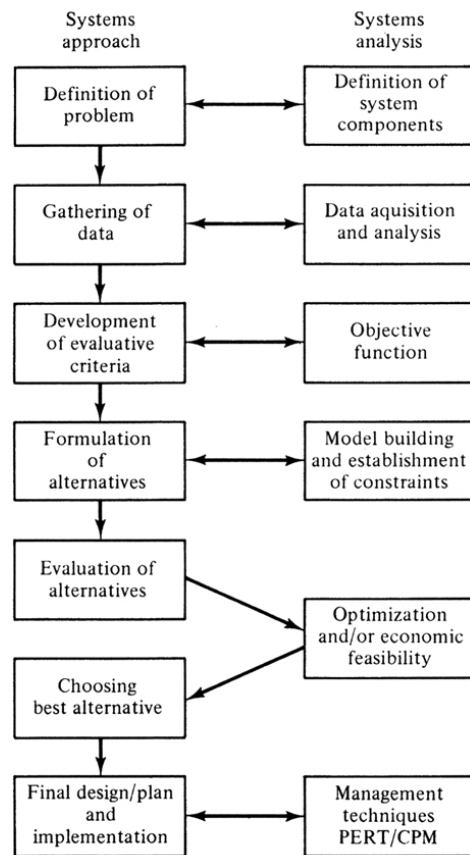


Figure 4.7 - Planning and design process (Jewell, 1986, p. 6), permission to use granted by: Thomas K. Jewell (March 6, 2007)

They instead provide quantitative measures of performance to be applied to the design process where and when appropriate. The design process, defined by Jewell (1986) as “the process of determining the specific form of an end product” (p. 8) was viewed as an implicit, often open-ended procedure that must be learned through experience and practice, and which must often be undertaken with incomplete or changing data. The more explicit systems approach was described by Jewell as an augmentation of, rather than a replacement for, the design process.

The systems approach is comprised of seven steps, with feedback loops, as shown in Figure 4.8.

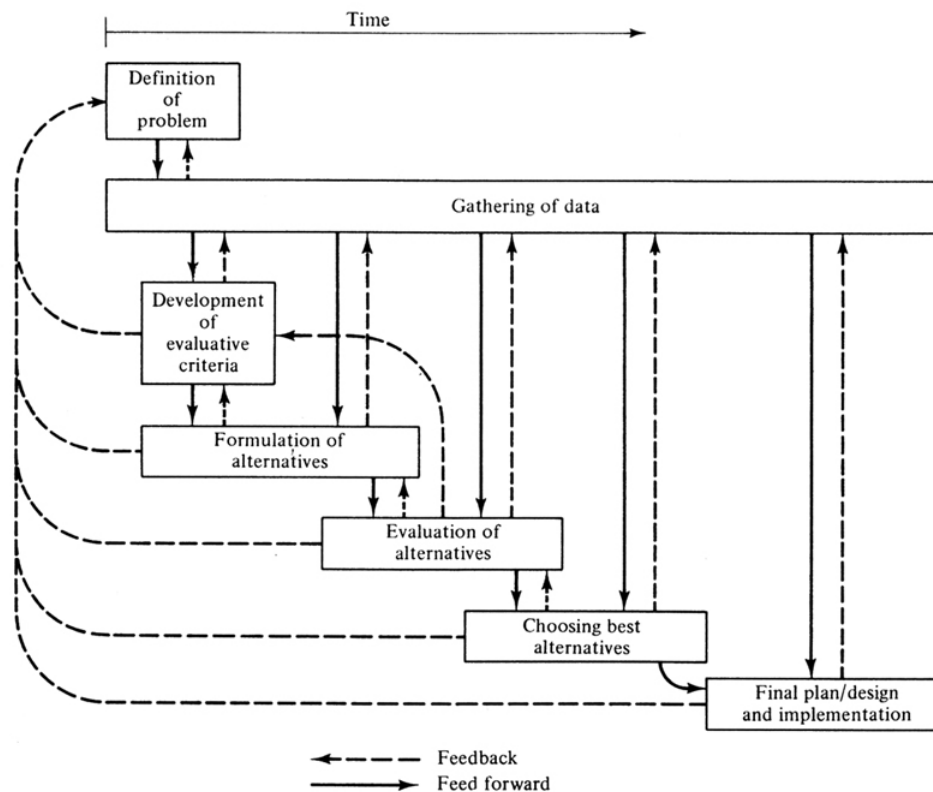


Figure 4.8 - Activity overlap and feedback within systems approach (Jewell, 1986, p. 14), permission to use granted by: Thomas K. Jewell (March 6, 2007)

To use the systems approach, the components of the system must first be identified. Because components may themselves be sub-systems, Jewell advocated the creation of a pyramid, or hierarchy of systems. Jewell traced this approach back to Aristotle's hierarchy of biological systems, and acknowledged that while it may not account for the complexity of non-hierarchical relationships, it provides a useful abstraction of reality that enables the decision-maker to address the problem at the appropriate level of specificity, and consequently to employ the appropriate analytical tools.

In building design in general, and vegetated roofing systems design in particular, there are a variety of quantifiable and non-quantifiable requirements that must be addressed. These can be classified in terms of Vitruvius' three objectives for architecture: firmness, commodity and delight. The order in which Vitruvius listed these characteristics is telling:

All these types of buildings must be built with due reference to durability, convenience and beauty. Durability will be assured when foundations are carried down to the solid

ground and materials wisely and liberally selected; convenience, when the arrangement of the apartments is faultless and presents no hindrance to use; and when each class of building is assigned to its suitable and appropriate exposure; and beauty, when the appearance of the work is pleasing and in good taste, and when its members are in due proportion according to correct principles of symmetry (Vitruvius, 1960, p. 17).

It seems appropriate that buildings be first sound, next accommodating, and finally, inspirational. One cannot normally ensure the second characteristic without the first, nor the third without the first two.

While it may also satisfy important spiritual, psychological, and spatial conditions, the primary function of a roof, vegetated or otherwise, is to support itself and any superimposed loads, and to protect the occupants of the building from the weather. Therefore, it is possible to develop a hierarchy, as seen in Figure 4.9, which provides for these most basic needs, and which includes the chief components of vegetated roofing systems and related systems described generically. These components are shown shaded in Figure 4.9. A typical cross-section of a vegetated roof system depicting these components is illustrated in Figure 4.10, and was first introduced in Chapter 2, where each of these components was explicated.

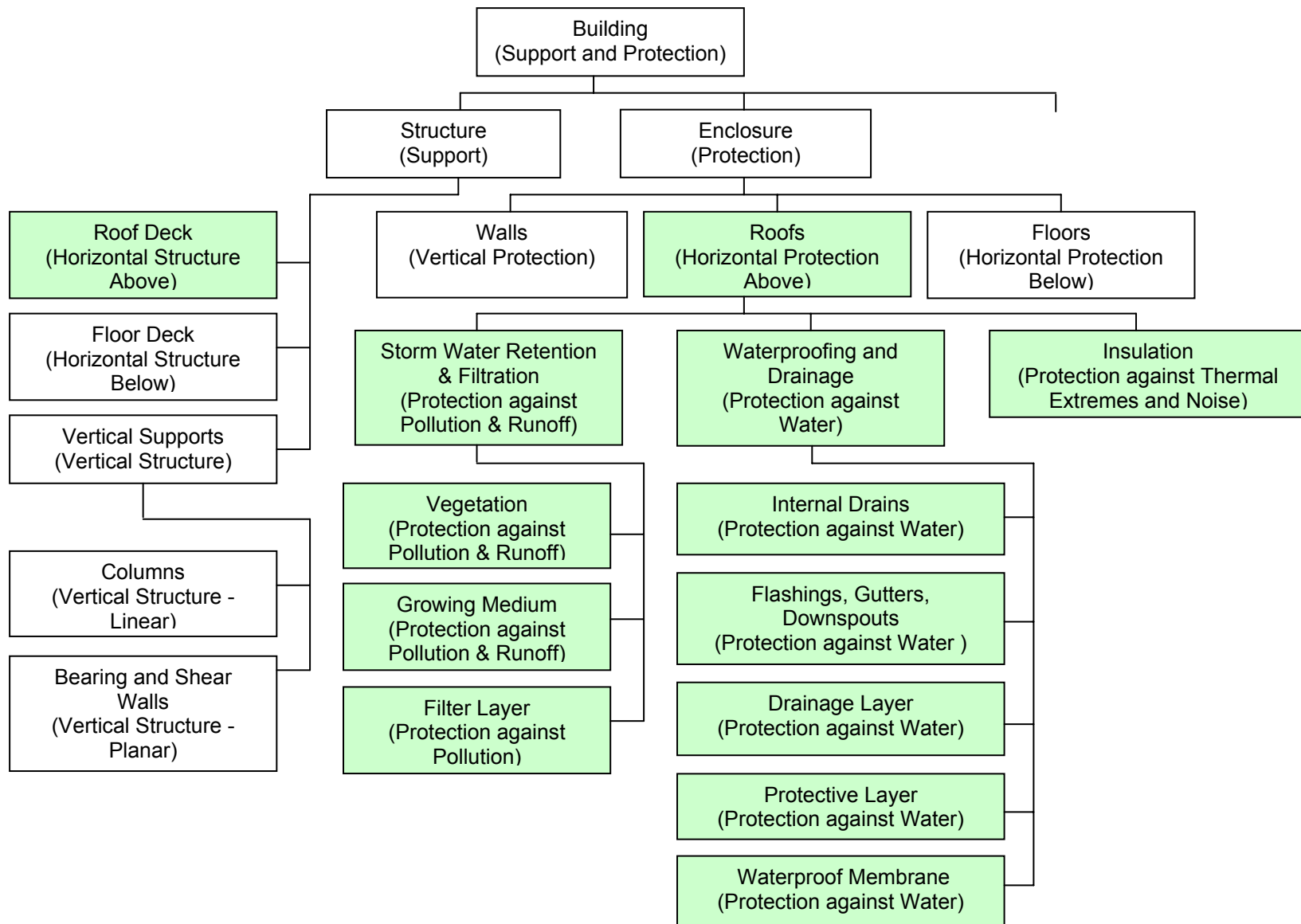


Figure 4.9 - Partial hierarchy of building components

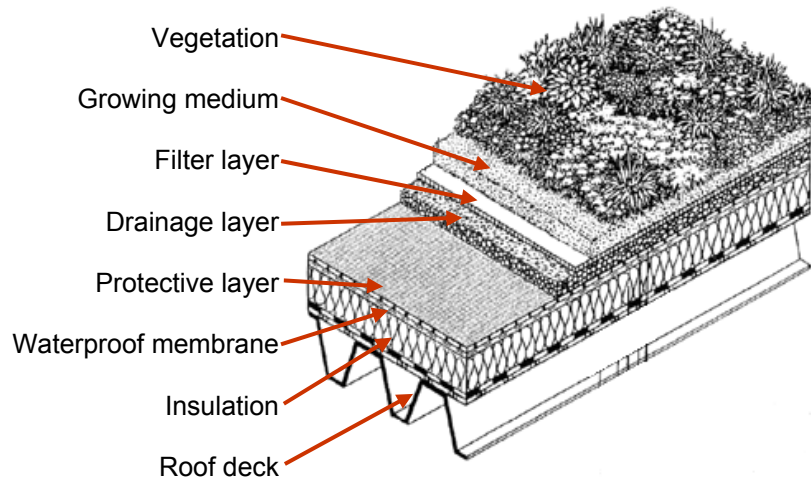


Figure 4.10 - Typical cross-section of a vegetated roofing system (Miller, 2006), permission to use granted by: Stefan Zeller, Optigrün International AG (April 10, 2007)

This hierarchy, used to rank systems and subsystems in a manner useful for analysis, must be recognized as satisfying only the most elemental requirements of a green roof, but those requirements crucial to its success. Fulfilling these functions does not necessarily make a vegetated roof an attractive or uplifting space, but without adequately satisfying these needs, the roof cannot achieve the higher levels of performance for which its designers strive. The hierarchy shown in Figure 4.9 can be seen as a point of departure; the analysis of performance at this level must be coupled with more subjective measures to provide a complete picture of what vegetated roofing ought to be. In the tradition of Vitruvius (1960),

After the standard of symmetry has been determined, and the proportionate dimensions adjusted by calculations, it is next the part of wisdom to consider the nature of the site, or questions of use or beauty, and modify the plan by diminutions or additions in such a manner that these diminutions or additions in the symmetrical relations may be seen to be made on correct principles, and without detracting at all from the effect (p. 174).

The systems approach involves the discovery of the environment of the problem. This environment cannot only be seen as physical, it is temporal as well. Therefore, it is important to view green roofs in their historical context to learn from past successes and failures and to understand the factors motivating owners to request them and architects to design them. It is also critical to view the lateral effects of the increasing popularity of vegetated roofing in the U.S., including effects on storm water management, energy use, public policy, the design

community, and the construction industry, among others. Future implications of this trend must be taken into account as well, such as the reframing of ideas about accountability for site runoff, the potential role of green roofs on mitigating the urban heat island effect, the rethinking of design and construction roles, and the new nature of roof maintenance where these systems are implemented. Jewell (1986) asserts that, as shown in Figure 4.8, data acquisition must continue throughout the decision-making process, potentially catalyzing a feedback to an earlier stage. This recycling is the key to finding a solution to a given problem that incorporates the best information available.

Jewell (1986) pointed to the “principle of least commitment” (p. 14) which allows all viable alternatives to be maintained as long as possible, reducing the risk that an optimal solution will be omitted before it is discovered. This principle justifies the need for a rigorous, rational approach to the design of vegetated roofs undertaken during the earliest possible phases of design, before the construction documentation, contracting and implementation phases of the project are reached and firm commitments to a particular design are made. Jewell also warned that as the complexity of a problem increases, the optimization of all subsystems is decreasingly reliable as a measure of the optimization of the whole system. In these cases, it may be necessary to look for a nearly optimal solution that best satisfies multiple objectives and priorities.

The systems approach itself incurs several obstacles, which will be examined here in the context of the attempt to generate a decision-making framework for vegetated roofing system selection. According to Jewell (1986), these include “perceptual, cultural, and habitual obstacles” (p. 15). First, it is difficult to motivate people to consider relationships and effects that are not immediately perceptible. For example, it is quite easy to neglect the contribution of a single building to the urban heat island effect or the overtaxing of a city’s storm sewer system or combined sewer system. The need for responsible stewardship may thus be ignored where results are not immediately seen or felt. Second, cultural mores may be hard to overcome. The roofing community has believed for thirty years or more that roofs should not hold water. To change this deep-seated perception will take significant convincing. Third, habit dictates the use of many tried and true roofing systems. In fact, the U.S. legal system tends to penalize innovative designs. In this litigious climate, many designers do not have the time or incentive to evaluate systems with which they are unfamiliar, and so habitually rely on those systems with which they are most familiar. All three of these obstacles must be overcome with a systematic

approach to selecting vegetated roofing systems that fundamentally addresses these concerns in the most rational, defensible way possible. In Jewell's words, "Engineers [or other designers] will also generally be responsible for constructing a theory of reality (model) which will guide all interested parties in their observations of the problem, which in turn will help in the revision of the theory of reality" (p. 15). To create such a theory of reality in the realm of vegetated roofing design is the goal of this research. The following sections address the steps of the systems approach as laid out in Figures 4.7 and 4.8.

4.3.1. Problem Definition

In defining a problem, some abstraction of reality is required. The most important factors must be incorporated into the problem statement, or must be viewed as inputs or outputs to the problem-solving process. These factors should be kept as general as possible to include the highest number of feasible solutions. A balance between computationally necessary abstraction and realistic comprehensiveness needs to be sought.

4.3.2. Data Gathering

This is an ongoing process throughout the systems approach as seen in Figure 4.8. As more data are acquired, they should be fed back into previous stages of the process to improve the solution. Statistical tools, such as sensitivity analysis, can afford some measure of the usefulness and applicability, as well as reasonable error bounds, of data at various stages of the process. Anticipated data collection relative to vegetated roofing systems and system components is shown in Figure 4.11, grouped into the hierarchical list of components shown in Figure 4.9. In Figure 4.11, the bold type represents the components.

The quality, availability and reliability of these data are by no means uniform. Some data are widely accessible, other data were extracted from various case studies; some were derived from interviews with experts, while some will need to be gathered from ongoing or future research projects. During the course of investigation, more components and data sets were discovered and were integrated into the hierarchy of components as the project progressed. In fact, one of the contributions of this research is an identification of data needed so that these knowledge gaps may be filled by future studies. The data listed vary from objective to subjective, and hence are processed in different ways. Methods for incorporating qualitative data are discussed in Section 4.4. Not all of the data are relevant to every decision. Criteria used to limit the

complexity of the decision by eliminating irrelevant information are incorporated into the decision-making framework.

Building

Structure

Roof Deck

- Historical data on outcomes of green roofs with various roof decks

- Structural data on roof deck allowable loads

- Thermal and moisture data on heat and vapor migration through roof decks

Enclosure

Roofs

- Data on contribution to heat island reduction

- Data on acoustical performance

- Data on comparative weights and costs of materials with similar acoustical properties

- Data on initial, maintenance and life cycle costs

- Data on financial value of green roof to owner

- Data on offset costs of other storm water BMPs

- Data on cost of needed structural upgrades

- Data on cost of accessibility and life safety features needed

- Data on degree of compliance with governmental incentives and LEED criteria

Storm Water Retention and Filtration

- Runoff volume and rate data

- Data on pollutants and temperature of runoff water

- Data on roof contribution to compliance with storm water regulations

Vegetation

- Measures of hardiness, wind resistance, and drought tolerance

- Weight data

- Availability and price data

- Evapotranspiration rates

- Data on thermal effects of evapotranspiration

- Leaf area indices

- Foliage heights

Growing Medium

- Saturated weight data

- Porosity

- Data on water retention properties

- Water content at field capacity

- Data on pollutant sorption

- Cation exchange capacity (CEC)

- Data on thermal performance

- Availability and price data

Filter Layer

- Silt retention data

- Availability and price data

Waterproofing and Drainage

Internal Drains

- Data on root- and silt- preventative properties

Flashings, Gutters, Downspouts

- Data on root- and silt- preventative properties

	Drainage Layer
	Data on drainage capacity Data on plant performance when used
	Protective Layer
	Data on root-preventative properties Data on membrane-protective properties
	Waterproof Membrane
	Data on uplift resistance Data on expected life
Insulation	Data on thermal performance
	Data on acoustical performance
	Data on compressive strength
	Data on moisture resistance

Figure 4.11 - Vegetated roofing system data needed

4.3.3. Development of Evaluative Criteria

In the creation of evaluative criteria, tradeoffs must often be made between various objectives. One way to accomplish this is to write an objective function with a set of constraints. Each constraint is a competing objective set at a given performance level. One dominant objective is left out of the constraint set; this becomes the objective function. Frequently cost effectiveness is used as the objective function with all other objectives formalized as constraints on that function. Based on sources read during the literature review there appear to be seven main objectives of vegetated roofing:

- 1) To maximize the positive influence of a building project on the environment
- 2) To maximize storm water mitigation
- 3) To minimize energy usage
- 4) To maximize acoustical performance
- 5) To minimize roof system structural loads
- 6) To maximize compliance with regulatory and performance criteria
- 7) To minimize roof system cost

While cost is always an important factor, the current high capital cost of green roofs makes them non-competitive with other roof systems in North America. The lack of widespread incentives such as increased warranties and storm water mitigation credits means that, at present, those who choose green roofs for their projects do so primarily for reasons other than financial ones. Even in cases where cost might appear to be the dominant factor, such as at the Ford Rouge

project in Dearborn, Michigan⁶, the financial case is usually made in a much broader project context. At Ford Rouge, factors outside the green roof project itself were sufficiently compelling to make the green roof financially preferable to other storm water mitigation measures, despite the fact that the initial cost estimates for the green roof exceeded the cost of a traditional roof by a factor of two to three (Russell, 2004). A holistic view of the project environment is ideal and should be encouraged in the decision-making process. However, for the sake of simplicity, this model must assume that the decision to implement a vegetated roof will be made based on a comparison with more conventional roofing systems, rather than solely in comparison with other storm water management systems, though this may be a heavily weighted advantage of some green roof systems considered within the analysis. In light of the impetus to achieve LEED credit and the desire to project a “green” image that seem to be the major driving forces for the trend toward incorporating vegetated roofing technology in North America, an assumption is made that the objective function is number 1 above, subject to numbers 2 through 7 as constraints.

4.3.4. Formation of Alternatives

According to Jewell (1986), alternative formation involves the construction of mathematical models to assist in the decision-making process. He described model building as both a science and an art. The model used must be sufficiently abstracted to be mathematically viable, but also sufficiently comparable to reality to be useful. There should be some way to test and calibrate the model. Methods for testing the acceptability of models are discussed in Section 4.8. Jewell also made the important point that where and when objective criteria paint a distorted picture of the situation, subjective criteria ought to be incorporated into the model. The model-maker must be vigilant and maintain a critical view of the model at all times, refining the model as necessary.

There are two types of variables in mathematical models, independent (or decision) variables and dependent variables. The modeler has control over the independent variables. Examples of independent variables in vegetated roofing are:

- 1) Type of vegetation
- 2) Type of growing medium

⁶ See discussion of case study projects in Section 3.8 and Appendix A.

Examples of dependent variables are:

- 1) Storm water quantity reduction
- 2) Heat flow reduction
- 3) Sound transmission reduction
- 4) Roof system weight
- 5) Degree of compliance with LEED criteria
- 6) Life cycle cost

Jewell (1986) described three types of models that can be used within the context of the systems approach: synthetic, descriptive and prescriptive. With systems synthesis, the modeler is able to initially design a system with certain inputs, or independent variables, and evaluate the resulting outputs, or dependent variables. Based on this information, the design can be further developed. In vegetated roofing, this process might be executed in the form of schematic roof designs which could be evaluated more inexpensively than full-blown roof designs. The schematic designs would enable designers to learn the relationships between inputs and outputs before committing to a final roof design. With a descriptive model, the modeler inputs the necessary data to a degree of precision necessary to derive an output with a given level of accuracy. This model would be useful in determining the performance of a specific roof design. In contrast to this, prescriptive models, which include optimization and near-optimization models, actually assist the modeler in choosing the design that will best meet a set of criteria. This facility would be extremely useful in the design phase because it would allow the designer to differentiate between inferior and non-inferior solutions before a significant amount of time has been invested in a particular solution. The prescriptive model best describes the framework to be developed in this dissertation.

4.3.5. Evaluation of Alternatives

An evaluative model should be applied to each potential alternative design. Sensitivity analysis will help determine which independent variables have an effect on the analysis, and which are irrelevant to the outcome. Based on the use of the prescriptive model, there will likely be several non-dominated solutions to the design problem. In this case, a qualitative choice needs to be made between alternatives using a decision-making methodology.

4.3.6. Choosing the Best Alternative(s)

It is important to realize that the optimum or near-optimum solution of a quantifiable analysis method needs to incorporate any non-quantifiable aspects that defy mathematical analysis, as well as economic factors that affect its implementation. An appropriate methodology for decision-making needs to incorporate all three types of evaluation and the framework itself must be structured to support this agenda. Julie Suhr Nelson (2000) made a case for the Choosing By Advantages (CBA) decision-making system, which acknowledges the unavoidably subjective nature of all decisions, even those made with the benefit of decidedly objective data. The CBA method determines the best alternative by totaling the advantages of each alternative, a process that requires a subjective rating of the importance of all relevant differences between alternatives. This process, and the CBA method, are discussed in Section 4.4.4.

4.3.7. Final Planning/Design and Implementation

From the beginning of the design process to the start of project implementation, the goals of the project may have shifted or changed. It is therefore important to check the results of analyses against the project's current objectives, and provide for reworking the problem if new, relevant information pertains. When making recommendations to the designer based on the results of a systems approach, it is crucial to define the terms of the analysis and its constraints. To enable designers to accept any recommendations arriving from the implementation of the systems approach, it is necessary to explain the tools used in the analyses and cite examples of the successful use of these tools in the past. Jewell (1986) warned that it is important to plan for the construction process where complex subsystems are involved; the best theoretical designs are only as good as their weakest field application. Roofing, especially vegetated roofing, is notorious for failures due to workmanship, so this element must be addressed in all recommendations regarding green roof system selection.

4.3.8. Application to Vegetated Roofing Research

Jewell (1986) stated that,

Meta Systems (1975) has described the optimal situation for application of systems analysis as being when conditions are changing too rapidly for new information to be assimilated by informal, unsystematic methods, but slowly enough to permit the development of a model that reflects the recent past and can predict the relevant future (p. 27).

Vegetated roofing as a sub-industry in North America appears to fit this situation. Architects and roof consultants frequently cannot rely solely on intuition or past experience when designing these systems, yet they could benefit from a framework for decision-making that draws from the experience of successful (and unsuccessful) applications of such systems worldwide, and that points toward trends in the industry in North America. The use of this framework, coupled with their own technical competence and judgment, will enable roof designers to better implement vegetated roofing system designs.

4.4. Accommodating Qualitative Validation

Most complex decisions cannot be made based on purely quantifiable metrics. The selection of vegetated roofing systems includes both quantifiable and qualitative parameters that must be accounted for in satisfying the fundamental objective of maximizing the positive influence of a building project on the environment. In addition, the outlook and priorities of the person making the decision must be made explicit in the decision analysis.

Robert Clemen (1996) provided a detailed and useful methodology for rating the attributes of alternatives according to criteria incorporated in decision analysis models, which he calls “fundamental objectives”. Some fundamental objectives inherently possess a natural scale, for instance, maximizing profit or minimizing temperature fluctuation. These scales have built-in levels relating quantities to one other, and are defined as interval scales with a meaningful separation between values (such as temperature), or as ratio scales with a true zero point (such as money). Such criteria allow simple comparisons between alternatives. But in a criterion where a natural scale is absent, a scale must be somehow included to permit evaluation of the degree to which a particular outcome will satisfy that criterion. Clemen offered two options in this case. Either a slightly different and closely related criterion with a natural scale may be used in place of the desired criterion, or an attribute scale may be constructed to measure achievement of the criterion.

4.4.1. Monetary Value as a Proxy Scale

Monetary value is frequently selected as a proxy scale for intangible criteria. In the discussion of non-monetary decision-making in Ron Wakefield’s Spring 2004 Engineering Economics and Decision Making course at Virginia Tech, several strategies for translating intangibles into monetary value were introduced. Financial values can be derived from the use, option and existence values of a commodity. In the case of green roofing, a use value could reflect the

cost benefit of employing a green roof for storm water mitigation, for energy use reduction, or as occupied space. The option and existence values refer to the value of the option for future use of a commodity and the value of the mere existence of the commodity without regard to personal use, respectively. The existence value in particular could account for the value of a green roof as a neighborhood amenity and as a mitigation device for urban storm water and heat island effects, because the financial value of these benefits to society are separate from the benefits to the building owner.

There are two methods for estimating the monetary equivalent of use, option and existence values: shadow pricing, which typically applies only to use value, and contingent valuation, which applies to all three types of values. Shadow pricing essentially determines the market value of characteristics of the commodity through techniques including cost of avoidance, indirect valuation, and hedonic pricing. For a green roof, one might determine the financial value of an on-site storm water management device that can be avoided by installing a green roof, the cost of insulation needed to achieve the same energy savings as that provided by a green roof, or the increase in property value gained by including a roof garden in a building project. Contingent valuation is derived from a survey instrument that determines the financial value to an individual of a commodity that has no presently calculable market value. In the case of green roofing, the survey would ask respondents how much more they would be willing to pay to live in, work in, or otherwise have access to a building with a vegetated roof as opposed to a traditional roof. This method of valuation is complicated both by the need to construct a questionnaire about a hypothetical situation, and by the typical concerns attached to qualitative research study design, e.g. the construction of the survey instrument itself and the makeup of the respondent pool.

Evaluation using monetary methods in general is subject to controversy due to the differing viewpoints of those persons making the valuations, and equity issues related to the lack of involvement of some interest groups in the decision-making process. It is therefore important to undertake the valuation from a variety of viewpoints and to investigate alternative non-economic valuations where possible. This need has led to the development of methods such as the Delphi method, the Leopold matrix, the Battelle method, and various systems modeling techniques to evaluate the environmental performance of engineering projects.

Julie Suhr Nelson (2000), a proponent of the Choosing By Advantages (CBA) decision-making system described in Section 4.4.4, has also criticized the use of contingent valuation. She asserted that money can never legitimately be used as a measure of importance of subjective criteria. As evidence she explained that a stakeholder's willingness to pay (WTP) for a certain commodity is often less than the same stakeholder's willingness to accept (WTA) the loss of the same commodity, creating uncertainty in the proxy monetary value assigned to that commodity. More importantly, she states that money is not a measure of importance of a commodity, merely a measure of what that commodity is worth in the market. The commodity itself has an intrinsic value that is unrelated to its monetary value, which may fluctuate either with market conditions or with the budget constraints of the stakeholder in the decision. In other words, a commodity has a value that is not related to money, but is instead related to the "utility, enjoyment and satisfaction" (Nelson, 2000) afforded by that commodity. This value does not necessarily change when the price of the commodity rises, instead, the increase in price only limits the amount of the commodity a person or entity can afford to buy.

For these reasons, Nelson (2000) claimed that money must not be used as a measure of preference when selecting between alternatives. The CBA method excludes money from the initial decision-making process. In short, with CBA the selection process consists of summing the importance of the advantages of each of a series of alternatives. Once this process is complete, cost is included in the decision using one of several sets of money decision-making methods depending on whether the alternatives are mutually exclusive or non-exclusive. Essentially, decision-makers use the market prices, prospective returns represented by each alternative, and overall budget constraints to select from among alternatives. The distinction between this method and contingent valuation is that money is only used as a constraint determining which alternative or alternatives are affordable, not as a measure of the value of alternatives themselves (Nelson, 2000).

4.4.2. Constructing Attribute Scales

Returning to Robert Clemen's (1996) two options for the evaluation of intangible criteria, if a proxy scale such as money is not used to represent levels of achievement of a fundamental objective, an attribute scale must instead be generated for that objective. The scale is made up of a hierarchy of levels with detailed definitions that are applicable to all options being considered and which permit measurement of the outcome of each option. The scale can be

based on a qualitative description of each level of performance, or on a comparison to other projects of similar quality, or both.

In the context of vegetated roofing, an attribute scale is demonstrated within a value function describing the degree to which a green roof blocks the transmission of noise through the roof assembly. While this parameter is based on sound transmission loss (STC) ratings, human perception of such noise levels is a subjective measure and must be defined using descriptions. This value function is found in Section 5.5.

4.4.3. The Environmental Evaluation System, or Battelle Method

The Environmental Evaluation System (EES), or Battelle method (Dee, Baker, Drobny, Duke, Whitman, & Fahringer, 1973) is an approach to evaluating alternative solutions relevant to vegetated roofing system selection. This method allows incorporation of intangible criteria as well as quantifiable indices of performance by rating a system according to various categories. To develop the various environmental quality parameters, a hierarchical checklist is developed, divided into categories, components, and parameters. Each parameter is rated on a cardinal scale and then translated to environmental impact units (EIU) on a scale from 0 to 1, worst to best.

This calculation is performed in a three-step process. First, levels of a given environmental parameter are assigned “commensurate values” between 0 and 1. This step was designed to avoid the all-or-nothing approach of meeting the standards of many environmental parameters, e.g. maximum pollutant concentrations in storm water runoff or minimum R-value of a roof system. The commensurate value differentiates between a design that merely meets a standard and one that provides additional benefits and/or avoids additional damage to the environment. The environmental quality values are assigned based on “value functions” that relate a measurable level of a parameter on the x-axis to an environmental quality level ranging from 0 to 1 on the y-axis. This process is essentially the construction and rating of an attribute scale for an otherwise non-quantifiable parameter as discussed in Section 4.4.2.

Second, each parameter is weighted based on its relative importance. The weights of all parameters combined must equal a constant; the Battelle method uses 1000 parameter importance units (PIU) distributed among the various parameters of the EES. In the Battelle study, the weight factors assigned to each parameter were generated by a team of experts’

subjective valuations obtained through a methodology of ranked pair-wise comparisons and selected feedback to the team members. The weighting factors, thus carefully generated, were intended in the Battelle study to remain constant for all projects evaluated. The authors cautioned that if the weighting factors were to change for each investigation, it would be the responsibility of the EES's user to reassign them, which could lead to results that would be hard to reproduce.

It is clear that within the context of an investigation of a set of competing alternatives, weight factors should be consistent for the duration of the investigation. It is also desirable to establish a set of weight factors based on a process similar to that used in the Battelle study; that is, determined by the value judgments of a group of well-informed experts. However, since the framework for decision-making in vegetated roof system selection is intended to be used by a wide range of practitioners, and since each green roof design project is unique, each decision-maker must be permitted to assign value to the advantages represented by different green roof systems in accordance with geographical and physical context of the building project and the priorities of the stakeholders in the decision. A method designed to provide this adjustability without undermining the operation of the framework is discussed in Section 4.4.4.

The third and final step in the Battelle methodology is the summation of the weighted parameters to determine the Environmental Index (EI) of the project outcome, calculated as shown in Equation 4.1. The higher the EI, the more desirable the project.

$$EI = \sum_{i=1}^m w_i [(V_i)_1 - (V_i)_0]$$

Equation 4.1 - Environmental Index Calculation

where EI is the environmental index, w_i is the relative weight of parameter i , $(V_i)_1$ is the environmental quality of parameter i *with* the project, $(V_i)_0$ is the environmental quality of parameter i *without* the project, and m is the total number of parameters (Dandy & Warner, p. 138).

Decision-making systems such as the Battelle method that multiply predetermined weight factors by measures of quality have been criticized for divorcing subjective valuation from the

specific context of the decision at hand, potentially resulting in distorted outcomes (Suhr, 1999). Ways to address this concern are discussed in Sections 4.4.3.1 and 4.4.4.

4.4.3.1. *Adaptation of the Battelle Method to Vegetated Roofing*

Despite the arguable flaws in its weighting methodology, the basic approach of the Battelle method is applicable to the selection of vegetated roofing systems. Green roofs are in most respects additive to traditional roofing systems and are therefore relatively simple to compare to a reference roof system. Specifically, the $(V_i)_0$ values seen in Equation 4.1 reflect the characteristics of a non-vegetated reference roof, as set by project-specific user inputs into the decision-making framework. The advantage of using the Battelle method is that green roofs can be compared to traditional roofs based on qualitative as well as quantitative data, and it is not necessary to convert all parameters to economic equivalents.

In the adaptation of the Battelle method for vegetated roofing system design, the process of assigning weight factors to parameters is replaced with a method based on the Choosing By Advantages decision-making system, described in Section 4.4.4. Because green roofs are considered desirable for different reasons depending upon the perspective of the building owner and the location of the project, it is necessary for the designer to adjust the weighting of the advantages represented by different green roof systems. For example, a designer of an urban apartment building in Portland, Oregon may be most concerned with storm water performance, while a designer of a suburban office building adjacent to an airport in San Bruno, California may be most interested in acoustical performance.

It is expected that conditions such as geographical location, urban density, and project- and roof-specific factors will influence the importance assigned to the advantages of each green roof system by green roof designers. It is further anticipated that, in the continuance of this research, the value functions used to determine the attributes of each system in terms of each parameter examined will be made accessible and updateable to the sophisticated user as new and improved information is obtained regarding the environmental impact of vegetated roofing systems.

4.4.4. The Choosing by Advantages (CBA) Decision-Making System

Choosing By Advantages is a decision-making system originally developed by Jim Suhr (1999) for the U.S. Department of Agriculture's Forest Service to help make complex resource allocation decisions in a multiple-stakeholder situation. The process is divided into five phases:

The Stage-Setting Phase, The Innovation Phase, The Decisionmaking Phase, The Reconsideration Phase, and the Implementation Phase. The third of these phases, the Decisionmaking Phase, was described in detail in *The Choosing By Advantages Decisionmaking System* (Suhr, 1999) and is itself composed of four steps. First, one must “summarize the *attributes* of each alternative” (p. 24). Second, one must “decide the *advantages* of each alternative” (p. 24). To accomplish this second step, one is required to “decide the least-preferred attribute in each factor” and then “determine the differences from the least-preferred attributes. These differences are the advantages of the alternatives” (p. 32). Third, one must “decide the *importance* of each advantage” (p. 24). Fourth, “if the costs of the alternatives are equal, choose the one with the greatest total importance of advantages” (p. 32).

The process differs from traditional “Weighting-Rating-and-Calculating” (WRC) methods, which include the Battelle method, because it involves weighing advantages of alternatives, rather than weighing factors or attributes of those alternatives. While he strongly acknowledged the need to incorporate subjective valuations such as weights in the decision-making process, Suhr argued that WRC methods are unsound because they do not tie these subjective weights to the actual facts of the decision situation. In his view, asking stakeholders in a decision to weigh factors amounts to asking them to weigh high-order abstractions. Without knowing the attributes of each alternative, and the degree and nature of the differences between these attributes, stakeholders cannot possibly compare them. According to Suhr, when factors are weighed in isolation, decision-makers automatically assume certain differences between alternatives and assign importance to these without grounding these assumptions in the reality of the situation. Even if the decision-maker has a very realistic picture of each alternative in mind, with WRC there is nothing present in the methodology to demonstrate the direct connection between the weights and the actual advantages one alternative possesses over others. This makes the weightings, and the resultant decision, difficult to justify to anyone not participating in the decision-making process.

The CBA process deliberately identifies only the advantages of alternatives, rather than advantages and disadvantages, in order to prevent double-counting and omissions, and to avoid the complication of negative values. Disadvantages of one alternative are simply redefined as advantages of one or more of the other alternatives. Perhaps the most critical feature of the CBA system is the importance scale, which is common to all the advantages of all the factors. To construct this scale in a complex decision, the decision-maker creates

preference scales or preference curves based on a series of questions which identify the subjective priorities of the stakeholder. This is done through a series of “defender-challenger” pair-wise comparison questions used to identify a paramount advantage, which is set as the upper limit of the importance scale. All other advantages, for all the factors of all the alternatives, are then rated on this scale. The process of identifying these priorities forces the stakeholders to consider the tradeoffs they are willing to make in terms of the actual attributes of the alternatives they are considering. This importance scale not only bases the decision in the reality of the situation at hand, but also serves to defend the rationale of the decision if necessary.

Costs are not included directly in the analysis described above. If the costs of the alternatives are unequal, or if the most-preferred system is not also the least expensive, cost is included in the analysis as a special factor. Suhr (1999) discussed the complexities of money, defined in CBA language as “an official message that serves as a medium of exchange”, as follows. A dollar has a different importance depending on how much money one has to spend, on the perceived benefit one may gain from that dollar, on the debt incurred when money is borrowed, and on the opportunity one loses to make other purchases once that dollar is spent (called the “principle of interdependency”). CBA does not view cost differences between alternatives directly as advantages, but rather as symbolic representations, or abstractions, of advantages. The CBA methodology used to deal with decisions involving money was explained in detail in *The Choosing By Advantages Decisionmaking System* (Suhr, 1999). Since the process is somewhat involved and multifaceted, it is not elaborated here.

4.4.4.1. Adaptation of Choosing By Advantages to Vegetated Roofing

The Choosing By Advantages system was initially developed to help the U.S. Forest Service manage land use. Kirk, Turk, and Hobbs (2005) discussed the importance of embracing value-based decision-making tools such as CBA. They mentioned the Reconsideration Phase as particularly valuable because it allows decision-makers to revisit the alternatives and potentially combine positive attributes from several of these in the creation of a new, integrated solution. Specifically, they cited the U.S. National Park Service’s use of CBA to make decisions based on the importance of advantages, rather than monetary value, and mentioned a case where the Park Service saved \$100 million through the use of CBA value methods. They issued a call for architects to include such decision-making methods to their list of skills in order to meet a wide range of goals: achieving desired architectural expression, maximizing both building and user

performance, optimizing life cycle cost, and achieving environmental quality. It is therefore reasonable to consider application of this decision-making process to the question of green roof system selection, a decision process with a similar degree of complexity to some land use decisions, albeit on a smaller scale.

One of the basic tenets of CBA is the Principle of Anchoring, which states that “decisions must be anchored to the relevant facts” (Suhr, 1999, p. 4). Another is to base decisions only on advantages, i.e. the relevant and perceivable differences between alternatives. This recognition both simplifies and intensifies the process of collecting and processing data. On one hand, only those advantages represented by the differences between attributes of one or more green roof systems over the others will need to be weighed. However, when it comes to weighing these advantages, there is no proverbial “free lunch”. It is not acceptable to weigh “high-order abstractions” such as green roof evaluative categories or parameters, without any description of what these weights are based on. Instead, a rigorous and thorough process of identifying attributes within each relevant factor for each green roof system must be conducted, and the advantages identified. Only then can the stakeholder in each particular situation identify the importance of each of these advantages.

In the framework for vegetated roofing system selection, the value functions described by the Battelle method are used to assign a value to the attributes of various green roof systems. However, the parameter-weighting methodology called for in the Battelle method is replaced with a project-specific, designer-specific method based on the weighting of the total importance of advantages between these systems, and accounting separately for the effect money has on the decision. Detailed interviews of individual green roof designers are conducted to assign these weights to demonstrate the framework’s functioning. In these interviews, the designers are asked a series of questions geared at identifying the importance they assign to the differences between certain generic green roof systems and others. The framework resulting from the creation of value functions for green roof attributes, coupled with subjective valuations of the differences between these attributes, is not conceived as an answer to the question, “Which green roof system should I select?” but rather as an answer to the question, “How should I go about making the selection?” That question must be answered by each designer, for each project. The framework assists the designer by describing, formalizing, simplifying and justifying the process of decision-making. Most importantly, it assures that the decision made is tied to the relevant knowledge about green roofs to the greatest extent possible.

4.4.5. Performance Rating Systems for Green Roofs: German Precedents

While one might argue with aspects of their methodology, it is useful to examine examples of green roof performance rating tools currently in use. In her review of green roof policies, Goya Ngan (2005a) has translated a performance rating tool used in Karlsruhe, Germany into English. She reported that in Karlsruhe, green roofs are employed as “ecological compensation measures” to satisfy requirements of German federal laws. The Karlsruhe rating tool evaluates green roofs according to five ecological parameters, which are assigned weighting percentages as follows: soil 15%, climate (evaporation) 15%, flora 30%, fauna 30%, and water balance 10%. Seven green roof systems, differentiated primarily by growing medium depth and plant mix type, are evaluated according to the degree to which they satisfy each of these five parameters. Total performance values for each of the seven systems are derived by multiplying the “percent function of nature balance achieved” by each system for each of the five ecological parameters by the weighting percentages assigned to each of these parameters, then summing the five subtotals. This approach is very similar to the operation of the Battelle method.

Ngan (2005a) also reported that the FLL (1998) has similarly developed a performance rating system for green roofs. While this rating system does not incorporate weights, it is separated into quantitative and qualitative parameters. The quantitative parameters are used to rate green roofs for planning, permitting and construction purposes while the qualitative parameters are often used to determine whether or not a green roof will qualify as an ecological compensation under Germany’s Federal Nature Conservation Act. In the quantitative index, points are assigned to green roof systems according to their root-penetrable depth (10 points per 0.4 inch (10 mm)) as well as for the “water retention capacity of the growing medium; water retention capacity of the drainage layer; number of plant species for extensive green roofs; and plant biomass for intensive green roofs.” The qualitative index gives a rating for each green roof system according to whether each of the following ecological compensation parameters are “possible to fulfill completely’, ‘possible to fulfill partially’, or ‘slightly or not possible to fulfill’”: soil; surface water; load shedding from the sewer system; groundwater recharge; purification of stormwater; filtering of air; oxygen production; temperature leveling; flora and fauna habitat; landscape and urban scenery; and people / leisure / healing” (Ngan 2005a, p. 29).

While certainly an important step toward providing consistency in evaluation of green roofs, these performance rating systems are apparently not widely implemented even in Germany.

Ngan (2005a) cited Stefan Zeller's (2002) research in which he reported that of 355 German municipalities responding to a survey, only 8% reported using a performance rating system for green roofs, and in these 29 municipalities, 24 different systems were used, with the FLL (1998) system being the most common (four municipalities). Ngan (2005a) also related Zeller's (2003) account of the desire to create a standardized performance rating system for vegetated roofs in Germany.

4.5. Framework Organization

To develop a workable list of factors for green roofing system selection, it is necessary to sort the pertinent parameters into a manageable number of categories. Six such categories have been identified:

- A. Storm Water
- B. Energy
- C. Acoustics
- D. Structure
- E. Compliance (with regulatory and performance criteria)
- F. Cost (this category will be incorporated as a special factor)

A graphic was developed to account for each of these categories and portray them visually, as seen in Figure 4.12.

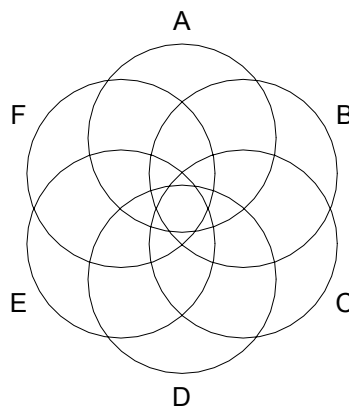
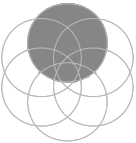
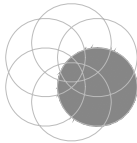
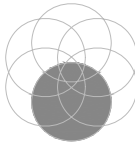


Figure 4.12 - Framework organization

Each of the circles represents one of the six categories. Table 4.3 illustrates the categories and their constituent parameters. Items appearing in gray indicate parameters for which no adequate evaluative criteria currently exist. Future research beyond the scope of this project will be necessary to fill in these blanks.

Table 4.3 - Framework parameters

					
A	B	C	D	E	F
STORM WATER	ENERGY	ACOUSTICS	STRUCTURE	COMPLIANCE	COST
Storm water retention	Potential energy savings	Approximate Sound Transmission Class	Surplus dead load of roof system	Potential contribution to LEED certification	Life cycle cost
Storm water pollutant control	Embodied energy and environmental impact	Approximate Noise Reduction Coefficient		Meets policy initiatives	
Runoff warming					

The Battelle method follows a specific hierarchy for the organization of evaluative criteria, which is represented in Figure 4.13 and which is adapted to suit the specific case of vegetated roofing system selection.

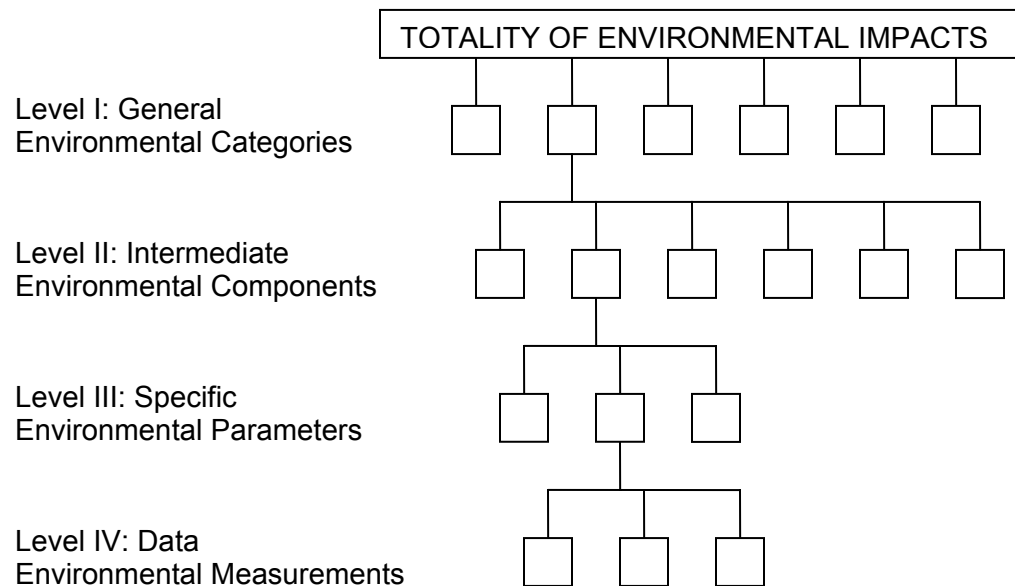


Figure 4.13 - Hierarchical structure of the EES, adapted from Dee et al. (1973, p. 524)

The structure of Figure 4.13 is translated into the framework for vegetated roofing system (VRS) selection as follows. The six categories listed as A through F at the beginning of this section serve as environmental categories. To avoid an unnecessary layer of complexity, the Battelle method's second level of specificity, the component, is not articulated separately here. Instead, each environmental category is broken directly into its constituent parameters. For example, the category Storm Water encompasses the parameters of storm water retention, storm water pollutant control, and runoff warming. Each parameter has a numerical value based on a value function, which is in turn based on empirical data or some other index of performance (see Figure 4.15 for a graphical depiction of a value function). For example, the value for storm water retention is given by a value function assigning an approximate percentage of storm water retained by the green roof based on the green roof system description. The framework can thus be represented as seen in Figure 4.14 and in Table 4.4.

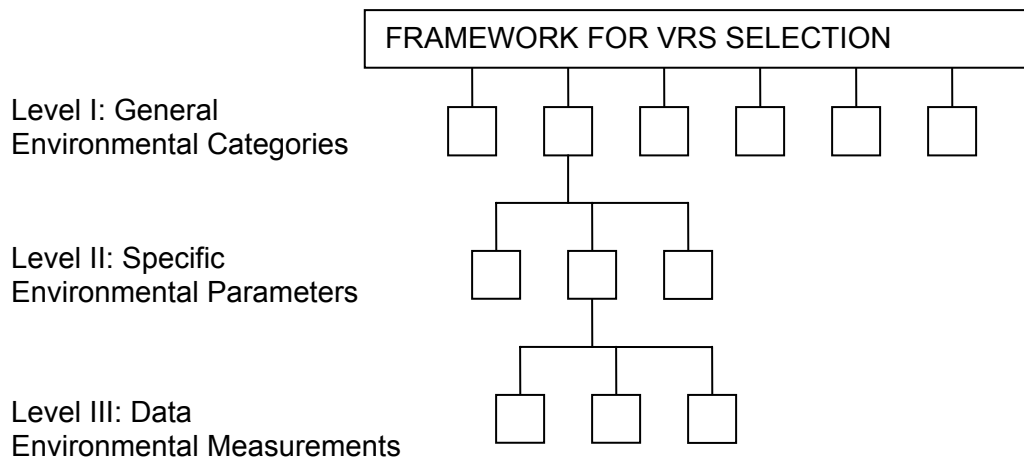


Figure 4.14 - Hierarchical structure of the EES, modified for the framework for vegetated roofing system selection

Table 4.4 - Framework breakdown

FRAMEWORK FOR VRS SELECTION
STORM WATER
Storm water retention
Storm water pollutant control
Runoff warming
ENERGY
Potential energy savings
Embodied energy and environmental impact
ACOUSTICS
Approximate Sound Transmission Class
Approximate Noise Reduction Coefficient
STRUCTURE
Surplus dead load of roof system
COMPLIANCE
Potential contribution to LEED certification
Meets policy initiatives
COST (treated as a special factor)
Life cycle cost

Like Table 4.3, Table 4.4 shows certain parameters shaded in gray. This shading signifies that there are currently insufficient data to legitimately include a value for these parameters in the

framework, but they are recognized as sufficiently important to be included as placeholders for future evaluations. Table 4.4 is further translated into a comprehensive diagram representing the complete green roof system design question using a graphical language identifiable to decision-makers from a variety of disciplines. This process is discussed in Section 4.5.2.

4.5.1. Flowchart of the Design Process

To define the attributes of a range of possible green roof systems, a set of values $(V_i)_1$ is calculated for a set of eight generic vegetated roofing system types (S_x) as identified by the *FLL Guideline* (2002), the source most cited in North American green roof specifications in the absence of North American guidelines. Using these predefined system types simplifies the framework and eliminates the need to identify proprietary systems. Rather than vary each sub-system variable (i.e. vegetation, growing medium, filter layer, drainage later, and protective layer) across its possible range, generating an unnecessarily cumbersome number of possible combinations, it is more useful to create a hierarchy of green roof system types based on system depth and plant type, in accordance with industry practice. The eight system types represent a sufficient range of differentiation among possible green roof system types and accommodate practically all possible green roof systems available in North America. The first five systems are classified by the FLL as extensive, while the last three are intensive.

Table 4.5 - Green roof system types S_x as derived from the *FLL Guideline* (adapted from FLL, 2002, p. 37)

Type of Greening	System Type S_x	Substrate depth (cm)	Substrate depth (in)	Plant type
Extensive greening	1	2.0 to 4.0	0.8 to 1.6	moss-sedum
	2	>4.0 to 6.0	>1.6 to 2.4	sedum-moss
	3	>6.0 to 10.0	>2.4 to 4.0	sedum-moss-herb
	4	>10.0 to 15.0	>4.0 to 6.0	sedum-herb-grass
	5	>15.0 to 20.0	>6.0 to 8.0	grass-herb
Intensive greening	6	15.0 to 25.0	6.0 to 10.0	lawn-perennial-small shrub
	7	>25.0 to 50.0	>10.0 to 20.0	lawn-perennial-shrub
	8	>50.0	>20.0	lawn-perennial-shrub-tree

Suhr (1999), in *The Choosing By Advantages Decisionmaking System*, made an argument against complicating a decision situation by evaluating a large number of factors with a high degree of interdependency. He used a colorful analogy to illustrate his point, stating that comparing two sundaes is not the same as comparing the constituent parts of each sundae; the quality of the sundae as a whole is the only relevant question. Likewise, Jewell (1986) warned that optimizing sub-systems makes optimization of the whole system less likely. There is a high degree of interactivity amongst the layers of a green roof system; to peel these apart and evaluate them in isolation is not only laborious, it is also inappropriate. Using eight generic green roof categories gives the designer enough information to be able to understand what type of green roof system to employ, and enables him or her to write a performance specification that allows for some variability in each of these layers, within certain performance ranges. This overcomes the barriers common to proprietary specifications, and allows for and perhaps even encourages innovation in the green roof industry.

Figure 4.15 is a flowchart of the decision-making process. Designer/Owner System inputs are divided into inputs such as Reference Roof Type and Characteristics and Project Location and Characteristics that determine the Design Constraints for the particular project contemplated, and Importance of Advantages and Budget Constraints that influence the weighing of the total importance of advantages of each alternative system. The Design Constraints influence the value functions used to define the attributes of the reference roof and the green roof systems for the project. The characteristics of the eight generic green roof systems are built into the framework. The output of the framework, resulting from the CBA Tabular and Cost Factor Methods, is a possible solution. This solution is re-evaluated in the CBA Reconsideration Phase, explained in Section 4.9. Finally, the designer selects a roofing system for implementation.

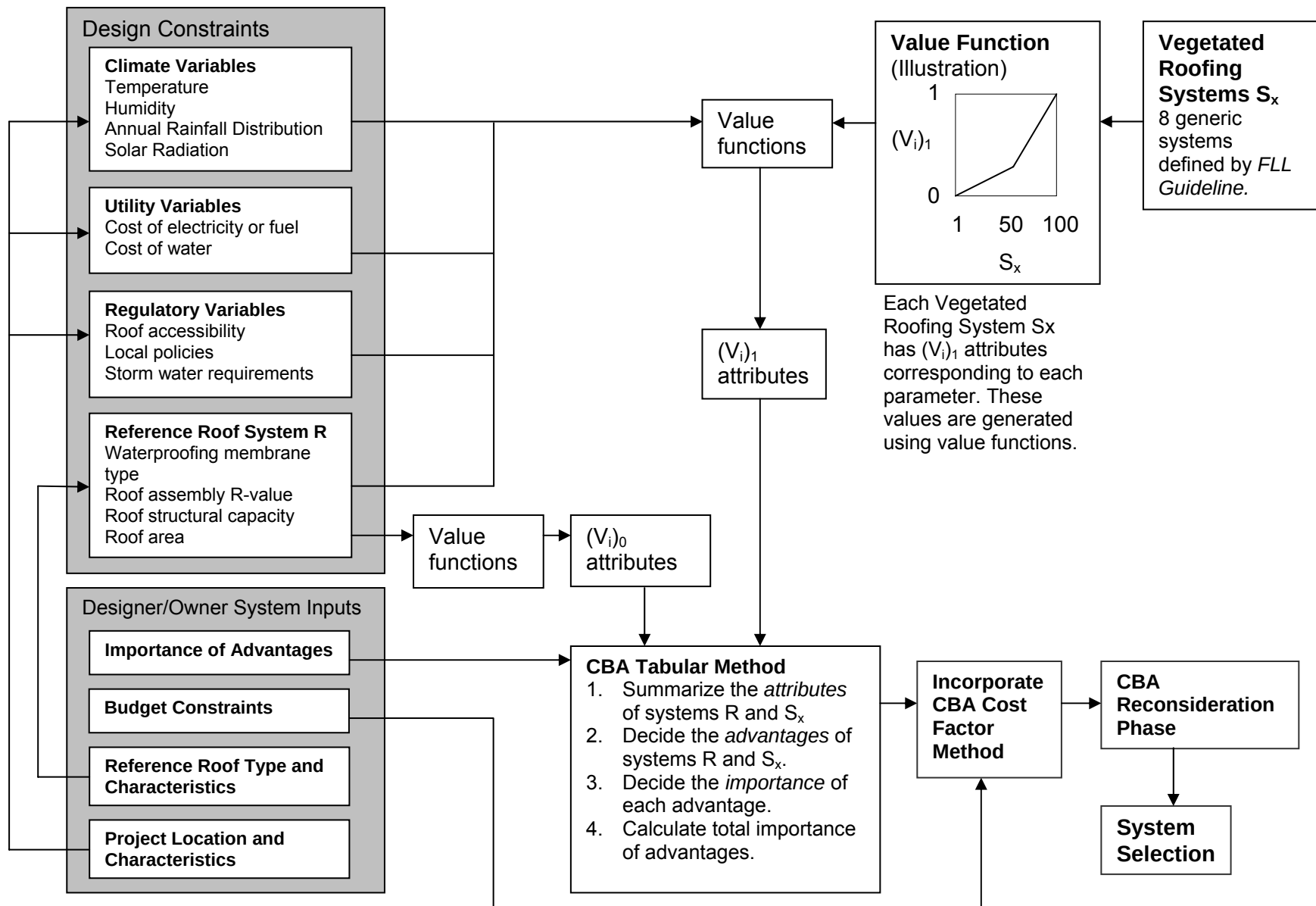


Figure 4.15 - Flowchart of the decision-making process

4.5.2. Graphical Representation

A graphical language needed to describe the framework for decision-making in the selection of vegetated roofing systems can be borrowed from fields outside the traditional boundaries of the discipline of architecture. Specifically, fields employing rigorous diagrams to document the decision-making process include business, government (Clemen, 1996) and engineering (Jewell, 1986). Because of the similarity of the types of diagrams used and their common iconography, methods of analysis employed by these disciplines have become universally recognizable and accessible to a wide range of users. Because the decision-making framework for vegetated roofing system selection will serve a potentially broad set of practitioners ranging from landscape architects to engineers to owners' representatives with a fiduciary interest, it is important to use a language accessible to all of these groups.

In *Making Hard Decisions*, Robert Clemen (1996) applied a structured decision-making approach to problems from a variety of sources, many of which share the characteristics of the vegetated roof system selection process. These characteristics, which make decisions “hard” and therefore candidates for careful analysis, are complexity, uncertainty, multiple and often competing objectives, and multiple perspectives leading to different conclusions. The influence diagrams introduced by Clemen in the text are a graphical shorthand used to capture and describe the characteristics of a decision problem in a holistic, recognizable way. The chief requirements of an influence diagram are that it follow a set of precise rules to represent decision elements, that it portray a “snapshot” of a decision situation at a specific point in time, and that it represent a “requisite model” of the decision, i.e. that it include all and only the objectives relevant to the problem under consideration. The main benefits of an influence diagram, when compared to other forms of analytic representation, are its legibility to those unfamiliar with mathematical analytical tools, and its compactness that permits it to encapsulate a large problem in a single diagram. Clemen stated that an effective influence diagram should be “isomorphic”, capable of generating a more detailed model such as a decision tree. He also referenced computer software programs, such as Decision Programming Language (DPL), that can generate decision trees from influence diagrams and perform various functions to automate and streamline the decision-making process.

The following basic rules, adapted from Clemen's *Making Hard Decisions* (1996), are used to create an influence diagram. Three shapes, called nodes, are used to represent elements of the decision process. Rectangles represent decisions; circles or ellipses represent chance

events, and rounded rectangles represent consequences, calculations, or constant values. Arrows connecting a predecessor node (at the beginning of the arrow) to a successor node (at the end of the arrow) are called arcs. Arcs fall into two categories. Arcs pointing into a chance node or a consequence, calculation or constant node are called relevance arcs, meaning that any predecessor nodes pointing to these nodes have an impact on the outcome of their successor nodes. Arcs pointing into a decision node are called sequence arcs, implying that the decision-maker has the benefit of the information represented by any predecessor node connected to that particular successor decision node before making the decision. These rules are graphically depicted in Figure 4.16.

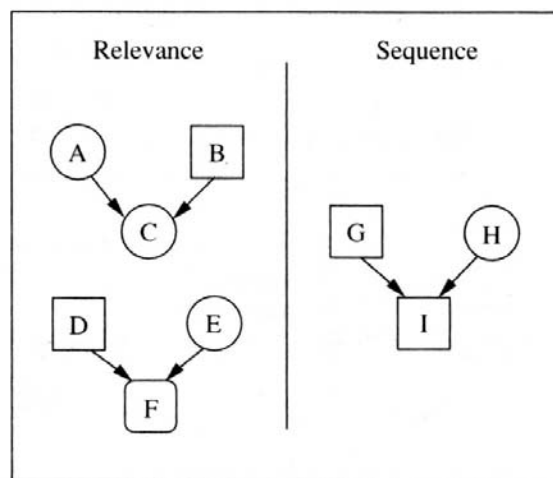


Figure 4.16 - Graphical rules for influence diagrams

Armed with these rules, it is possible to translate the initial flowchart representing the decision-making framework for vegetated roofing system design, shown in Figure 4.15, into the formal language of an influence diagram, as shown in Figure 4.17.

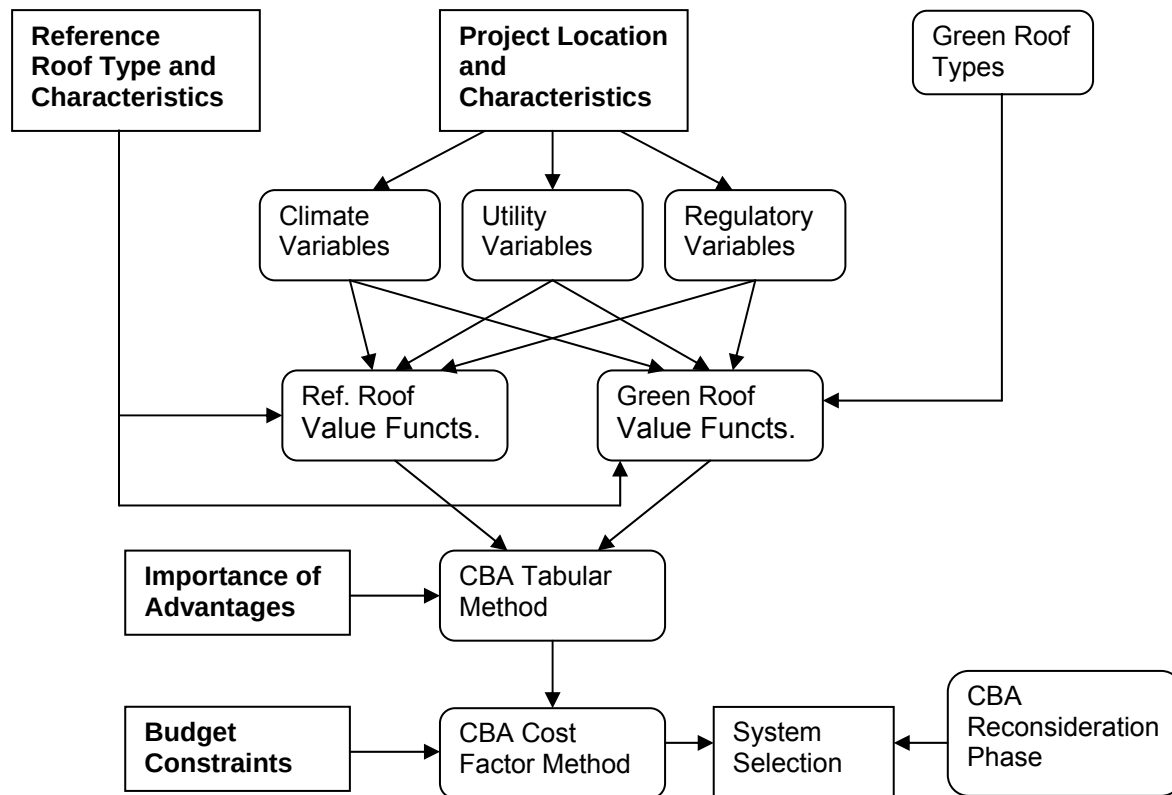


Figure 4.17- Influence diagram of vegetated roofing system selection process

Inputs required from the user, which serve as design constraints, are depicted as decision nodes in bold type (reference roof type and characteristics, project location and characteristics, importance of advantages, and budget constraints). The green roof type is depicted as a calculation node. One green roof type at a time is input from a set of eight generic types, as listed in Table 4.5, for evaluation.

Intermediate calculation nodes are included to represent values of specific variables as they apply to a given design problem at a given point in time (climate, utility and regulatory). There are no chance nodes in this influence diagram because all relevant variables will be calculated from known or estimated values. For example, while weather cannot be predicted with complete certainty, the climate variables used are design values reflecting a historic pattern of weather specific to the region in which the roof is located. A similar methodology is followed for utility and regulatory variables, which depend on the project location and characteristics input by the diagram's user. More intermediate calculation nodes (reference roof value functions, green roof value functions, CBA Tabular Method, and CBA Cost Factor Method) represent the

analytical processes necessary to convert the user's input and the characteristics of the roof systems into useful output. The final decision node is system selection. This process is preceded by the CBA Reconsideration Phase, where analysis of the result may be performed and viewpoints and preferences reconsidered. This is shown as a predecessor calculation node to system selection at the bottom right of the graph.

The influence diagram shown in Figure 4.17 represents the big picture of the decision situation. In Chapter 5, it is further elaborated with more specific diagrams and textual descriptions identifying the specific categories, parameters, and data incorporated into the value functions and the CBA Tabular Method. An example of the CBA Tabular Format is shown in Appendix D.

4.6. Framework Development

4.6.1. The Interview as a Research Method

The framework for vegetated roofing system selection resides largely within a postpositivist tradition of inquiry. The value functions used to rate various green roof system types are, for the most part, generated from experimental studies in various disciplines such as engineering and horticulture. But there is also an irrefutably important element of human choice in any design process, even one as specific as green roof system selection. Acknowledgment of this element has led to the rejection of the Battelle method's fixed weighting of parameters for all projects, and the implementation of the CBA method which encourages differential weighting of the importance of the advantages of one system over another, in the specific context of a given project. Concomitant with this approach, which embodies some phenomenological or naturalistic characteristics, is the necessity to include in this dissertation a research method which acknowledges the importance of context and subjective reality in architectural decision-making. Irving Seidman (1998) explained the value of the interview as a phenomenological approach in social science research. He argued that the human being's ability to communicate with language gives the researcher a unique window into the subjective reality that guides the behavior of the subject of inquiry. In the design world, this means that merely observing how designers behave, or make decisions, may not be sufficient. A richer understanding may be achieved by asking these designers to describe their design process in their own words. The interview may be used as a vehicle for determining how a designer's perception of a given context guides his or her decision-making process.

Linda Groat and David Wang (2002) addressed the pros and cons of qualitative research strategies in general. Interviewing is considered one tactic of several grouped within this strategy. The benefits of qualitative research are similar to those of the case study, namely that a holistic, context-rich picture of the experiences of the interviewee may be obtained, allowing for the unearthing of meanings underlying behaviors and outcomes. In this case, the process of selection of vegetated roofing systems is not merely observed, but also explained in light of the circumstances surrounding a specific project. Additionally, Groat and Wang asserted that qualitative research methods are sufficiently adjustable to meet the changing needs of a developing study. As evidenced by the development of the interview questions through the process of trial and error, this has been a crucial benefit in this dissertation. The attendant weaknesses of qualitative research, according to Groat and Wang, are the large quantities of data typically gathered, the relatively few guidelines for gathering, organizing and interpreting that data, and the fact that qualitative research may not achieve a great a degree of credibility within a post-positivist paradigm. They emphasize that peer review of qualitative studies are perhaps the best way to establish their credibility. It is hoped that future peer-reviewed publications derived from this dissertation will lend such credibility to the inclusion of interviews as one measure of acceptability for the framework for vegetated roof system selection.

The process of selecting interviewees closely mirrors the process of selecting case studies. With both techniques, representative sampling of a study population is practically impossible, and therefore generalizing to that population is an unachievable endeavor. Seidman (1998) suggested that the purpose of interviewing is instead to capture the experiences of interviewees, with a possible outcome of discovering relevance between the experiences of two or more interviewees, or between interviewees and the audience of the study itself. In light of these goals, Seidman introduced the idea of “purposeful sampling” where the criteria of “sufficiency” and “saturation of information” replace representative sampling. Essentially, Seidman recommended interviewing a sufficient number of persons to reasonably reflect the range represented by the population under study, and perhaps one or two outside this population in order to test the basic assumptions of the study. He also suggested that one sensible way of knowing that a critical number of interviewees has been reached is when interviews start unearthing information and viewpoints encountered in previous interviews.

4.6.1.1. *The Interview Process*

An interview instrument is incorporated into the methodology of this dissertation to capture the green roof system selection process as conceived by several designers and compare it with the developed framework. The development of the interview instrument proceeded through a series of stages: IRB approval, review by the Virginia Tech Center for Survey Research, a test interview, and subsequent reformulation as a combined survey and interview instrument. These steps are elaborated in the following discussion.

Training was completed in Human Subjects Protection as required by the Institutional Review Board (IRB) for Projects Involving Human Subjects at Virginia Tech, which is the first step of the process required to conduct interviews. A Research Protocol was submitted to the Virginia Tech IRB along with an Informed Consent form and other required paperwork. These documents have been approved, allowing interviews to proceed. An outline of interview questions was submitted to the IRB as part of the initial Research Protocol found in Appendix B. Two extensions of IRB approval were requested and granted to permit interviews taking place after May 12, 2006, along with an approved amendment that included the two questionnaires found in Appendices C2 and C#. While some of the specific interview questions were changed, and the nature of the “weight factors” mentioned in the outline was fundamentally changed, the scope of the interviews was narrowed somewhat, rather than widened, and neither the purposes of the inquiry nor the level of risk to human subjects was altered.

In the next phase of development of the interview instrument, Dr. Alan Bayer of Virginia Tech’s Center for Survey Research graciously provided a courtesy review of the first draft of proposed interview questions. He recommended several changes that are reflected in the test interview questionnaire that appears in Appendix C1. Dr. Bayer also made several general recommendations regarding the interview process. First, he suggested that the selection process used to obtain the sample set of green roof designers interviewed be well-documented, and that logical categories, such as location within a certain geographic boundary, be used to group these designers. Next, he recommended that the general structure of the questionnaire should be geared from the general to the specific and from the simple to the difficult to set the tone of the interview and to help determine the interviewee’s area of expertise. He then introduced the concept of “skip patterns”, whereby the interviewer may, after an introductory set of questions, skip forward within the questionnaire to certain topic areas specific to the interviewee’s knowledge base. He suggested that ideally all the interviews should be conducted

either in person or over the phone to provide a degree of consistency. He presented a protocol in which an initial letter is sent to the designers along with the IRB Informed Consent and then followed by a telephone call to arrange an interview time. Finally, he made the case for brevity when developing the questionnaire to minimize the time commitment required of each interviewee, and cautioned that it may be difficult to obtain follow-up from interviewees if a two-step interview process is employed.

The insights garnered from Dr. Bayer's comments, an initial test of the questionnaire in an interview setting, and ongoing literature review helped to focus the intent of the questionnaire and to streamline its functioning. The three main objectives of the questionnaire as originally contemplated were to determine how the interviewees would weight categories of green roof system performance, to elicit a description of the green roof system design process, and to obtain information on the appropriateness of attribute scales generated for specific green roof parameters. After a review of the CBA process and difficulties encountered in the test interview, it became clear that asking interviewees to rank broad categories of green roof performance was inappropriate. The line of questioning shown in Part I of the outline in Appendix B and the corresponding questions in Appendix C1 were revised to support the CBA methodology, as shown in Appendices C2 and C3. The refocused aim of the interviews is to capture the decision-making processes used by different practitioners and to determine how these processes compare to the proposed framework for vegetated roof system selection.

While the initial outline submitted to the IRB envisioned asking green roof designers to evaluate and lend guidance to the structure of the framework itself, it was afterwards concluded that this was too ambitious a goal for an interview process due to the intricacy of the framework and to the many possible situational permutations it includes. Additionally, proposing a framework to interviewees might have steered them toward a different set of responses than those they might have given without the power of suggestion. Instead, open-ended interviews were conducted wherein designers were asked the questions shown in Appendices C2 and C3, which were reformulated from the test interview included in Appendix C1. One notable change from the test interview is that the questions were restructured to focus only on an individual project, rather than on green roof projects in general. This was done to ensure that the responses reflected an actual design process in context, rather than one abstracted by the designer from several such processes. It was not expected that all questions would be answered by all respondents. Rather, designers' descriptions of the importance of the advantages of a given green roof

system over another, or over a traditional roof, were extracted from the narrative of the interviews when possible. Another difference between the test interview questionnaire and the revised questionnaires shown in Appendices C2 and C3 is the abandonment of the line of questioning regarding the itemization of green roof system components. Literature review conducted since the test interview indicated that green roof systems are more usefully perceived in their totality, rather than as an accumulation of layers. Finally, Purpose III listed on the outline in Appendix B was not reflected in the revised questionnaire. Questions regarding attribute scales were deemed too specific to be included in an open-ended interview about the process of green roof system selection.

4.7. Accommodating Uncertainty within the Framework

4.7.1. Error Propagation

Most of the models available for evaluating vegetated roofs are crude abstractions of reality. Examples from each of the six categories of green roof design considered in this study include rules of thumb relative to storm water retention, rough calculations of thermal performance, general equivalencies to sound reduction in decibels, approximate structural weights, simplified life cycle cost estimates, and representation of project efficacy with a measure of conformance to LEED criteria. When using values derived from these abstracted models, errors may be significant. When multiple models are employed in the evaluation of each category, and six categories are combined in the decision-making process, there is a potentially additive effect to this error.

There are certainly some correlations between parameters in the framework for vegetated roofing system selection. For example, energy performance relative to thermal mass effects is positively correlated to noise reduction, and negatively correlated to structural lightness and economy per square foot. The effects of these correlations on the error propagation within the framework will need to be investigated in future iterations of the framework since, at present, the value functions are too rudimentary to be properly evaluated, and the number of cases tested is small. In the context of the decision-making framework, there are several ways in which correlation between the various categories under evaluation are encountered. The correlations mentioned above appear as a necessary result of subdividing the features of a green roof into various categories and parameters. Patterns will likely form once the framework is tested using a larger sample of green roof projects, as certain types of green roof systems will probably be consistently valued highly for certain parameters and low for others, indicating a positive or

negative correlation between these parameters. The value attached to these patterns will, based on the organization of the framework (see Section 4.5), be either amplified or dampened according to the importance assigned by the user to the advantages of each alternative system. Another source of error is the accumulated uncertainty associated with imprecise or approximate valuation of the attributes of each alternative within the framework. Uncertainty analysis can be used to determine the variability of the solution based on the range of possible values of each of the attributes, which may be imprecise (American Society of Civil Engineers, 2000). This measure of degree of variability will also lend insight into the acceptability of the framework as a measure of the appropriateness of green roof systems for a specific set of design constraints, especially once the framework moves beyond its current limitations and incorporates more highly articulated value functions.

4.7.2. Uncertainty Analysis

H. Todd Mowrer (2000) explored the effects of uncertainty, which he defined in the context of his discussion of natural resource decision support systems (DSS) and statistics as the “quantifiable inexactness of a point estimate” (p. 141). Uncertainty is subject to measures of accuracy and bias where a benchmark value is present, and statistical precision where a benchmark value is absent. Mowrer reported that many decision support systems, which are used to describe, evaluate and order alternatives and provide a comprehensive understanding of a problem, do not adequately address uncertainty in their methodologies. This omission can lead to an incorrect perception that the solutions offered by a DSS are absolute and deterministic, rather than based on a series of average or probable values. He discussed the sources of uncertainty in DSS, ranging from quantitative errors in input to qualitative errors in the processes operating within the system. He offered methods for dealing with the propagation of uncertainty through DSS, which he deemed critical to the reliability of the results of any such system.

Mowrer (2000) cautioned that the error of each term in a multi-variable function cannot be considered in isolation when there is a correlation between the terms, since error propagates throughout the series of calculations used in a DSS. He invoked two standard statistical equations to illustrate his point:

$$\text{Variance } [X_1 + X_2] = \text{variance } [X_1] + \text{variance } [X_2] \pm 2 \text{ covariance } [X_1, X_2]$$

Equation 4.2 - Calculation of variance (Mowrer, 2000, p. 143)

$$\text{Covariance} = [\text{correlation}] \times [\text{standard deviation of } X_1] \times [\text{standard deviation of } X_2]$$

Equation 4.3 - Calculation of covariance (Mowrer, 2000, p. 144)

If variables X_1 and X_2 have a positive correlation, the covariance will increase with their variances, making the overall variance greater. If these two variables have a negative correlation, the covariance will decrease, decreasing the combined variance. Covariance must be considered in measurements of uncertainty to avoid skewed results.

There are several techniques for determining the degree of uncertainty in multi-variable equations. But before these are used, it is important for the study designer to evaluate the big picture. Multi-variable analysis draws much of its complexity from the number of variables considered, and is more streamlined if some of these variables can be removed before the analysis is performed. It is a poor use of time and resources to rigorously analyze an element that has little effect on the outcome of the problem at hand. Sensitivity analysis should first be performed to determine where to apply uncertainty analysis.

Once sensitivity analysis has been conducted, uncertainty analysis may be performed on those portions of a problem that require further investigation. Clemen (1996) and Mowrer (2000) both cited Monte Carlo simulation as a powerful and useful tool to estimate uncertainty in the input values, as well as in the interaction between the variables within the equations generating outcomes. Monte Carlo simulation's efficacy is based upon its ability to randomly select values for each variable across its probability distribution a sufficient number of times to give a realistic picture of the error as it is propagated throughout a multi-variable equation. Clemen cautioned that the modeler must be judicious in selecting the uncertainties to be evaluated, and that the ease and rigor of simulation is no replacement for careful sensitivity analysis. Both authors gave guidelines for the application of simulation procedures, and explained how the results of uncertainty analysis can be used to determine the most desirable outcome of a problem, using decision rules such as the minimax criterion and Bayes' Criterion. Put simply, these techniques can help one decide between the "best" outcome in terms of maximum average value, and

outcomes with slightly lower average values, but also with less uncertainty, i.e. outcomes that are more of a “sure thing” than the “best” outcome.

The common thread in Clemen’s (1996) and Mowrer’s (2000) discussion of uncertainty laid in the importance of addressing error propagation with the same attention to creating a requisite, or sufficient, model of the decision situation that was used to generate the model itself. Management of error was viewed as a necessary part of representing a real-world situation as realistically as possible, to obtain relevant results. It is important for users of a decision-making tool to remember that results are not perfect simply because they are translated into explicit numerical values. The explicit nature of the tool should be used to make visible the gaps in the decision maker’s knowledge so that they can be dealt with in an appropriate way. The tool’s great value is in organizing what is known and making explicit that which is not known, so that the decision-maker is aware of this distinction when making a decision.

4.7.2.1. *Uncertainty Analysis Applied to Vegetated Roofing System Selection*

Simulations used to predict error propagation, such as the Monte Carlo simulation method discussed in Section 4.7.2, depend upon the ability of the modeler to describe the range of values for each of the variables in the equation in terms of a probability distribution. In most cases, probability distributions are unavailable for the green roof performance parameters being measured. It is more likely that values for many parameters will be either point estimates, or simple ranges without probability distributions. In this case, performing an initial sensitivity analysis is critical. For example, some potentially sensitive parameters, such as the weight of a green roof system, have little uncertainty associated with them, while others, such as storm water quantity reduction, have wide error bounds. Uncertainty within the current framework is addressed in Section 6.9.3.

When the CBA decision-making system is employed, the weighting of importance of advantages may change based on the degree of difference between attributes. The magnitude of these differences depends in part on the error bounds of the values assigned to these attributes. For example, if one green roof system retains from 50 to 60% of incident annual rainfall, and another retains 20 to 30%, there is a difference of between 20 and 40% rainfall retained between the two systems, depending upon the values chosen. Clearly, a 20% advantage is somewhat less important than a 40% advantage. The degree to which the error bounds of the attribute values affect the alternative that is determined to have the greatest total importance of

advantages will need to be investigated in future versions of the framework. This will involve assigning importance to the difference between attributes of green roof systems along a preference curve as precisely as possible, to test the outcome of the decision as the value of these attributes move along the continua of their error bounds. The parameters with the greatest effect on the outcome of the decision-making process will be flagged for further evaluation. While a complex process, this will yield a more realistic view of the decision situation and will avoid the error of valuing certain systems over others based on false assumptions.

4.8. Testing for Acceptability

When determining how best to evaluate the framework for vegetated roofing system selection it is useful to consider how studies of this nature are typically assessed for quality. In this way, the reasons for such an assessment and the standards to which the framework should be subjected can also be examined. In *Architectural Research Methods*, Linda Groat and David Wang (2002) explicated an outline of quality standards for research from both a postpositivist and a naturalist perspective, as initially proposed by Egon Guba in Figure 4.18. Each of these evaluative standards is elucidated in reference to the vegetated roofing decision support system, with strategies given for accomplishing each of the goals described.

Standard	Positivism / Postpositivism	Naturalistic
Truth value	<i>Internal validity</i> Equivalence of data of inquiry and phenomena they represent	<i>Credibility</i> Check data with interviewees; triangulation — multiple data sources of data collection
Applicability	<i>External validity</i> Generalizability	<i>Transferability</i> Thick description of context to assess similarity
Consistency	<i>Reliability</i> Instruments must produce stable results	<i>Dependability</i> Trackability of expected instability of data
Neutrality	<i>Objectivity</i> Methods explicated; replicable; investigator one-step removed from object of study	<i>Confirmability</i> Triangulation of data; practice of reflexivity by investigator

Figure 4.18 - Egon Guba's comparative analysis of quality standards (Groat & Wang, 2002, p. 35),
permission to use granted by: Egon G. Guba (March 2, 2007)

Viewed from a postpositivist perspective, the truth value of the decision-making apparatus is only as strong as the representational power of the tools embedded within it. As mentioned in the discussion of natural and proxy scales in Section 4.4, the criteria actually measured must match a fundamental objective of the study as closely as possible. Further, the data used must be reasonably accurate measures of the criteria under investigation. To ensure this, the value functions used to develop an environmental quality rating for each parameter must be taken, as frequently as is practical, from actual physical models of green roofs. Empirically validated numerical models are sought for use as estimating tools for the more quantitative green roof valuation criteria. Where these are not available, future parameters are identified. These tell the user that future research is needed to conduct a rigorous quantitative analysis of these parameters. Qualitative criteria can often be substituted for the absent data. (Dee et al., 1973) Qualitative criteria can be evaluated from a naturalistic viewpoint on the basis of credibility, by using what Groat and Wang (2002) referred to as “triangulation” and “member checks” (p. 38). Triangulation involves approaching a question from several sources or perspectives, and member checks involve asking contributors to a study to evaluate the data and outcomes of that

study. Triangulation of data sources is achieved in this study by including an interview instrument to test the basic assumptions of the framework. While the reviewed literature and case study projects tend to focus on certain critical green roof evaluative categories, the interviews paint a somewhat different picture of the way green roofs are designed in practice. A comparison of the framework's structure to designers' methods gives the study a "reality check" and identifies areas for future improvement and development of the framework.

Perhaps the most potent measure of the quality of the framework is its external validity, or ability to be generalized to green roofing system selection throughout North America. The best way to test this is to use the framework to evaluate one or more real-world projects. Field tests of a river system were used to calibrate the EES used in the Battelle Method (Dee et al., 1973). In a similar fashion, three recently designed green roof projects were subjected to the analytical engine of the framework to determine whether or not the framework generated results similar to those chosen by the designers. The designer of the green roof then informally evaluated the results of the framework for compliance with his or her design objectives, practicality, degree of fit with the context of the project, and other factors. Ideally, this process could be repeated in the future for green roofs in various locations in North America to determine if the framework truly can be applied in all regions. As seen from the naturalist perspective, the framework's context will need to be drawn quite broadly to pass this test.

Inputting the design parameters of actual green roof projects into the framework and evaluating the quality of the outcomes can also measure consistency of results. Likewise, the framework should yield similar results from user to user for similar projects when the decision-makers have similar priorities. Reliability also implies that the framework's results should remain consistent until the context of the problem is fundamentally changed (Groat & Wang, 2002). It would seem that the physical phenomena measured by the framework, e.g. storm water, energy, acoustical and structural behaviors, will remain fairly stable, while the cost and compliance factors will change frequently based on variables such as the market and the political climate of the building industry. Future versions of the framework will need to adapt to reflect such conditions if it is to remain reliable.

Finally, objectivity can be assured more readily in the empirical measurements, which can be replicated by another analyst with similar results. For the qualitative indices, the acid test becomes confirmability, wherein the modeler must describe the epistemological context from

which he or she is operating and triangulate this with that of other experts in the field (Groat & Wang, 2002). The priorities and embedded preferences of the framework are made explicit and adjustable by the user by allowing him or her to attach value to the advantages of various alternatives, satisfying this criterion to some degree.

In summary, the practical ways to ensure the quality of the framework for decision-making in vegetated roofing system design are to incorporate in it as many empirical data as possible, to approach its key questions through a range of research methods, to compare its functioning to the green roof system selection process as described by designers, and to ground its analysis in the context of specific projects and users. More rigorous tests of acceptability will occur after the completion of this research, when the framework is subjected to the scrutiny of the green roof design community through the publication of papers and the decision support system is used to select green roof systems for a variety of projects.

4.9. CBA Reconsideration Phase

As described in Section 4.4.4, the fourth phase of the CBA Decisionmaking System is the Reconsideration Phase. Once the alternative with the greatest total importance of advantages has been identified, the decision-maker asks the following questions:

Are there any additional alternatives that should have been considered?

Are there any additional advantages that should have been included?

Do the importance scores accurately represent the viewpoints of the stakeholders?

Based on examining each alternative as a whole, are there any adjustments that need to be made? For example are there any significant interdependencies among the factors?

If so, were they taken into account?

Are any other changes needed? (Suhr, 1999, pp. 84-85)

The framework for decision-making in vegetated roofing system selection is, like the influence diagram that represents it, a momentary picture of the decision situation. The solution it generates should therefore be reexamined in light of any new information, priorities, or alternatives that may change the decision before the solution is implemented.

While reviewing graphical representation of the results, designers must remain mindful of the original reason for using the framework for decision-making. When in the future the framework is translated into a computer-based decision support tool, results of the analysis of the

framework should be presented accompanied by a cross-sectional and pictorial representation of the green roof system recommended by the framework for selection, helping the designer to form a realistic mental picture of the system selected, and allowing the implementation of the solution in the form of creative green roof design to begin.

5. MAPPING THE FRAMEWORK

This chapter comprises a mapping of the decision-making framework for vegetated roofing system selection into the common graphic language shared by decision-makers in various fields. The intended users of the framework are defined in Section 5.1. A well-known graphic language is utilized to make the decision-making process both transparent to these users and adaptable to new and changing information regarding green roofs. A computer program called PrecisionTree 1.0 for Excel, produced by the Palisade Corporation, is employed to support this effort. PrecisionTree incorporates tools for creating both decision trees and influence diagrams, and makes the transition between these two forms of representation. It also includes sensitivity analysis tools such as tornado diagrams and it interfaces with other programs within the DecisionTools suite that perform uncertainty and statistical analysis.

5.1. Intended Users of the Framework

The Green Roof Design 101 Introductory course offered by Green Roofs for Healthy Cities is targeted toward “architects, landscape architects, engineers, planners, roofing consultants and roofing contractors, horticulturists, specifiers, developers and policy makers” (The Cardinal Group, 2004). Green Roofs for Healthy Cities (GRHC) is the preeminent organization supporting vegetated roofing awareness in North America, host of annual international green roofing conferences and publisher of the Green Roofs Infrastructure Monitor. It seems realistic to assume that the groups represented at the training course would be interested in a decision support system for green roof system selection. According to Alex Johnston of GRHC (personal communication, January 7, 2005), landscape architects, architects and engineers represented over 50% of attendees to the Design 101 course. These registered professionals are involved in the designing and specifying of vegetated roofing systems. Not surprisingly, the American Institute of Architects, the American Society of Landscape Architects and the Roof Consultants Institute accept the Green Roof Design 101 Course for continuing education credit, and GRHC is working toward the creation of a Green Roof Accreditation Program.

The lines of responsibility drawn between disciplines are currently quite blurry in the world of green roof design. Alex Johnston (personal communication, January 7, 2005) stated that several of the attendees to GRHC’s design course claimed two or three professional affiliations. For example, many roof consultants are also architects, engineers, or roofing contractors by trade. Frequently, architects consult landscape architects for the design of the “green” portion

of vegetated roofing systems, as was the case for the green roof at the Woodward Academy in Atlanta, Georgia.¹ In other cases, sophisticated subcontractors essentially provide design services to meet owners' performance specifications, but are contractually obligated only to the general contractor on the project, as was seen in the green roof design for the Life Expression Wellness Center in Hazleton, Pennsylvania.² The relative newness of vegetated roofing in North America has caused many designers to seek the help of experts in the field, widening the range of possible participants in the design process. Projects frequently involve an integrated team of specialists, variously including horticulturalists, civil engineers, landscape architects, cost estimators, LEED accredited professionals, construction firms, material suppliers and other experts with differing levels of contractual obligation to the owner. And the owner's entity itself can be a governmental or corporate organization with very specific goals for the green roof and with professional staff members equipped to play a role in its programming, design, and maintenance.

Because of the difficulty of identifying the specific professions of the targeted user group for the decision support framework, it is more useful to define its user as any person assuming professional and legal liability for the design of all or part of a vegetated roofing system. In most jurisdictions, this person or persons must be a licensed architect, landscape architect, roof consultant or engineer, depending on the nature and location of the vegetated roof. The user or users of the framework for a given project will be the person or persons in responsible charge of the design; therefore the framework should be rigorous enough to support the obligation of design professionals to protect the health, safety and welfare of the public. This definition of the framework's user assumes that at minimum a building owner or developer has made a commitment to enlist a professional to do a feasibility study to determine whether a green roof is plausible, and if so, what kind of green roof system should be considered.

5.2. Influence Diagrams and Decision Trees in PrecisionTree

5.2.1. Influence Diagrams

Influence diagrams in PrecisionTree are formed with combinations of nodes and arcs similar to those described by Robert Clemen in *Making Hard Decisions* (1996), discussed in Section 4.5.2. There are four types of nodes in PrecisionTree, as follows:

¹ See discussion of case study projects in Section 4.1 and Appendix A.

² See discussion of case study projects in Section 4.1 and Appendix A.

Chance - a red circle representing an event with a set of possible outcomes that the decision maker has no control over.

Decision - a green square representing an event where the decision maker must choose one of a number of options.

Calculation - a blue rounded rectangle representing a calculation that takes values from predecessor nodes and combines them using formulas to generate new values. There is no uncertainty or different options associated with a calculation node.

Payoff - a blue diamond representing the final payoff calculation or result from the model.

Arcs are defined as follows:

Arcs point from a predecessor node to a successor node, indicating a dependence between the two nodes. An arc may contain different forms of influence: value, timing or structural or a combination of the three....

A Value influence specifies that the values for the successor node will be influenced by the possible outcomes for the predecessor node. If the successor node is a decision node, only values can be influenced; if it is a chance node, both values and probabilities can be influenced. All arcs entering a calculation node must have a value influence. This is because a calculation node by definition combines the values of outcomes from predecessor nodes to calculate new values. No new outcomes or uncertainty are associated with calculation nodes....

A Timing influence specifies that the arc between two nodes in an influence diagram implies timing; that is, the predecessor node always occurs prior to the successor node in time. When a node has a Timing influence on another the predecessor node will be placed prior to (i.e., to the left) of the successor node in a decision tree created from the influence diagram....

Structure influence specifies that the structure of the outcomes of the successor node is affected by the outcome of the predecessor node. Structure influence is specified by outcome of the predecessor node, i.e. each possible outcome of the predecessor node can have an influence on the type of outcomes that occur for the successor node. With a Structure influence, successor node outcomes can be forced or skipped depending on

the outcome that occurs for the predecessor node.... Structure influence is used to convert influence diagrams into "asymmetric" decision trees, or trees where all the possible branches (as specified by all possible outcomes defined in the influence diagram) are not drawn. Asymmetric trees are quite common.

5.2.2. Decision Trees

Decision Trees in PrecisionTree are geared mainly toward financial decision-making, therefore some adaptation is required to use them in the context of calculating unit-less values for incorporation into a decision-making system based on Choosing By Advantages. The trees in this chapter are created by expanding influence diagrams and assigning values, taken from value functions, to each potential outcome. The decision tree is set to "optimize" the decision, or choose the highest value. The branch or branches which provide this value are automatically labeled "true", while all other branches are labeled "false". Examples of this may be seen in all of the decision trees within this chapter. Additionally, since there are no chance nodes defined within this decision-making framework, there is also no probability associated with the various outcomes. The upper number of each pair of numbers to the right of each payoff node (blue triangle) is reserved for the probability of that outcome occurring. In the trees generated within this framework, the probability of the "false" outcomes is automatically labeled with a "0", while the "true" outcomes are labeled with a "1". These functions of PrecisionTree are superfluous but not detrimental to the goals of this analysis and may be safely disregarded.

Before breaking the decision down into its elemental categories, the original influence diagram generated in Section 4.5.2. should be reviewed, as drawn using the PrecisionTree software. This diagram is shown in Figure 5.1. The reader is directed to Section 4.5.2 for a detailed discussion of each of the nodes within the diagram, which change little in their translation into PrecisionTree. Nodes for "Project Location and Characteristics" and "Reference Roof Type and Characteristics" have been changed from decision nodes to calculation nodes because they actually represent a complex web of designer decisions and values based on those decisions, as will be demonstrated in the explication of the parameters making up the framework. The names of all the nodes are abbreviated due to the constraints of the software. This diagram remains a shorthand version of a more involved decision situation, and is revisited at the end of this chapter.

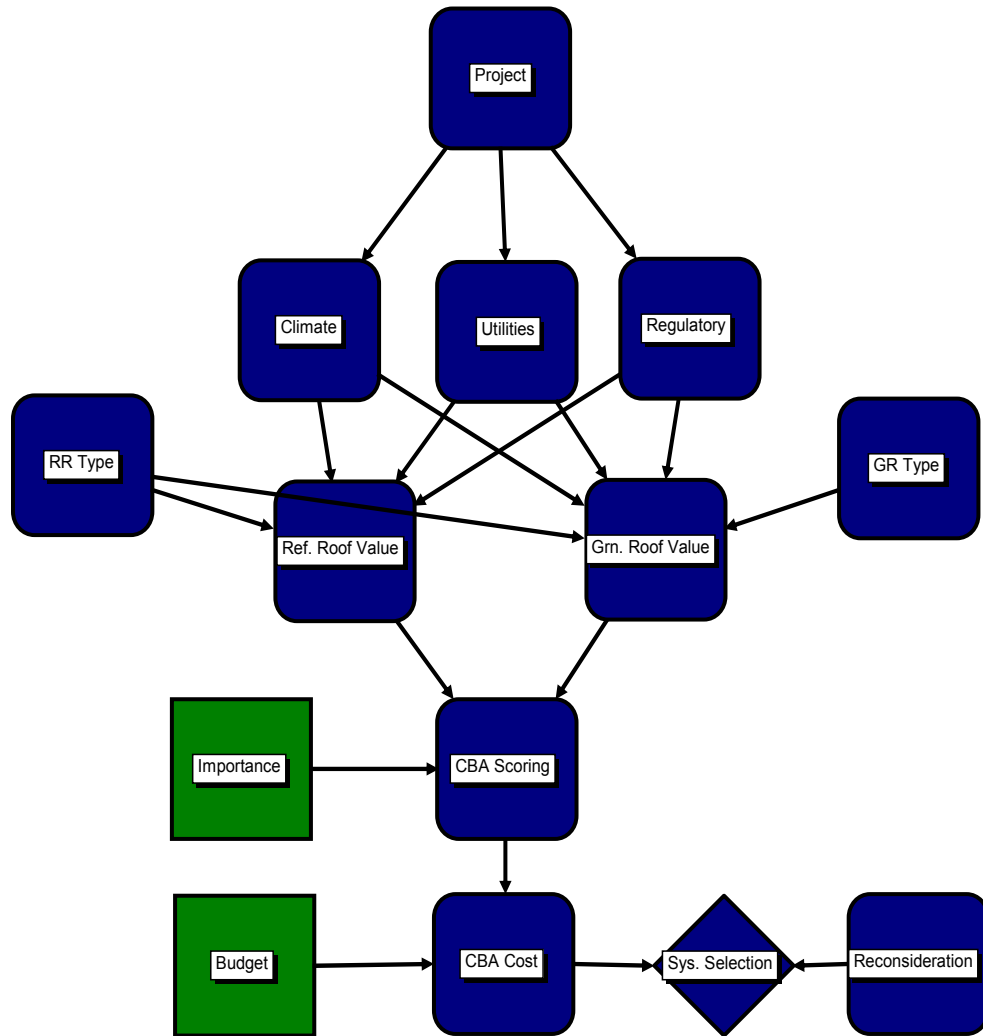


Figure 5.1 - Initial overall influence diagram of decision-making framework

5.3. Category A: Storm Water

5.3.1. Parameter A1: Storm Water Retention

5.3.1.1. Included Attributes and Design Variables

Roof system type

5.3.1.2. Derivation of Value Function

The green roof system types, depths, and corresponding annual coefficients of discharge ψ_a comprising Table 5.2 are drawn directly from the *FLL Guideline for the Planning, Execution, and Upkeep of Green-Roof Sites* (2002) (*FLL Guideline*), as discussed in Section 3.1.1. The value

function shown in Figure 5.2 graphically presents this same information. The annual coefficient of discharge for the reference roof is set at 0.80, the number assigned by the *FLL Guideline* to non-vegetated gravel areas on green roofs (FLL, 2002) for a “reference rain of $r_{(15)} = [2.74 \text{ in/hr}]$ (300 l/(s x ha)) upon previous saturation with water and a 24-hour dropping off period” (FLL, 2000, p. 36). A gravel area on a green roof is similar to a gravel ballast reference roof, which would tend to retain more rain water than other, smoother reference roof surfaces. A value of 0.80 can therefore be assumed to be a conservative estimate of the coefficient of discharge of a typical reference roof. The coefficients of discharge for vegetated roofs represent a consensus used widely in Germany, and are used here in the absence of such consensus in North America.

One North American study presented annual storm water retention data that may be roughly compared to the coefficients assigned by these charts. Liu and Minor (2005) reported a 57% annual reduction in roof runoff compared to a control roof for green roof test sections 4 inches (100 mm) and 3 inches (75 mm) deep in Toronto, Ontario. The 3-inch (75-mm) roof falls within Roof System Type 3, and the 4-inch (100-mm) roof falls within Roof System Type 3 or 4. The 57% reduction may be translated to an annual coefficient of discharge of 0.43, which lies between the values given for Roof System Types 4 and 5. This means that the Toronto test roofs retained slightly more rainfall annually than would be expected using the FLL annual coefficients of discharge for their system types.³ While this study was by no means adequate to verify the applicability of the annual coefficient of discharge to all locations in the continental U.S., it at least supported its use as a crude rule of thumb to predict the annual capacity of green roofs to retain rainwater.

Another guide to the applicability of the annual coefficient of discharge ψ_a to North American green roofs is found in a footnote to the chart in the *FLL Guideline* (2002) that assigns these coefficients to green roofs of various course depths. It states that “all figures relate to locations with annual precipitation values of [26 to 32 inches] (650 to 800 mm) where monitoring has been performed over a period of several years. In regions with lower annual precipitation values water retention is higher, in regions with higher annual precipitation it is lower” (FLL, 2002, p. 37). For the sake of comparison, average annual precipitation rates for the period

³ Some error is introduced here because the percent reduction of green roof runoff cited in the Liu and Minor study is compared to that of a reference roof, while the coefficient of discharge ψ_a in the *FLL Guideline* is the ratio of annual green roof runoff volume to annual rain volume.

1971 through 2000 for the six major North American cities closest to the case study projects reviewed in this dissertation are presented in Table 5.1. The case studies in the Midwest share a similar average annual rainfall rate to the range cited in the *FLL Guideline*, while the case studies in the Mid-Atlantic region have a higher rainfall rate. Future research should incorporate analysis of not only the average annual precipitation at various North American locations, but also the rainfall intensity in those locations, as this factor also impacts the amounts of rainfall retained.

Table 5.1 - Average annual precipitation for six North American cities closest to case study projects

Case Study Project	City	Average Annual Precipitation (inches)	Average Annual Precipitation (mm)
Montgomery Park Business Center	Baltimore, MD	41.94 ⁴	1049
Life Expression Chiropractic Center	Philadelphia, PA	42.05 ⁴	1051
Chicago City Hall	Chicago, IL	36.27 ⁴	806.8
Ford Dearborn Truck Assembly Plant	Detroit, MI	32.89 ⁴	822.3
Toronto MEC	Toronto, ON	31.71	792.7 ⁵
Woodward Academy	Atlanta, GA	50.20 ⁴	1255

The value function shown in Figure 5.2 is constructed based on the data in Table 5.2. The lower the annual coefficient of discharge ψ_a , the higher the relative value of the roof system as a storm water management device. The y values are therefore expressed as the fraction of the annual average rainwater retained by the green roof.

⁴ (National Climatic Data Center, 2007)

⁵ (Environment Canada, 2007)

Table 5.2 - Annual average rainwater retained by roof system types (adapted from FLL, 2002, p. 37)

Roof System Type	Substrate Depth (in)	Substrate Depth (cm)	Annual Coefficient of Discharge ψ_a	Y value (fraction of annual average rainwater retained or dissipated)
RR	-	-	0.80	0.20
1	0.8 to 1.6	2.0 to 4.0	0.60	0.40
2	>1.6 to 2.4	>4.0 to 6.0	0.55	0.45
3	>2.4 to 4.0	>6.0 to 10.0	0.50	0.50
4	>4.0 to 6.0	>10.0 to 15.0	0.45	0.55
5	>6.0 to 8.0	>15.0 to 20.0	0.40	0.60
6	>6.0 to 10.0	>15.0 to 25.0	0.40	0.60
7	>10.0 to 20.0	>25.0 to 50.0	0.30	0.70
8	>20.0	>50.0	0.10	0.90

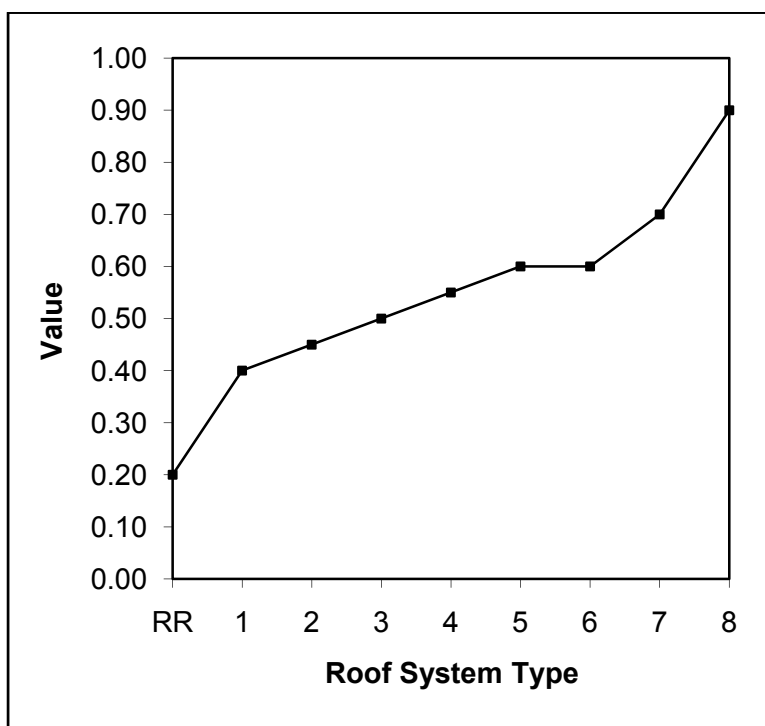


Figure 5.2 - Fraction of annual average rainwater retained by roof system types

5.3.1.3. Influence Diagram of Parameter A1

Figure 5.3 is the influence diagram of Parameter A1. The first decision node requires the designer to decide the roof system type. The roof type decision determines the “payoff” value, simply the result of the value function shown in Figure 5.2. The three gray calculation nodes at the top of the diagram, connected to the Roof Type node with dotted influence arcs, are not currently part of the decision situation. They serve as placeholders for future variables as explained in Section 5.3.1.5.

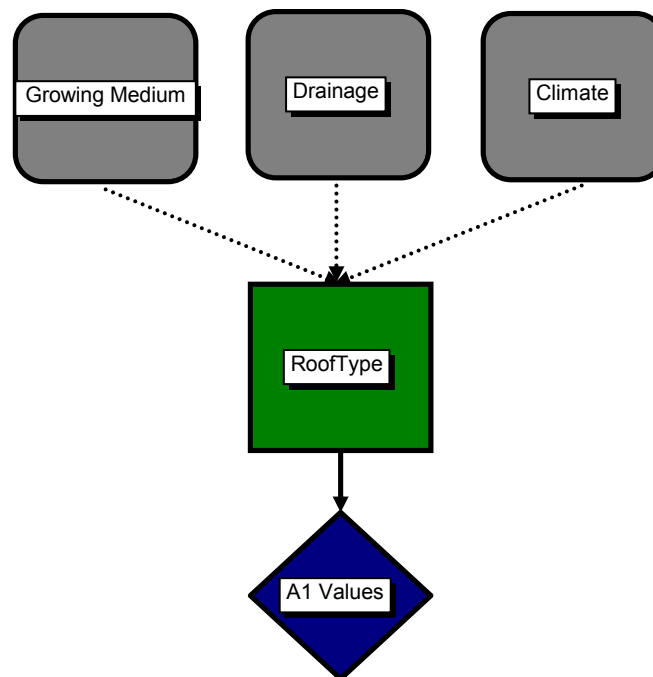


Figure 5.3 - Influence diagram of Parameter A1

5.3.1.4. Decision Tree of Parameter A1

Figure 5.4 is the decision tree generated from the influence diagram of Parameter A1. From left to right, it may be read as follows, using the numbers at the top of the figure as a key. The first node (1) is a decision node describing the roof system type. The triangles terminating each branch (2) are “payoff” values. As discussed in Section 5.2.2, the path labeled “True” and assigned a probability of 1 is the roof with the highest possible value for this parameter, namely FLL System 8.

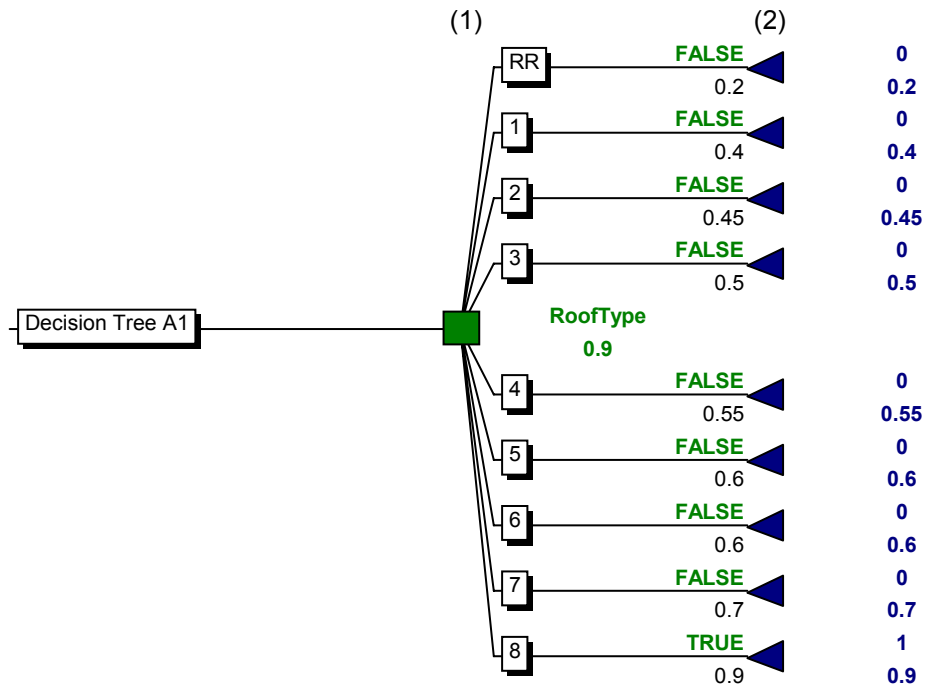


Figure 5.4 - Decision tree of Parameter A1

5.3.1.5. Excluded Attributes and Design Variables Affecting Parameter A1

In reality, many other factors help determine the actual storm water retention capacity of a vegetated roofing system. One attribute excluded from the value function but discussed in the *FLL Guideline* (2002) is roof slope, which affects the coefficient of discharge for a given design storm. Green roofs with a slope of 15% or greater retain less rainwater than low-slope green roofs. According to the *FLL Guideline* (2002), other relevant factors include the specific makeup of the roof system components including the capacity of the growing medium to both drain and retain water, the weather patterns in the project location, and the time of year, with summer performance being much higher than winter. The value function shown in Figure 5.2 is a crude approximation based on the performance of green roof system types defined by the FLL, which determined that the depth of substrate is the most sensitive parameter of those intrinsic to the green roof system itself. In addition to parameters already mentioned, Kolb (2004) identified roof features such as the distance water travels to drains, as well as climatic features such as air moisture content, as relevant to green roof storm water performance. Liu (2004) pointed out that while average annual retention of incident rainfall can be estimated, the actual performance of green roofs varies greatly depending upon the intensity and duration of any particular storm, as well as the moisture content of the growing medium prior to the storm event. Since the

annual coefficient of discharge ψ_a defined here is an averaged value, the season- and storm-specific factors are ignored, while the others are incorporated as calculation nodes with values to be determined in future studies.

5.3.1.6. *Excluded Parameters Affecting Category A*

The literature review has revealed two additional parameters, storm water pollutant control (Parameter A2) and runoff warming (Parameter A3), within the category of storm water performance that might distinguish green roof systems from one another and from a reference roof. However, there is either insufficient data, or too much conflicting data, to construct value functions for these parameters at this time. These are included as calculation nodes in the final influence diagram, but do not contain values.

5.4. Category B: Energy

5.4.1. Parameter B1: Potential Energy Savings

5.4.1.1. *Included Attributes and Design Variables*

All of the following are input variables to the DOE Cool Roof Calculator described in Section 5.4.1.2.

- Project Location

- State

- City

- Proposed Roof Characteristics

- R-value of roof assembly

- Solar reflectance (Reference and Vegetated)

- Infrared emittance (Reference and Vegetated)

- Energy Costs and Equipment Efficiencies

- Summertime cost of electricity

- Air conditioner efficiency (Coefficient of Performance)

- Energy source and cost for heating

- Heating system efficiency

5.4.1.2. *Value Functions and Derivations*

While the theoretical thermal performance of green roofs has been analyzed by a number of researchers, there is a dearth of experimental testing yielding results extensible to future projects. The value function defining the potential for energy savings is therefore based on

broad-brush assumptions about the character of the building project at large, and is focused on identifying whether or not a project will benefit from the implementation of a green roof. As stated by Jeff Sonne (2006) in the ASHRAE Journal, these energy savings are based on a wide range of factors external to the vegetated roof itself, such as the area, height, and occupancy type of the building, as well as the use and construction of the space immediately below the roof. Brad Bass of Environment Canada's Adaptation & Impacts Research Division (2006) also described the complexity of undertaking a detailed energy analysis in the beginning stages of design. The proportions and nature of the building envelope, expected internal heat loads, and the type of heating, refrigeration and air conditioning systems contemplated must be known to perform this analysis.

There have been a number of green roof energy models developed and calibrated for specific climates worldwide. A discussion of these is provided in Section 3.2.4. While Bass (2006) has presented plans to launch a web-based tool to allow green roof designers in Canada to estimate potential energy savings of extensive and intensive green roofs as compared to asphalt roofs, this is not yet available. Bass and colleagues are currently in the process of determining how best to group green roof benefits, by generic building type or by roof-to-envelope ratio (personal communication, September 10, 2006). Until such a tool becomes widely available, green roof energy performance needs to be estimated by fairly sophisticated energy analysis models, often calibrated to a specific region's weather data and requiring significant time, money, and expertise to construct. Similarly, the Q-value calculator developed by Christopher Wark, while promising, is not available for purchase, and therefore was not included as a value function in the framework.

Perhaps the most useful parameter for making the decision whether to implement a green roof or a conventional roof is the "equivalent albedo" developed by Gaffin et al. (2005). This number, while highly dependent on the Bowen ratio assumed (see Section 3.2.4 for a discussion of this ratio), is useful as a single-number attribute that can give an early estimate of potential energy savings attributable to a green roof. This is achieved by implementing an established tool called the "Cool Roof Calculator" created by the U.S. Department of Energy to help building owners determine if a reflective roof is appropriate and economically viable for their buildings. This user-friendly web-based calculator was developed to help designers quickly and easily assess the economic impact of the color of the roof membrane, and make appropriate decisions based on this information. The calculator is available on the worldwide web at

<http://www.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>. Green roof designers can use the “equivalent albedo” of 0.7 to 0.85 established by Gaffin et al. (2005) for vegetated roofing to compare a green roof to a typical roof for a particular project. Since the calculator and its associated help screen do not provide estimates of the infrared emittance (ϵ) of a green roof surface, the literature was surveyed for an acceptable estimate. Jin and Liang (2006) discussed the derivation of, and typical values for, land surface emissivity, and described a sensitivity analysis that suggests a wider range of values for infrared emittance than those typically used for energy modeling of the global climate. Their literature review and subsequent analysis suggested broadband ϵ values ranging from slightly less than 0.9 for bare desert soils to near 1 for densely vegetated areas. For the purposes of determining a general value for green roof infrared emittance, it is clear from the paper that using a value of 0.9, or “high” infrared emittance according to the Cool Roof Calculator, is a conservative estimate and would account for the slightly reduced emissivity of a sparsely vegetated, recently planted green roof.

The influence diagram of Parameter B1 shows the necessary inputs to the Cool Roof Calculator; these account for project specifics which can be grouped into three categories: project location, proposed roof thermal specifications, and energy and building conditioning equipment characteristics. The prepackaged nature of the Cool Roof Calculator gives it the required speed and simplicity to be useful to a designer. The results generated by the calculator are input into a simple value function that assigns value as follows:

Higher netting option in net savings (\$/ft² per year) over a black roof = 1

Lower netting option in net savings (\$/ft² per year) over a black roof = ratio of net savings of lower netting option (\$/ft² per year) divided by net savings of higher netting option (\$/ft² per year)

For example, if a green roof netted 0.50 \$/ft² per year over a black roof, and a conventional roof also under consideration netted 0.10 \$/ft² per year over a black roof, the green roof would be assigned a value of 1, and the conventional roof a value of 0.2, or 0.10/0.50. Unfortunately, because some of the variables affecting the heat flow values of green roofs have not yet been isolated and tested at a sufficient number of North American sites, this value function is only able to distinguish between vegetated roofs as a whole, and non-vegetated roofs with known albedos. These excluded variables are reviewed in Section 5.4.1.5. There are additional

limitations to the usefulness of the value function due to the simplifications embedded in the Cool Roof Calculator itself; which are explained on the calculator's website.

5.4.1.3. *Influence Diagram of Parameter B1*

For this parameter, the value of each roof system is not calculated within the PrecisionTree model. Instead, the calculations occur within an external source, the Cool Roof Calculator described in Section 5.4.1.2. The influence diagram shown in Figure 5.5 is a summary sketch of the necessary input data and the process by which the comparison between a reference and a vegetated roof is made within the Cool Roof Calculator. It is both impractical and unnecessary to embed into this influence diagram all associated data for every combination of variables identified within the Calculator. Since the nodes are instead placeholders, and carry no numerical values, there is no corresponding decision tree generated from this influence diagram.

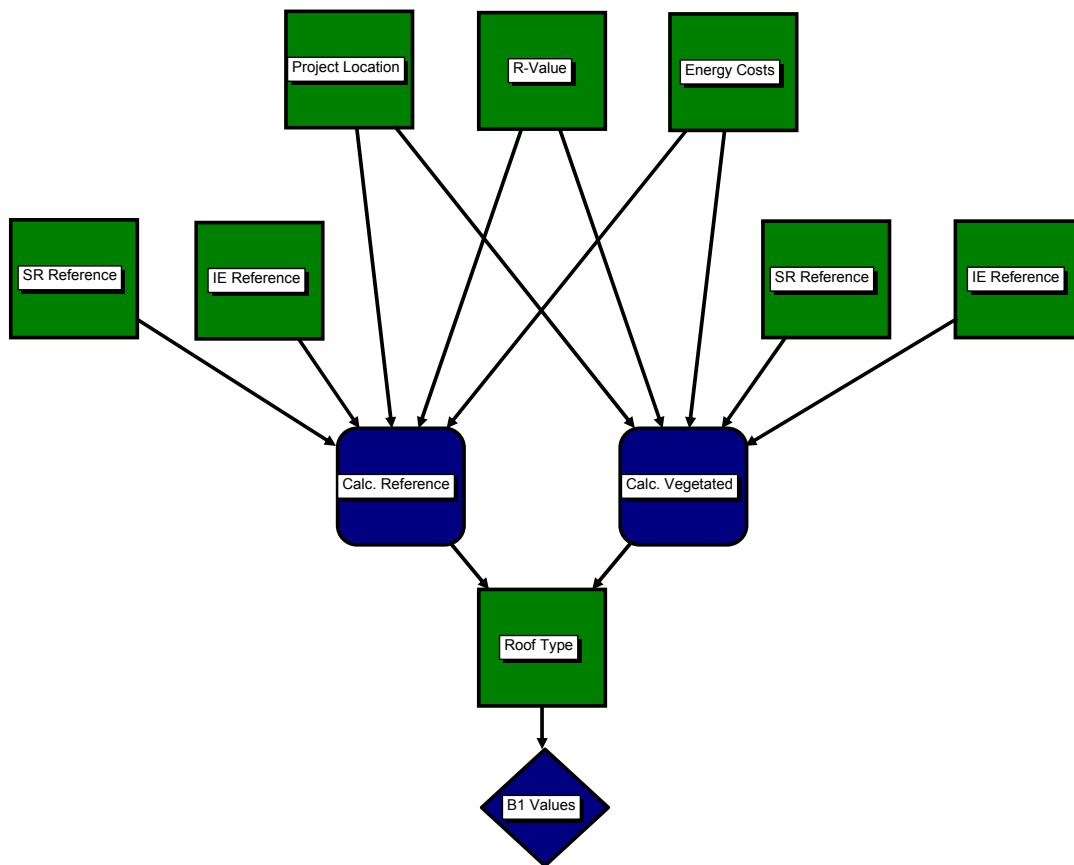


Figure 5.5 - Influence diagram of Parameter B1

5.4.1.4. Excluded Attributes and Design Variables Affecting Parameter B1

There are several relevant climatic, spatial and thermal attributes and design variables that are not fully addressed within Parameter B1. The climate in which the proposed roof is located is accounted for in part by the DOE Cool Roof Calculator, but some variables identified as sensitive within the literature review, such as relative humidity and wind speed, are not addressed due to their complexity. While several green roof thermal models have been developed using climate data from various regions worldwide, these are currently incapable of drawing reasonable distinctions between system types in the context of a decision-making system spanning North American vegetated roof system selection.

As explained Section 3.2.4, the roof-to-envelope ratio of a building greatly affects the importance of any reductions in heat transfer through the roof. In the absence of a comprehensive tool accounting for building geometry, the Cool Roof Calculator gives a measure of energy savings in monetary terms, which can then be put into perspective by the user of the decision-making framework in the context of the building project at large through the vehicle of the CBA Tabular Method used after all parameters are considered.

Besides the amount of insulation in the roof assembly, accounted for in the potential energy savings parameter, other sensitive variables identified within the literature are the green roof system type itself, categorized along a spectrum from extensive to intensive, the density of foliage (usually defined using the leaf area index) of the green roof system, and the moisture capacity of the growing medium. There are not currently enough data to support meaningful distinctions between green roof system types in terms of potential energy savings. And, as observed with the storm water parameter, the possible permutations of types of vegetation with different vegetation densities, combined with FLL green roof system types are too unwieldy to be analyzed at the early design stages. The moisture content of green roof media remains a somewhat elusive variable even to scientists well-versed in heat and moisture transfer calculations, and has the added complication of changing over time with precipitation patterns in built projects. Until more comprehensive models can be created and tested, the DOE Cool Roof Calculator is used to give a rough estimate of the potential energy savings assignable to green roof implementation.

5.4.1.5. Excluded Parameters Affecting Category B

While the significant weight of intensive green roof systems obviously contributes to the thermal mass of the roof assembly, this parameter is not addressed separately. While it is intuitively clear, and has been demonstrated in several in-situ green roof tests, that deep growing medium has sufficient heat capacity to create a time lag effect reducing undesired temperature swings due to heat flow through the roof assembly, there is not currently a simple or convenient way to assign different value to green roof systems based on their thermal mass. Similarly, the conductive properties of green roof assemblies have been found by most researchers to be far less significant than the effects of evapotranspiration and solar shading, which are effectively accounted for using the “equivalent albedo” in the DOE Cool Roof Calculator.

It would also be ideal to include a measure of the embodied energy and environmental impact of different vegetated roof system types within the broad category of “Energy”. However, such an analysis is beyond the scope of this investigation due to the great variability in origin, composition, and combination of green roof systems’ constituent components. Lesser quantifiable still are their downstream effects, many of which are as yet unknown due to the relative newness of this technology, especially in North America. A placeholder for this future parameter is represented in the final influence diagram with the notation “B2 Embodied energy and environmental impact”.

5.5. Category C: Acoustics

5.5.1. Parameter C1: Approximate Sound Transmission Class

5.5.1.1. Included Attributes and Design Variables

Roof system type

Sound transmission properties of roof structure.

5.5.1.2. Value Functions and Derivations

Since data determining the approximate sound transmission class (STC) of green roofs are nearly nonexistent, a proxy scale based loosely on the “mass law” (described in Section 3.3) is adopted. Because the mass law itself is theoretical, STC ratings are a useful tool for determining a rough estimate of sound transmission through a barrier. Stein and Reynolds (1992) define STC as follows,

To avoid the shortcomings of averages [of sound transmission loss at a range of frequencies] and yet to benefit from the indisputable convenience of single-number

systems, a system of standard contours was developed, called sound transmission class (STC) contours. Actual test results for a given construction, measured in a series of sixteen 1/3 octave bands, are compared to the standard STC contours according to a fixed procedure, and the STC number for that barrier is derived.

STC ratings have not been developed for green roof systems. Virtually the only published findings on green roof acoustical performance are found in *Häuser Mit Grünem Pelz: Ein Handbuch Zur Hausbegrünung* by Minke and Witter (1983). They claimed that typically it is the sound absorptive capacity of the plant substrate and not of the plants themselves that determines sound absorption on green roofs. When sound waves strike the roof perpendicularly, only minor absorption of high-frequency sound by the plant layer occurs, while the soil layer reduces noise by about 40 dB when it is 4.8 inches (120 mm) thick and 46 dB when it is 8 inches (200 mm) thick. In the absence of more substantial data, it is useful to employ a proxy material to estimate the average sound attenuation achievable by vegetated roofs of various thicknesses. “Surface mass” is the relevant factor used to predict the acoustical behavior of building materials according to the mass law, defined by Stein and Reynolds for walls as “the weight of the wall per square foot of surface area” (1992, p. 1383).

Actual growing media density and other variables such as the nature of the vegetation and the characteristics of the filter, drainage and protective layers obviously have an effect on the surface mass of a green roof system taken as a whole. Since the growing medium is typically the heaviest component of green roof systems, the density of the system is, for the sake of simplicity, defined here as its weight divided by the thickness of the growing medium layer. To compare green roof systems of various thickness, the weight of green roof systems in pounds per square foot (kilograms per square meter) must be divided by their thickness to yield density in pounds per cubic foot (kilograms per cubic meter). Two materials with the same density and the same thickness will have the same mass for a given surface area.

Stein and Reynolds (1992) give STC values for lightweight hollow masonry block walls which align well along a logarithmic scale with the small number of acoustic values reported by Minke and Witter. Lightweight concrete block also has a similar “surface mass” to green roof media, based on the reported wet densities of the six case study projects investigated. These are shown in Table 5.3. Since the operation of the mass law is based on the “surface mass” of materials, a comparison of the density of green roof systems and of lightweight concrete blocks

determines whether or not the STC ratings for lightweight concrete masonry units may be used as a proxy for the expected STC ratings of green roof systems.

Table 5.3 - Density of green roof media from case study green roof systems

Case Study Project	Saturated Weight of Green Roof System (psf)		Media Depth		Density	
	psf	kg/m ²	inches	mm	pcf	kg/m ³
Montgomery Park Business Center	18 (MDE, 2004b)	88	2.0 to 3.0 ⁶	50 to 75	108 to 72	1730 to 1200
Life Expression Chiropractic Center	28 (Miller, 2002)	140	5.0 (Miller, 2002)	130	67.2	1080
Chicago City Hall	30 to 90 (per project specifications)	150 to 440	3.0 to 18 ⁷	75 to 450	120 to 60	1900 to 960
Ford Dearborn Truck Assembly Plant	11 (Russell, 2004)	54	2.5 to 3.0 (Russell, 2004)	63 to 75	52.8 to 44	846 to 700
Mountain Equipment Cooperative (MEC)	38 (Johnson, 2003)	190	5.0 (Johnson, 2003)	130	91.2	1460
Jordan N. Carlos Middle School Art Building	35 ⁵	170	6.5 ⁸	160	64.6	1030

The densities in pounds per cubic foot for lightweight concrete masonry units (CMU) of various thickness are calculated from the weight of these blocks divided by their dimensions, as shown in Table 5.4. Weight data is taken from the Concrete and Masonry Databook (Beall & Jaffe, 2003, p.1.37). The actual, as opposed to nominal, outside dimensions of the blocks are used without subtracting the core spaces.

⁶ (Stewart Comstock, personal communication, April 12, 2004)

⁷ (Kevin Laberge, personal communication, July 16, 2004)

⁸ (R. Alfred Vick, personal communication, September 23, 2004)

Table 5.4 - Density of Lightweight Concrete Masonry Units

Nominal Unit Dimensions		Average Weight of CMU		Approximate Density Including Cores	
inches	mm	pounds	kg	pcf	kg/m ³
4 x 8 x 16	100 x 200 x 400	16	7.3	64	1000
6 x 8 x 16	150 x 200 x 400	23	10	59	950
8 x 8 x 16	200 x 200 x 400	27	12	51	820
12 x 8 x 16	300 x 200 x 400	42	19	52	830

If one compares the density of green roof media to that of lightweight concrete masonry units, it appears that the densities, and therefore the surface masses, of these two generically described building materials are acceptably close to permit the use of STC ratings of lightweight CMU as an approximation of a green roof system of similar depth. Table 5.5 combines the limited acoustic data on green roofs with the reported STC ratings for lightweight CMU walls of depths equivalent to green roof systems. Additional system depths are extrapolated from the CMU data, in other words, an increase of 10 dB in STC is assigned to a doubling of system depth, while a decrease of 10 dB is assigned to a halving of system depth. This is done to assign an expected STC rating to each of the eight generic FLL vegetated roof system types. Figure 5.6 shows the logarithm of the system depth on the x axis with the expected STC on the y axis. In the right two columns of Table 5.5, acoustic ratings and numeric ratings are assigned to these STC values, as explained below.

Table 5.5 - Acoustic rating based on system type

System Depth x (in)	FLL System Type	Log x	Y (STC)	Acoustic Rating	Numeric Rating
1 ¹	1	0.0	16	poor	0
2 ¹	2	0.3	26	poor	0
3 ¹	3	0.5	31	fair	0.25
4 ²		0.6	36		-
5 ³	4	0.7	40	good	0.5
6 ²		0.8	41		-
7 ⁴	5	0.8	44	very good	0.75
8 ^{2,3}	6	0.9	46	excellent	1
10 ¹		1.00	50		-
12 ²		1.08	51		-
16 ¹	7	1.20	56	excellent	1
20 ¹	8	1.30	60	excellent	1

¹Extrapolated value based on halving of depth = 10 dB decrease or doubling of depth = 10 dB increase in STC.

²Value for lightweight hollow block (Stein & Reynolds, 1992).

³Value taken from Minke and Witter (1983).

⁴Interpolated value based on trendline of $y = 34 (\log x) + 16$

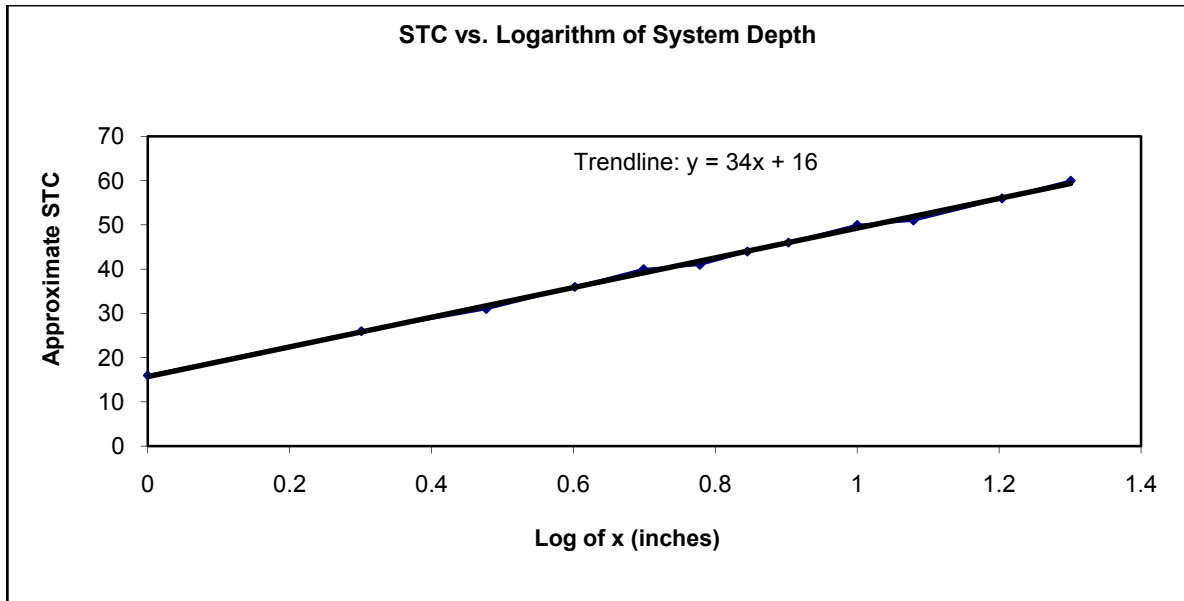


Figure 5.6 - Sound Transmission Class vs. Logarithm of System Depth

The ratings of poor, fair, good, very good and excellent assigned to the STC proxy ratings for green roof systems are derived from Stein and Reynolds' subjective descriptions of the quality of acoustic barriers between rooms, shown in Table 5.6. The ratings of 0, 0.25, 0.5, 0.75 and 1 respectively have been assigned to these terms assuming equal spacing between each of these subjective ratings.

Table 5.6 - Relations Between Barrier STC Rating and Hearing Condition on the Receiving Side (Stein & Reynolds, 2002, p. 1400)⁹

<i>Barrier STC^a</i>	<i>Hearing Condition</i>	<i>Description</i>	<i>Application</i>
25	Normal speech can be understood quite easily and distinctly through the wall.	Poor	Space divider
30	Loud speech can be understood fairly well. Normal speech can be heard but not easily understood	Fair	Room divider where concentration not essential
35	Loud speech can be heard, but is not easily intelligible. Normal speech can be heard only faintly, if at all.	Good	Suitable for offices next to quiet spaces
42-45	Loud speech can be faintly heard but not understood. Normal speech is inaudible	Very good	For dividing noisy and quiet areas; party wall between apartments
46-50	Very loud sounds, such as loud singing, brass musical instruments, or a radio at full volume can be heard only faintly or not at all.	Excellent	Music room, practice room, sound studio, bedrooms adjacent to noisy areas

^aAssuming a background noise level of NC-25. With higher background, (e.g., NC-35), STC can be degraded one step.

After these many necessary transformations, it is possible to draw a value function, shown in Figure 5.7, relating FLL system type to acoustic performance. The methodology leading to this function is based on crude approximations of surface mass of green roof systems, and a simplification of acoustic performance in the form of the STC rating. It also bears the flaw of comparing roofing systems with their roughly horizontal orientation to the vertical wall systems typically tested. The value function thus derived should be viewed as a first step in differentiating between green roof systems in terms of acoustical performance.

⁹ Stein, B., & Reynolds, J.S. *Mechanical and electrical equipment for buildings (8th ed.)*. Copyright © 1992 by John Wiley and Sons, Inc. Reprinted by permission of John Wiley & Sons, inc.

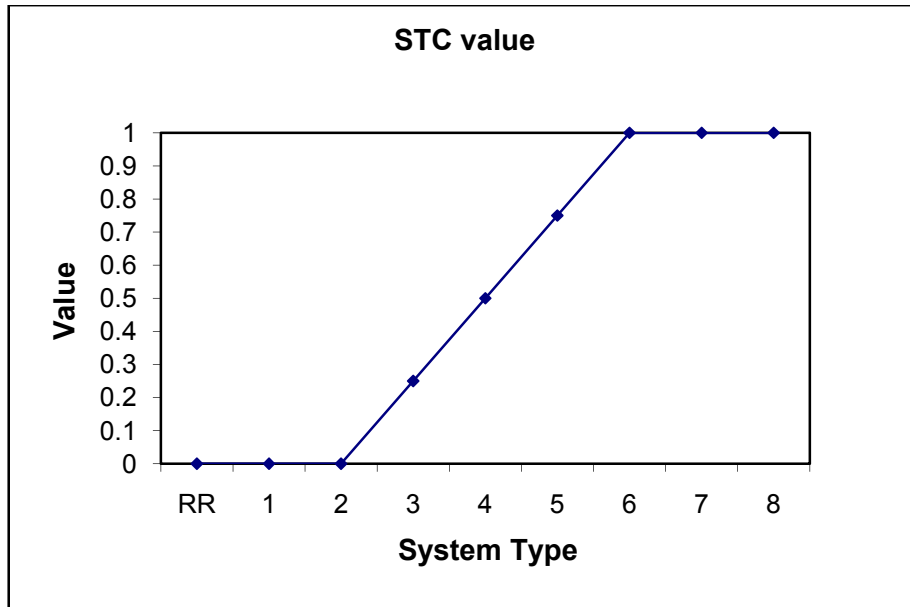


Figure 5.7 - Value of System STC on Cardinal Scale

This value function is useful to designers because it assigns no acoustical value to green roof systems with little mass, a maximum value to those systems with substantial mass, and values in between for systems that are assumed to be roughly analogous to a known acoustical barrier familiar to most architects. It is hoped that future studies, both theoretical and in-situ, will replace this value function with a more robust set of data.

5.5.1.3. *Influence Diagram of Parameter C1*

The influence diagram shown in Figure 5.8 requires the designer to first decide whether the roof deck for the project in question possesses “adequate” acoustical properties. For instance, roofs in some climates must be relatively massive to resist snow loads, therefore the addition of a green roof will have little relevance to the overall acoustic performance of such a roof. For example, Stein and Reynolds (1992) assigned an STC of 47, 50, 53, and 56 to 6-inch, 8-inch, 10-inch and 12-inch (150-mm, 200-mm, 250-mm, and 300-mm) solid concrete walls, respectively. Since all of these fall within the “excellent” category for acoustical barriers, a green roof atop a roof deck of solid concrete of this magnitude would be expected to add little or no benefit. Rather than add mathematical complexity to an already abstracted value function by creating a complete set of value scales for borderline cases, e.g. those where the reference roof is a “fair” to “very good” acoustic barrier, a cutoff is arbitrarily set at STC 42, and designers are

cautioned to consider the reference roof's performance when ultimately deciding the importance of the acoustic advantage of one green roof over the other, or over the reference roof.

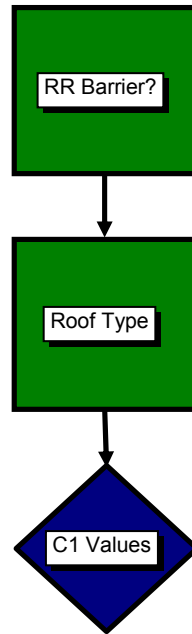


Figure 5.8 - Influence diagram of Parameter C1

5.5.1.4. Decision Tree of Parameter C1

From left to right, using the numbers at the top of the figure as a key, the decision tree in Figure 5.9 first depicts the decision of whether or not the project's roof deck is a significant sound insulator (1). If it is, the lower half of the asymmetrical tree shows all roof systems with a zero value, since their contribution to acoustical performance is negligible. The upper half of the tree leads to the next decision (2), the roof system type, where values (3) are assigned based on Table 5.5. It is an anomaly of the PrecisionTree software that FLL System 6 is shown as the only "true" choice with a probability of 1; it is merely the first system on the list to achieve the maximum value of 1, which is also achieved by Systems 7 and 8.

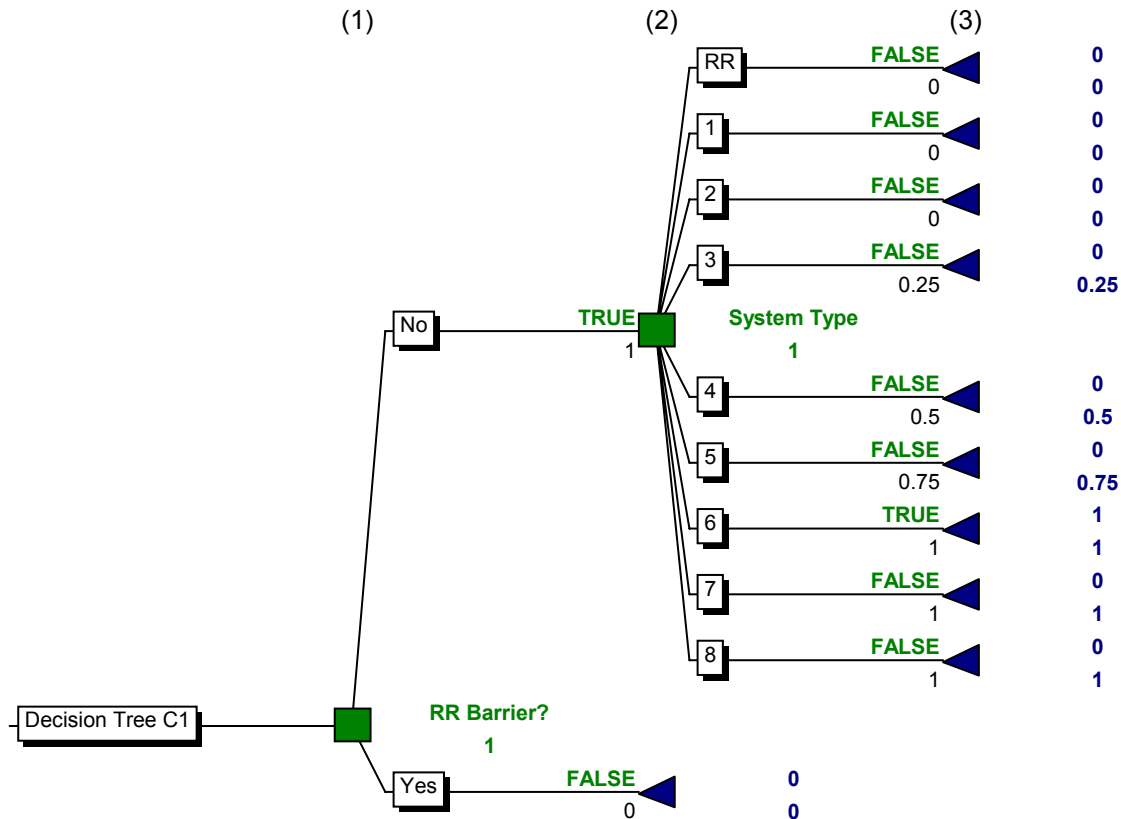


Figure 5.9 - Decision tree of Parameter C1

5.5.1.5. Excluded Attributes and Design Variables Affecting Parameter C1

The simplicity of the value function is due in large part to the virtual absence of supporting data. The theoretical nature of the current value function makes it nearly impossible to account for the acoustic effects of such complexities as roof penetrations and the contributions of underlying roof assemblies, except as most broadly interpreted in the initial question, “Is the reference roof an adequate acoustical barrier?”. The intricacies of various green roof system components, and the ramifications of combining them in different ways, are not dealt with, nor are the frequency-specific resistances of various plant and growing media products addressed. However, for making general comparisons, the approach is founded in the fundamental physics of sound transmission.

5.5.1.6. Excluded Parameters Affecting Category C

The noise reduction coefficient is another measure of acoustic performance. It was defined by Stein and Reynolds (1992) as “the arithmetic average of the absorption coefficients at 250, 500,

1000 and 2000 Hz” (p. 1372). Stein and Reynolds pointed out that it is an averaged measure of mid-range performance of an material, and as such it is a poor predictor of effectiveness at low, high, and specific frequencies. In this sense it shares the limitations of the STC rating, but is similarly convenient for rough comparisons. In layman’s terms, it is an approximation of the degree to which a surface is absorptive of sound (dead) or reflective of sound (live). While the vegetation atop green roofs tends to be more absorptive than most traditional roofing materials, there have not been sufficient studies to document this. Further, the range of possible traditional roof materials and the potential variation in vegetation even within a given generic green roof system type mean that drawing comparisons among the plethora of options would be a daunting proposition. Therefore this parameter is left as a placeholder, called “C2 Approximate Noise Reduction Coefficient”, until sufficient data exist that would help draw a meaningful distinction between traditional roofs and green roofs, and between various types of green roof systems.

5.6. Category D: Structure

5.6.1. Parameter D1: Surplus Dead Load of Roof System

5.6.1.1. *Included Attributes and Design Variables*

Dead load capacity of proposed roof project

Approximate expected weight of green roof system

Approximate expected weight of reference roof system

5.6.1.2. *Derivation of Value Functions*

The dead load capacity of a roof structure may or may not be precisely defined at the time the roof system is selected. Theodore Osmundson (1999) characterized the situation best. “Most engineers will answer the question, ‘How much load can be put on a roof?’ with the question, ‘How much do you want to put on the roof?’ That simply means you should work together to come up with a reasonable answer” (p. 154). The transparency of the framework for green roof system type selection allows for an iterative approach to this parameter. A reasonable guess about structural capacity can be made during the first analysis, then can be replaced with a firmer number as the design of the roof and the rest of the building proceed.

Because there is variation in the makeup of green roof systems both in terms of layers included and the character of each of these layers, total weights of systems per unit area may vary. However, for preliminary selection purposes, the industry rule-of-thumb is to assign an

approximate weight to each unit depth, either of the whole system or of the growing medium. As roofs get deeper, these two values converge. The added weight of larger plants on intensive green roof systems as compared to extensive systems must also be accounted for. ASTM has developed Standard E 2397 - 05, *Standard Practice for Determination of Dead Loads and Live Loads associated with Green Roof Systems* which describes a testing methodology for determining the dead load of green roof assemblies. Roofscapes, Inc., a leading provider of a range of green roof system products, references this standard in their model specifications for each green roof type. The specifications require the designer to define a maximum allowable wet dead weight per square foot to green roof systems, and give an approximation of this weight per inch of depth as a suggestion to the specification writer, assuming standard materials are used, and the ASTM test procedure is followed. For the five basic types of Roofscapes products, suggested wet dead weights per unit of system depth are shown in Table 5.7.

Table 5.7 - Approximate system weights of Roofscapes *Roofmeadow* Assemblies (Roofscapes, 2006)

System name	Typical system depth		Approximate weight per unit of depth	
	inches	mm	psf per inch	kg/m ² per cm
Type I: <i>Roofmeadow</i> ® <i>Flower Carpet</i>	2.0 to 3.0	50 to 75	7.5 for 2.0 inch system, 6.7 for 3.0 inch system ¹⁰	13 for 50 mm and 75 mm systems
Type II: <i>Roofmeadow</i> ® <i>Aromatic Garden</i>	3.0 to 6.0	75 to 150	6.75 ¹¹	13.2
Type III: <i>Roofmeadow</i> ® <i>Savannah</i>	4.0 to 8.0	100 to 200	6.75 ¹²	13.2
Type IV: <i>Roofmeadow</i> ® <i>Meadow</i>	6.0 to 9.0 (9.0 to 12.0 for turf)	150 to 230 (230 to 300 for turf)	6.75 ¹³	13.2
Type V: <i>Roofmeadow</i> ® <i>Heath</i>	6.0 to 9.0	150 to 230	6.75 ¹⁴	13.2

ASTM Standard E2397-05 provides a table useful for adding the weight of various system components to determine the total dead load. Because the standard does not prescribe a way to estimate the weight of vegetation, the table assigns a weight of 2 pounds per square foot (psf) (10 kilograms per square meter (kg/m²)) to “extensive plant material” and 3 psf (15 kg/m²) to “intensive plant material, excluding large perennials and trees” (p.1289). These numbers agree with those published in the *FLL Guideline* (2002) for vegetation loads.

The *FLL Guideline* also includes reference values for design loads for a broad range of green roof components under the general headings of “materials for use in drainage courses” including drainage materials, drainage matting, drainage boards, and drainage and substrate boards; “materials for vegetation support courses” including vegetation substrates, substrate

¹⁰ (Roofscapes, Sept. 2006a)

¹¹ (Roofscapes, Sept. 2006b)

¹² (Roofscapes, Nov. 2006a)

¹³ (Roofscapes, Nov. 2006b)

¹⁴ (Roofscapes, Nov. 2006c)

boards, and vegetation matting; and “vegetation”. Loads vary widely according to material type, and the potential combinations of components to create a green roof system profile are numerous. To simplify matters, a value of 9.7 psf per inch of course depth (19 kg/m^2 per cm of course depth) may be assumed as a logical maximum, since the maximum load for a drainage course is 9.2 psf per inch (18 kg/m^2 per cm) of course depth for gravel, and the maximum load for vegetation support courses is 9.7 psf per inch (19 kg/m^2 per cm) of course depth for soil mixtures with mineral and organic additives.¹⁵ To keep dead load designations aligned with the system types used elsewhere in the framework for decision-making, approximate weights for each of the FLL’s eight generic green roof system types is determined by combining reference weights from the Roofscapes, Inc. specifications, the ASTM test method, and the *FLL Guideline*. For systems less than or equal to 12 inches (300 mm) of depth, the Roofscapes, Inc. data is used, and for systems over 12 inches (300 mm) deep, the FLL data is used, as shown in Table 5.8. While somewhat arbitrary, this distinction reflects the fact that extensive and semi-intensive systems are frequently designed with weight restrictions in mind, while intensive systems generally are less sensitive to this parameter. It also permits use of load data presented for vegetated roofing systems currently available in North America where possible, and substitutes the conservative estimate generated from the German standards everywhere else.

¹⁵ There is a slightly larger value for vegetation matting, specifically a turf lawn of 0.8 inch (2 cm) nominal depth, listed as weighing 6 to 8 psf (30 to 40 kg/m^2), which translates to a maximum of 10 psf per inch (20 kg/m^2 per cm) of depth. This value is used in the calculations for Systems 7 and 8 as a conservative estimate.

Table 5.8 - Estimated dead loads for green roof system types

System type	Maximum media depth		Maximum dead load of system	
	inches	cm	psf	kg/m ²
1	1.6	4.0	12 ¹⁶	59
2	2.4	6.0	16 ¹⁷	78
3	4.0	10.0	27 ¹⁸	130
4	6.0	15.0	41 ¹⁹	200
5	8.0	20.0	54 ²⁰	260
6	10.0	25.0	68 ²¹	330
7	20.0	50.0	211 ²²	1030
8	>20.0	>50.0	>213 ²³	>1040

Further corroborating the values chosen for the expected dead load of green roof system types are Dunnett & Kingsbury's (2004) estimates of extensive and intensive green roof weights. They estimated a 2 to 6 inch (50 to 150 mm) green roof would weigh 14 to 35 psf (70 to 170 kg/m²), translating to a weight of 5.8 to 6 psf per inch (11.3 to 14 kg/m² per cm). Intensive roofs, with no reference depth given, are expected to weigh between 59 and 199 psf (290 to 970 kg/m²).²⁴

The next parameter necessary is the expected dead load of the reference roof. Ballasted roofs must support considerable weight which may equate to that of an extensive green roof system. The framework accounts for this by taking the allowable design dead load, subtracting the

¹⁶ (Roofscapes, Sept. 2006a)

¹⁷ (Roofscapes, Sept. 2006a)

¹⁸ (Roofscapes, Sept. 2006b)

¹⁹ (Roofscapes, Sept. 2006b)

²⁰ (Roofscapes, Nov. 2006a)

²¹ (Roofscapes, Nov. 2006b)

²² Heaviest media at 10 psf per inch (20 kg/m² per cm) plus 6 psf (30 kg/m²) for plants based on FLL system description

²³ Heaviest media at 10 psf per inch (20 kg/m² per cm) plus 8 psf (40 kg/m²) for plants based on FLL system description

²⁴ Dunnett and Kingsbury (2004) draw the distinction between extensive and intensive roofs at 6 inches (150 mm).

weight of a reference roof, and adding the weight of a green roof system. While ballasted roofs are common in Europe (Griffin & Fricklas, 2006), and may weigh up to 41 psf (200 kg/m²) (Dunnett & Kingsbury, 2004), they tend to weigh much less in North America, where roof structures are generally less substantial. The most accepted standard for ballasted single-ply roofing systems in the United States is published by the Single Ply Roofing Industry and the American National Standards Institute under the title *Wind Design Standard for Ballasted Single-ply Roofing Systems, ANSI/SPRI RP-4-2002*. This standard defines three different classes of ballasted roofs as weighing as little as 10 psf (49 kg/m²) in the field of the roof while still meeting wind uplift resistance specifications. Ballast at roof perimeters and corners must meet stricter wind uplift resistance criteria. Griffin and Fricklas (2006) assign a typical weight of 10 to 15 psf (49 to 73 kg/m²) to gravel ballast roofs, and up to 25 psf (120 kg/m²) for pavers. Since, at the schematic stage of design, the exact depth of gravel ballast or type of paver will likely be unknown, a figure of 10 psf (49 kg/m²) will be used for ballasted systems, and all other types of low-slope roofing will be assigned a value of 0, since green roof components are typically additive to a basic low-slope roofing system. For steep-slope roofing, the heaviest systems are slate roofs and clay tile roofs. Slate roofs, which range from 10 psf (49 kg/m²) for a standard system of 3/16 to 1/4 inch (5 to 6 mm) thick slates with 3 inches (75 mm) of head lap, to 20 psf (98 kg/m²) for a 1/2 inch (13 mm) thick slate tile roof (Patterson & Mehta, 2001). Again, the conservative figure of 10 psf (49 kg/m²) is used. Similarly, the typical 1/2 inch (13 mm) thick clay tile roof will weigh approximately 10 psf (49 kg/m²) (Patterson & Mehta, 2001). In North America, only an ultra-extensive green roof system can compete with the typical weights of even the heaviest roof systems.

The value function for Parameter D1 assigns a value to each roof system as follows:

$$x = \text{Allowable dead load} - \text{selected roof system dead load}$$

Equation 5.1 - Roof structural capacity calculation

Where x is greater or equal to 0, a value of 1 is assigned to Parameter D1.

Where x is less than 0, a value of 0 is assigned to Parameter D1.

Rather than include a set of values for various reference roofs, the negligible weight of most traditional roofing systems is ignored, while the parameter includes a value for heavier systems

such as ballasted, slate and clay tile roofs within the list of green roof system types. This approach avoids the step of subtracting the weight of the reference roof from the weight of the proposed green roof, greatly simplifying the decision tree for this parameter.

Obviously, the difference between upgrading the structure of a roof to support 10 psf (49 kg/m²) of additional load is far less significant than to support an increase of 100 psf (490 kg/m²). However, it is impossible to quantify the difference between these two scenarios without knowing specific information about the project, such as the type of structural system contemplated, and the feasibility of upgrading or retrofitting the roof structure. Further, the decision to do so impacts other building systems to such a degree that it is unrealistic to address all possible ramifications here. The purpose of this value function is to alert the designer to the fact that green roofs are at least as heavy as the heaviest of standard reference roofs, and to make use of a structural engineer's initial estimate of available dead load to determine what is possible. In some cases, the extra weight of some green roof system types may simply rule them out altogether; in other cases, particularly early in the design process, there will be time to make changes to accommodate them. If the weight of some or all green roof system types exceeds available capacity, the designer will have the opportunity to qualify the importance of the advantage of the systems that do meet dead load restrictions during the CBA Tabular Method step of the decision-making process.

5.6.1.3. *Influence Diagram of Parameter D1*

The influence diagram shown in Figure 5.10 simply shows the result of Equation 5.1 leading to a payoff of 1 for systems where there exists sufficient structural capacity for a given roof system type, and 0 where this capacity is lacking. While it seems more appropriate to represent this equation with a calculation node instead of a decision node, the workings of PrecisionTree require the equation to be shown as a decision node so that two outcomes can be defined and assigned values.

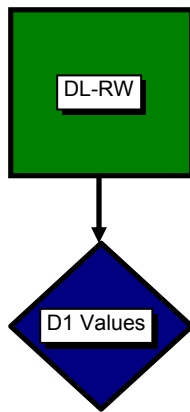


Figure 5.10 - Influence diagram of Parameter D1

5.6.1.4. *Decision Tree of Parameter D1*

The decision tree for Parameter D1 depicts the roof weight calculation (1) with its two possible outcomes (2).

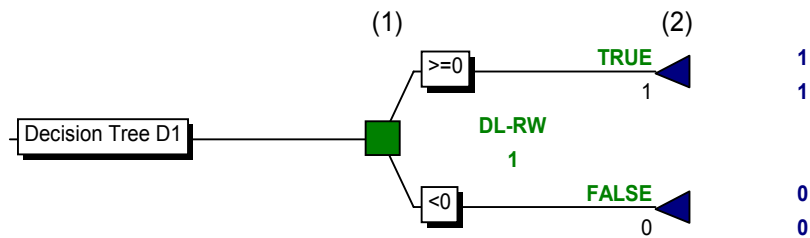


Figure 5.11 - Decision tree of Parameter D1

5.6.1.5. *Excluded Attributes and Design Variables Affecting Parameter D1*

The value function used in Parameter D1 does not accommodate the actual depth of the green roof media, but assumes the maximum depth for each system type. It also does not differentiate between very light, engineered media and more traditional gardening materials, but uses estimates provided by industry experts in North America and Germany. One important caveat concerns the implementation of turf grasses; according to Dunnett and Kingsbury (2004), a 4 to 6 inch (100 to 150 mm) turf roof may weigh as much as 103 psf (503 kg/m²), or more than twice the estimate used in this parameter. Additionally, the weights per unit area used in the analysis are averages across the field of the roof and do not account for differentiation within the green roof design.

5.6.1.6. Excluded Parameters Affecting Category D

Beyond dead load estimates, three other structural considerations affect the design of green roofs, namely, live loads including snow loads, concentrated or “point” loads, and wind loads. ASTM Standard E 2397 - 05, *Standard Practice for Determination of Dead Loads and Live Loads associated with Green Roof Systems* defines live loads for green roofs as the difference between their weight when fully filled with water while precipitation or irrigation are ongoing, and their weight when they have drained after precipitation or irrigation are complete. The standard provides a methodology for calculating the weight of this “transient” water, which is trapped temporarily within the drainage layer or layers. A broader definition of live load was provided by Theodore Osmundson (1999) as “human occupants, furnishings, temporary maintenance equipment such as moveable window-washing equipment, and other items of a transient nature” (pp. 154-155). The 2006 International Building Code defines roof live loads as “those loads produced (1) during maintenance by workers, equipment and materials; and (2) during the life of the structure by movable objects such as planters and by people” (p. 277). The IBC considers snow load separately in structural calculations. Ordinarily, live loads will not limit the type of green roof system selected, but they will often impact whether or not, and how, a roof may be occupied (Osmundson, 1999). Similarly, concentrated loads are not dealt with in the framework since they have no bearing on the general type of green or traditional roof system used. They do determine the maximum weight and placement of architectural items however, such as pergolas, larger plants, or ponds, within a roof garden design. Finally, while green roofs must withstand the significant forces of wind uplift, they are typically well suited to do so, since the rough plant surfaces tend to create turbulence, disrupting airflow and therefore reducing the strength of uplifting pressures. As plants grow, they weave with one another and with underlying layers to form a monolithic construction that also resists uplift (Miller, 2006). Meshes are available to protect plants and growing medium from wind scour, and the underlying membrane from wind uplift, until plants are well established. In areas of high wind pressure, such as roof corners and perimeters unprotected by parapets or other obstructions, green roofs systems can be terminated, and concrete pavers or other forms of ballast can be installed in these areas (FLL, 2002).

5.7. Category E: Compliance

5.7.1. Parameter E1: Potential Contribution to LEED Certification

5.7.1.1. *Included Attributes and Design Variables*

Project site location

Roof system type

5.7.1.2. *Value Functions and Derivations*

Parameter E1 assigns value to green roofs based on the likelihood that they will contribute to the earning of points within the Leadership in Energy and Environmental Design (LEED) system. There are many variables interwoven with the green roof system selection that will affect whether or not the green roof in fact leads to the earning of any specific credit. Rather than reward the actual earning of points, which will not be truly known until the project has been evaluated by the USGBC, often long after the roof is completed, the framework assigns values in areas (credits) where green roofs potentially contribute to the earning of points, or toward the goal rewarded by the credit. However, a conservative approach is assumed, and green roofs are rewarded within the scope of this parameter only where they are specifically mentioned within the text of the LEED credit itself, and where their benefits are most widely accepted.

Proceeding in order of their appearance in the LEED-NC 2.2 guidelines, the relevant credits are as follows.

Sustainable Sites (SS) Credit 5.1: Site Development: Protect or Restore Habitat

Sustainable Sites (SS) Credit 5.2: Site Development: Maximize Open Space

Sustainable Sites (SS) Credit 6.1: Stormwater Design: Quantity Control

Sustainable Sites (SS) Credit 6.2: Stormwater Design: Quality Control

Sustainable Sites (SS) Credit 7.2: Heat Island Effect: Roof

The first two credits, SS Credit 5.1 and SS Credit 5.2, give credit for the use of a vegetated roof provided that Sustainable Sites (SS) Credit 2 is also satisfied. SS Credit 2 requires the project to meet development density and/or community connectivity requirements. This stipulation prevents non-urban green roof projects from contributing directly to the earning of SS Credit 5.1 and SS Credit 5.2. For those projects meeting SS Credit 2, value is assigned as follows. For SS Credit 5.1, FLL green roof system types 3 through 8 receive a value of 1, while all reference roofs and FLL green roof system types 1 and 2 receive a value of 0. This determination was made because of the credit's requirement to provide native or adapted vegetation on the roof

surface. Very thin extensive roofs, often called ultra-extensive, are optimized for performance through the use of a limited range of often non-native plant species. Dunnett and Kingsbury (2004) claimed that the use of native vegetation “is currently the most important model for roofs with substrates between 6 and 15 cm (2.4 and 6 in)” (p. 100) with non-native species also playing a role in some cases. As green roof medium becomes thicker, greater diversity in plant selection becomes possible, though not strictly necessary. While issues of aesthetics, availability, and performance will determine the plant selection on individual roof projects, value is given to green roof system types which at least allow the possibility of growing native or adapted species. For SS Credit 5.2, all green roofs are assigned a value of 1, while all reference roofs receive a value of 0. This credit puts no stipulation on the nature of vegetated roofs contributing to compliance.

SS Credit 6.1 lists vegetated roofs as one of several strategies to meet the storm water management goals necessary to qualify for credit. Sustainable Sites Credit 6.2 also explicitly mentions the use of vegetated roofs as one way to “reduce imperviousness and promote infiltration thereby reducing pollutant loadings” (LEED, 2005, p. 21). While clearly green roofs do absorb more rainfall than traditional roofs, literature on green roofing pollutant removal performance does not support their categorization as a best management practice (BMP) to treat runoff. The value assigned to green roofs in SS Credit 6.2 supports the goal of reducing pollutant loads by reducing the quantity of runoff to be treated by other BMPs. Since green roofs are often coupled with other strategies to manage site runoff, it is difficult to determine, especially at the earliest stages of design, the degree to which a green roof will contribute to storm water quantity control measures. As explained in the discussion of Parameter A1, the most meaningful shorthand comparison of various surfaces is the annual coefficient of discharge ψ_a . Therefore the fraction of average annual rainwater retained by a roof system type corresponding to each coefficient is used to give greater value to green roofs with greater capacity to absorb and retain rainfall, as it is in Parameter A1. Reference roofs are assigned a value of 0.20. Value based on the fraction of the average annual rainwater retained for each roof system type is determined for both SS Credit 6.1 and 6.2.

Finally, SS Credit 7.2 gives a value of 1 to all vegetated roofs, and 0 to reference roofs. To receive credit, vegetated roofs, used alone or in combination with roofs with a high Solar Reflectance Index (SRI), must meet specific roof area requirements listed in the text of the credit. Since the roof area assigned to various roof types is often a design issue, rather than an

issue of system selection, all green roofs are valued equally within the parameter. If the reference roof is a white reflective roof, it receives a value of 1 for this credit. This situation requires a manual calculation of the value for parameter E1 since it is not accommodated within the current decision tree and influence diagram.

The following tables summarize the discussion above and show the values assigned to each roof type and slope based on its potential contribution to earning each LEED Credit.

Only where SS Credit 2 is assigned,

Table 5.9 - Sustainable Sites Credit 5.1

Roof System Type	Value
Reference Roof	0
Green Roofs 1 to 2	0
Green Roofs 3 to 8	1

Table 5.10 - Sustainable Sites Credit 5.2

Roof System Type	Value
Reference Roof	0
Green Roofs 1 to 8	1

Regardless of whether SS Credit 2 is assigned,

Table 5.11 - Sustainable Sites Credits 6.1 and 6.2

Roof System Type	Value
Reference Roof	0.40
Green Roof 1	0.80
Green Roof 2	0.90
Green Roof 3	1.00
Green Roof 4	1.10
Green Roof 5	1.20
Green Roof 6	1.20
Green Roof 7	1.40
Green Roof 8	1.80

Since green roofs potentially contribute to both of these credits, the values assigned to each system are doubled.

Table 5.12 - Sustainable Sites Credit 7.1

Roof System Type	Value
Reference Roof	0
Green Roofs 1 to 8	1

Value is assigned to each green roof system type by summing the values earned for each credit, then dividing this number by the highest value possible. The resulting number is the output of the value function for Parameter E1.

5.7.1.3. Influence Diagram of Parameter E1

Figure 5.12 shows the influence diagram of Parameter E1, including the relationship of SS Credit 2 to SS Credits 5.1 and 5.2 and the influence of roof type on the potential earning of five LEED credits.

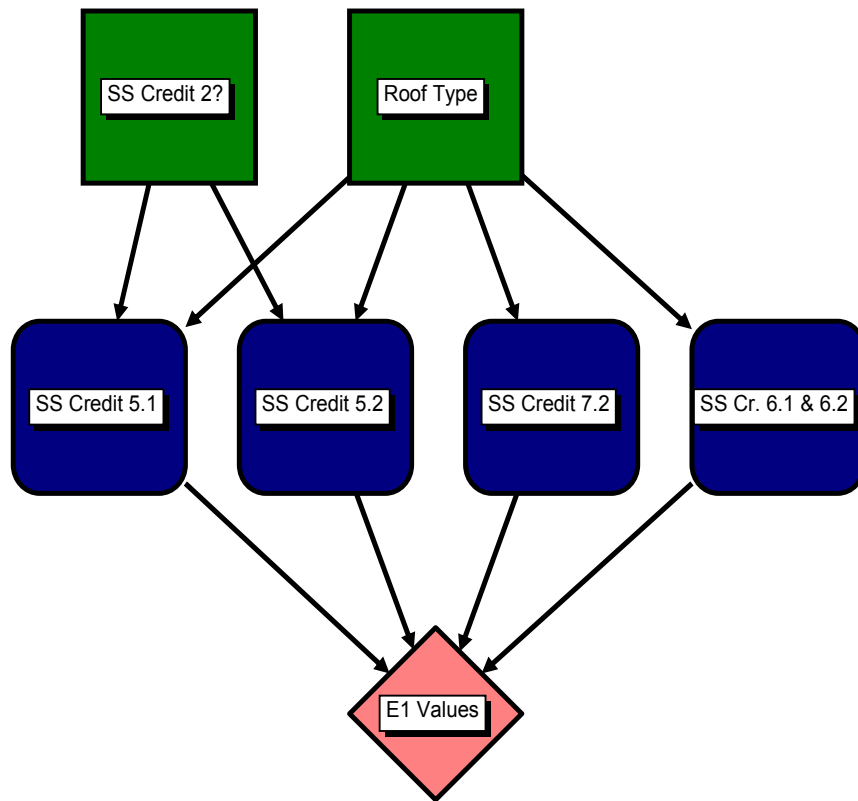


Figure 5.12 - Influence diagram of Parameter E1

5.7.1.4. **Decision Tree of Parameter E1**

Figure 5.13 shows the decision tree for Parameter E1. This is a collapsed version of the complete tree, which is graphically cumbersome. The values shown at the terminus, or “payoff” of each branch of the tree are described in Equation 5.2.

$$\text{Value} = (\text{BranchVal}(\text{"SS Credit 5.1"}) + \text{BranchVal}(\text{"SS Credit 5.2"}) + \text{BranchVal}(\text{"SS Credit 7.2"}) + \text{BranchVal}(\text{"SS Cr. 6.1 \& 6.2"})) / 4.8$$

Equation 5.2 - Equation to determine E1 values where SS Credit 2 applies

“BranchVal” simply means the value assigned to the node shown in parentheses immediately following. The tree is asymmetrical because where SS Credit 2 does not apply, neither will SS Credits 5.1 and SS Credit 5.2. In these cases, shown in the lower half of the decision tree, the payoff calculation is shown in Equation 5.3.

$$\text{Value}=(\text{BranchVal}(\text{"SS Credit 7.2"})+\text{BranchVal}(\text{"SS Cr. 6.1 \& 6.2"}))/4.8$$

Equation 5.3 - Equation to determine E1 values where SS Credit 2 does not apply

The tree is set up to assign value to each roof system type in the following order. From left to right using the numbers at the top of the figure as a key, the first decision node (1) asks whether or not SS Credit 2 applies to the project. The tree's next decision node (2) indicates the roof type, ranging from a reference roof to the eight FLL green roof system types. The next four calculation nodes are collapsed into one for visual clarity (3). They are SS Credit 5.1 (3), SS Credit 5.2 (4), SS Credit 7.2 (5) and SS Credits 6.1 and 6.2 (6), which are combined into one value (3). Each roof type is assigned a value for each of these four variables, or two variables where SS Credits 5.1 and 5.2 cannot be earned. The payoff calculation sums these values, then divides them by the maximum possible value of 4.8. This maximum value is achieved by a green roof system Type 8 where SS Credit 2 is granted. The resulting values at the far right of the tree range from 0 to 1, with the system achieving the greatest possible value within the LEED rating system assigned a rating of 1, and all other systems assigned a fraction of that maximum value. Figure 5.14 shows a closer view of the upper half of the decision tree for Parameter E1, with the branch with the maximum value expanded to show how each calculation node is accounted for in each final value (7).

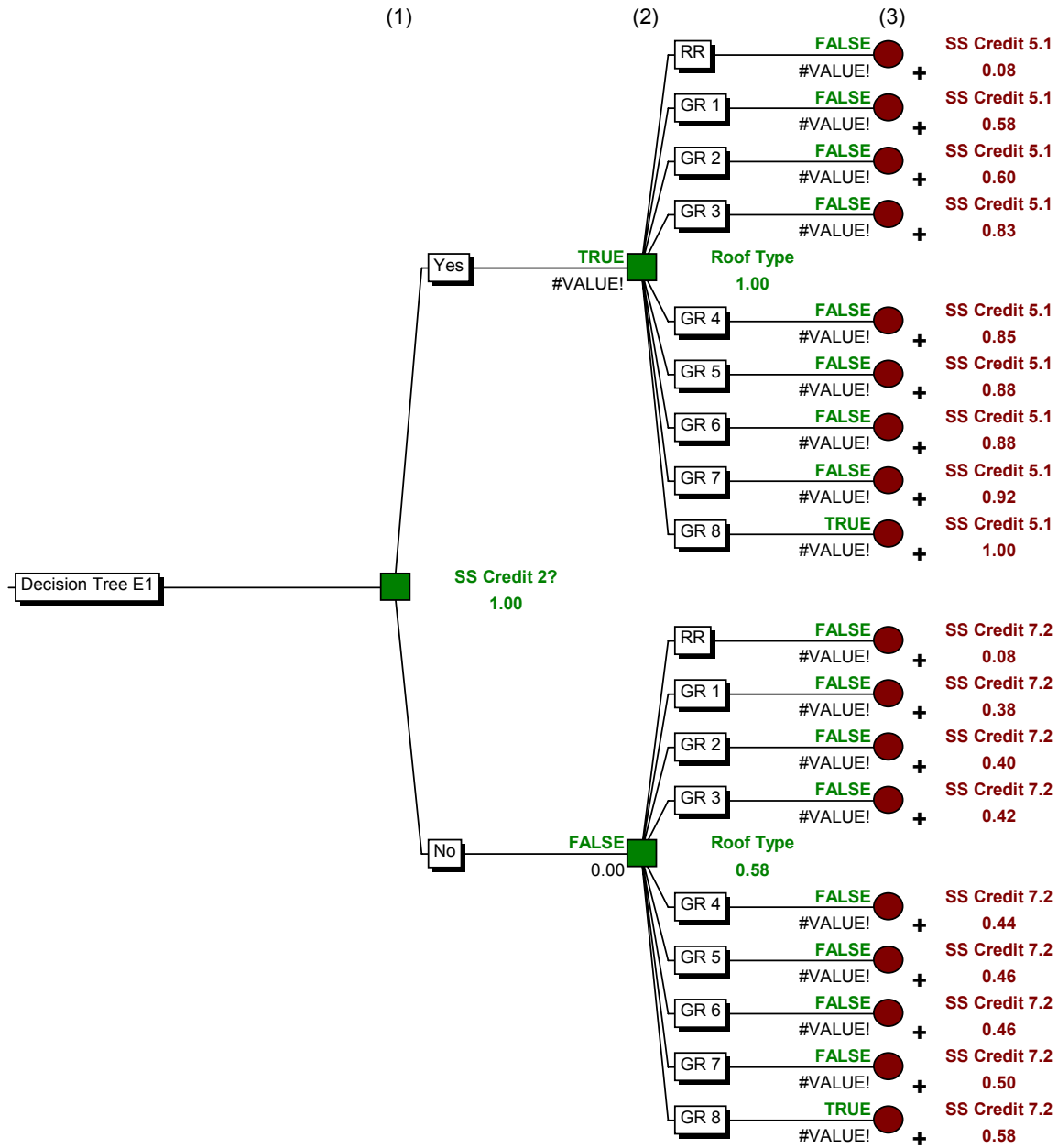


Figure 5.13 - Decision tree of Parameter E1

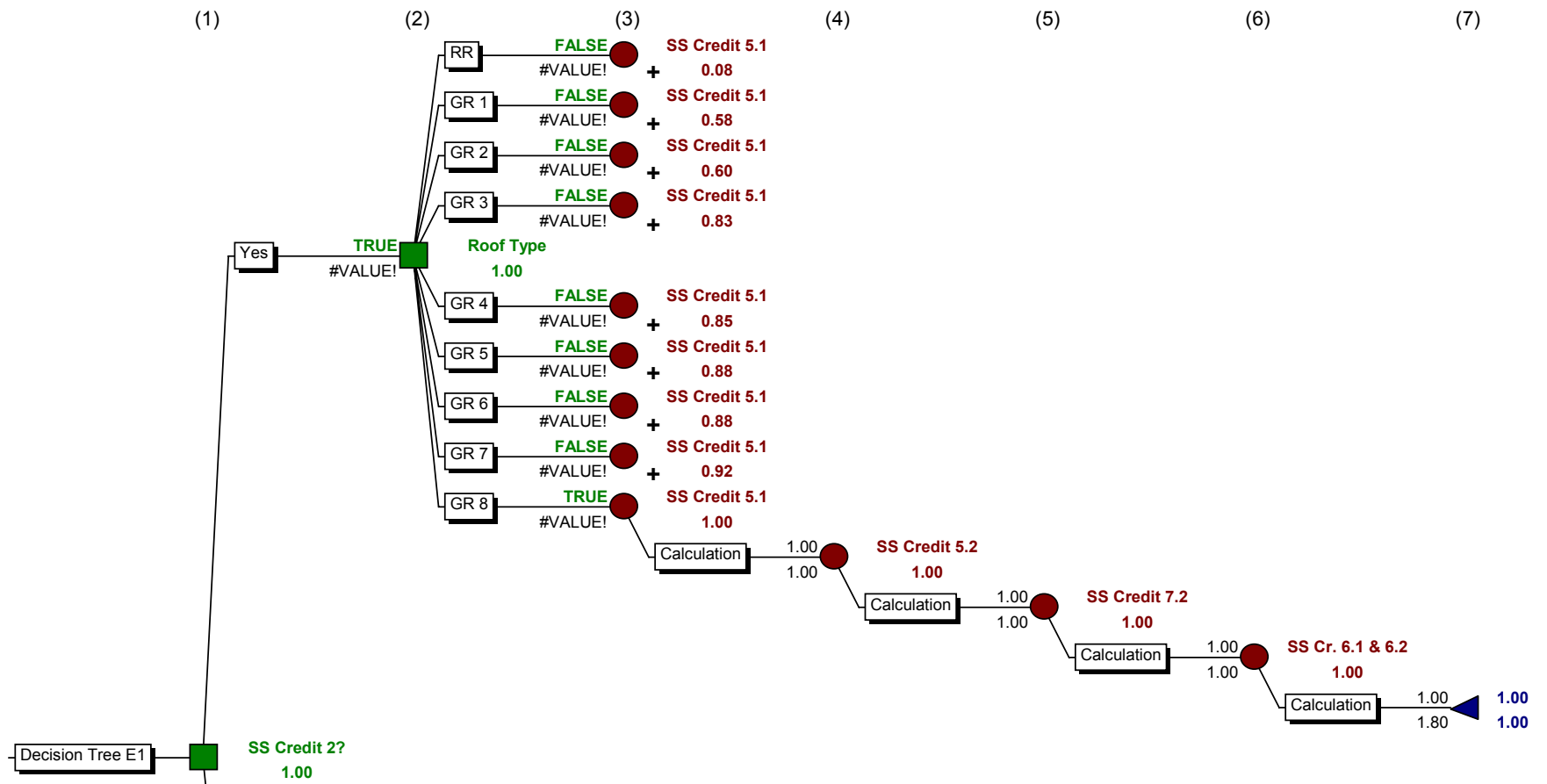


Figure 5.14 - Upper half of decision tree for Parameter E1

5.7.1.5. *Excluded Attributes and Design Variables Affecting Parameter E1*

As discussed in Section 3.5.3, green roofs can contribute to the earning of several additional LEED credits. Two such credits, WE Credit 1.1: Water Efficient Landscaping: Reduce by 50% and WE Credit 1.2: Water Efficient Landscaping: No Potable Water Use or No Irrigation, are excluded because the decision to use drought-tolerant plants, or to employ gray water or rainwater for irrigation, is a design decision that transcends the selection of green roof system type. This decision also extends to the project site as a whole, not merely the green roof. A green roof requiring irrigation, especially during the establishment phase, will potentially be a liability in earning these two credits, unless measures are taken to use non-potable water for this purpose. These complexities are not dealt with in the value function for Parameter E1, and are left for future elaboration. Similarly, while Richard Kula (2005b) claimed the green roof at the Winnipeg MEC store earned credit for the equivalent of WE Credit 1: Innovative Wastewater Technologies and ID Credits 1-1.4: Innovation in Design, these are not included in the value function for potential contribution to LEED certification because they require the green roof to be integrated with other building systems. Where this is the case, green roofs stand to increase the total number of LEED credits earned, but again, this is a design issue and these additional credits are by no means guaranteed merely by incorporating a vegetated roof into a project design. Section 3.5.3 explicates a number of additional LEED credits to which a green roof can contribute, but these are also too far removed from green roof system selection to be incorporated into a meaningful value function.

5.7.1.6. *Excluded Parameters Affecting Category E*

There are many policy efforts underway in North America to reward the implementation of green roofs, and in some cases, green roofs meeting certain performance criteria. However, these are so varied and location-specific in nature that they are not dealt with in the current framework for green roof system type selection. The reader is referred to Section 3.5.1.6. for a list of questions that serve to alert the designer to potential benefits possible when including a green roof in a design project. A grayed “Parameter E2 Meets policy initiatives” is included in the final framework. As green roof policies are implemented, and the recognized benefits of green roofs become more widespread and commonplace, values based on the policy questions raised in Section 3.5.1 may be identified for different green roof system types. As this occurs, Parameter E2 may be further developed and incorporated within the framework.

Code issues are not used to assign value to different green roof system types in this framework, as they largely relate to the design of a green roof rather than the class of system selected. Because it is currently impractical to rank green roof system types according to their ability to meet code requirements in locales with differing stipulations, these questions are shown as an influence diagram distinct from the framework, but helpful to the green roof designer. Until further investigation is performed to make system comparison possible, this diagram, found in Section 3.5.2.9, may be employed as a useful outline of topics a designer must research in the applicable codes when undertaking a green roof design.

5.8. Category F: Cost (Special Factor)

In Section 3.6, various attempts to calculate green roof construction costs and life-cycle costs were reviewed. Figure 5.15 collects variables from these sources and organizes them in an influence diagram depicting the relationships among them. The decision nodes depict variables for which the designer must choose a value, while calculation nodes depict variables that depend upon the value of predecessor nodes, or over which the designer typically has no, or little, control. This first rather complex diagram does not include influence arcs from each of the variables to a payoff node to preserve graphic clarity.

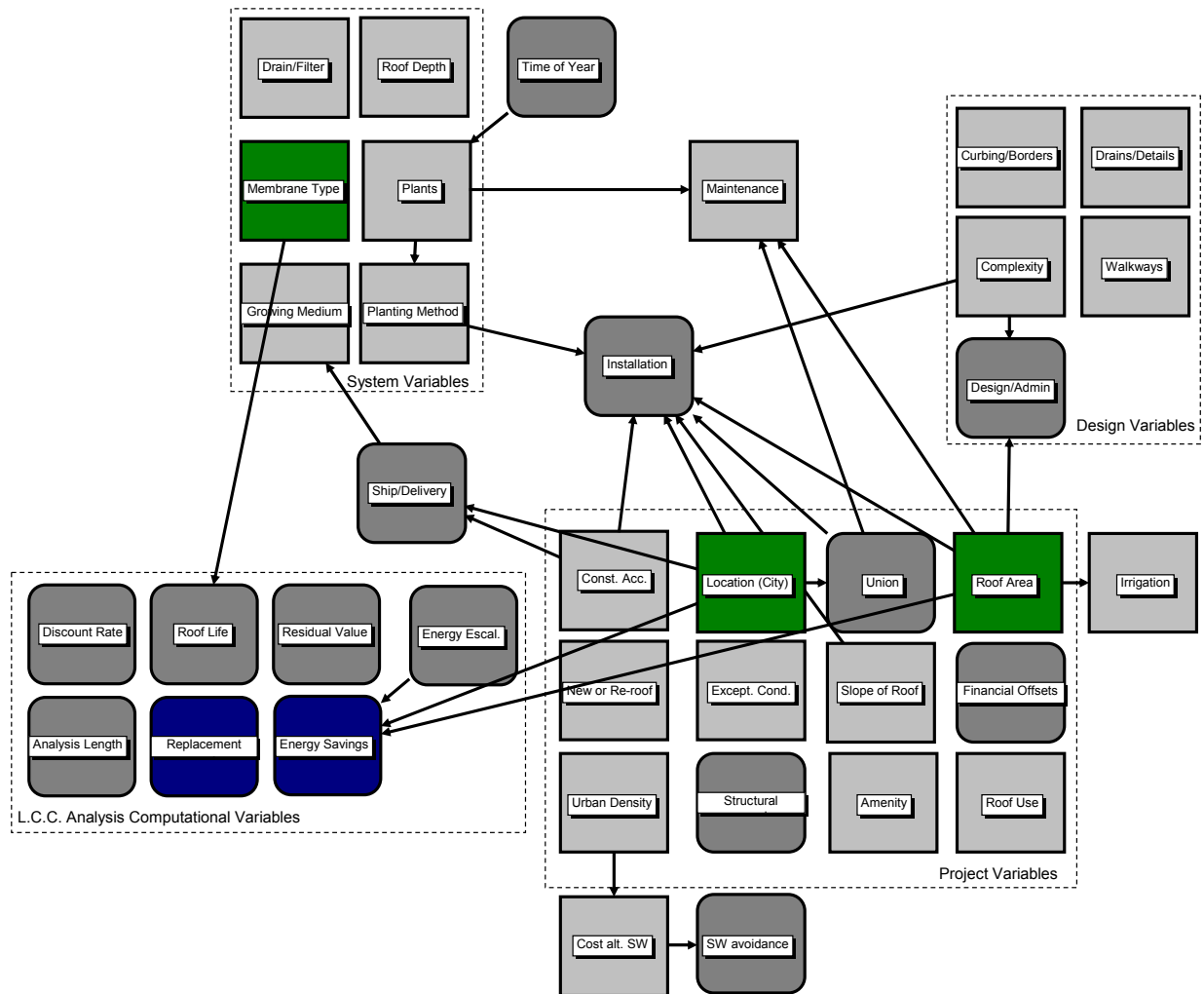


Figure 5.15 - Influence diagram of green roof cost Parameter F1

Approaching the diagram from the top left, the system variables include waterproofing membrane type, roof system depth, type of drainage and filter layers, type and size of plants, type of growing medium, and method of planting, i.e. from seeds, mats, cuttings, plugs, pots, or containers. The time of year influences the availability, and hence the cost, of plants. The type of plants often influences the planting method, and the planting method affects the cost of installation according to its degree of difficulty. Growing medium and plant costs are affected by the cost to ship them and the method used to deliver them to the roof, e.g. via lifts or cranes. The type of plants chosen also affects their long-term maintenance costs.

Design variables comprise the type and layout of curbing, borders, or walkways, the layout of roof drainage and other roof detailing, and the complexity of the overall green roof design. For the sake of simplicity, degree of complexity is shown as the generalized variable affecting installation cost. Roof area and complexity also affect design and project administration costs, a variable that includes design, project administration, site review, and initial structural evaluation, each of which was addressed separately by Green Roofs for Healthy Cities (2004a) as explained in Section 3.6.1.

Project variables include whether the green roof will be a new or re-roofing project, the ease of access to the roof for construction, the project location and its urban density, the presence of unions in the project location, the size and slope of the green roof, the expected use of the roof (which may necessitate installation of new guards or means of egress), the costs required to structurally upgrade the roof beyond what might be required for a traditional roof, the value of the roof as an amenity in terms of additional rent or other measurable income, and the presence of any exceptional conditions, e.g. high heat, wind, rainfall, drought, or foot traffic (Roofscapes, 2006). Subtracted from these variables is the value of any financial offsets that reduce the project cost. Project location and construction access affect the cost to deliver green roof materials to the site as well as the cost to install them. Installation cost is also affected by the area and slope of the roof, and the union or non-union labor rates in place at the project location. Labor rates and the size of the roof will influence ongoing maintenance costs. The cost of an irrigation system, if present, is affected by the roof area. As explained in Section 3.6.1, urban density, i.e., whether a project is located within an urban, suburban or rural area may influence the cost benefit of implementing a green roof in lieu of another storm water management system at grade. The cost of the alternate storm water system must be estimated to make this comparison.

The final group consists of variables that must be given value in order to perform a life cycle cost (L.C.C.) analysis. These are additive to the other variables in the diagram already described, which contribute to first or ongoing costs of roofing systems. The length of the analysis, coupled with assumptions made about the roof life of various systems, their replacement costs, and residual values, often strongly influence the outcome of the L.C.C. analysis. The discount rate, an interest rate used to relate future sums to their present value, and the assumed rate of energy price escalation, which affects the importance of any expected energy savings, may also have significant effect on the result (Lee, 2004). The expected

energy savings are affected by project location and roof area. These savings are potentially also affected by system variables such as green roof depth, but this framework does not attempt to define that relationship at this time. Membrane type is the system variable most often associated with the expected roof life, as the membrane supplier usually furnishes the roof warranty.

While it attempts to integrate issues raised in the literature discussing green roof costs, Figure 5.15 is not an exhaustive list of cost variables and connections between them. In a given project, there will be others identified, particularly as the design develops. Figure 5.16 simplifies the wide array of contributing factors by grouping some of them into system variables, design variables, project variables, and life cycle cost (L.C.C.) variables, while maintaining the relationships between these groups of variables and other factors. While the interrelationships within the variable groups, i.e. system, design, project, and L.C.C. analysis, are lost, the simplified diagram's groupings may prove more useful as containers for new variables as they are defined.

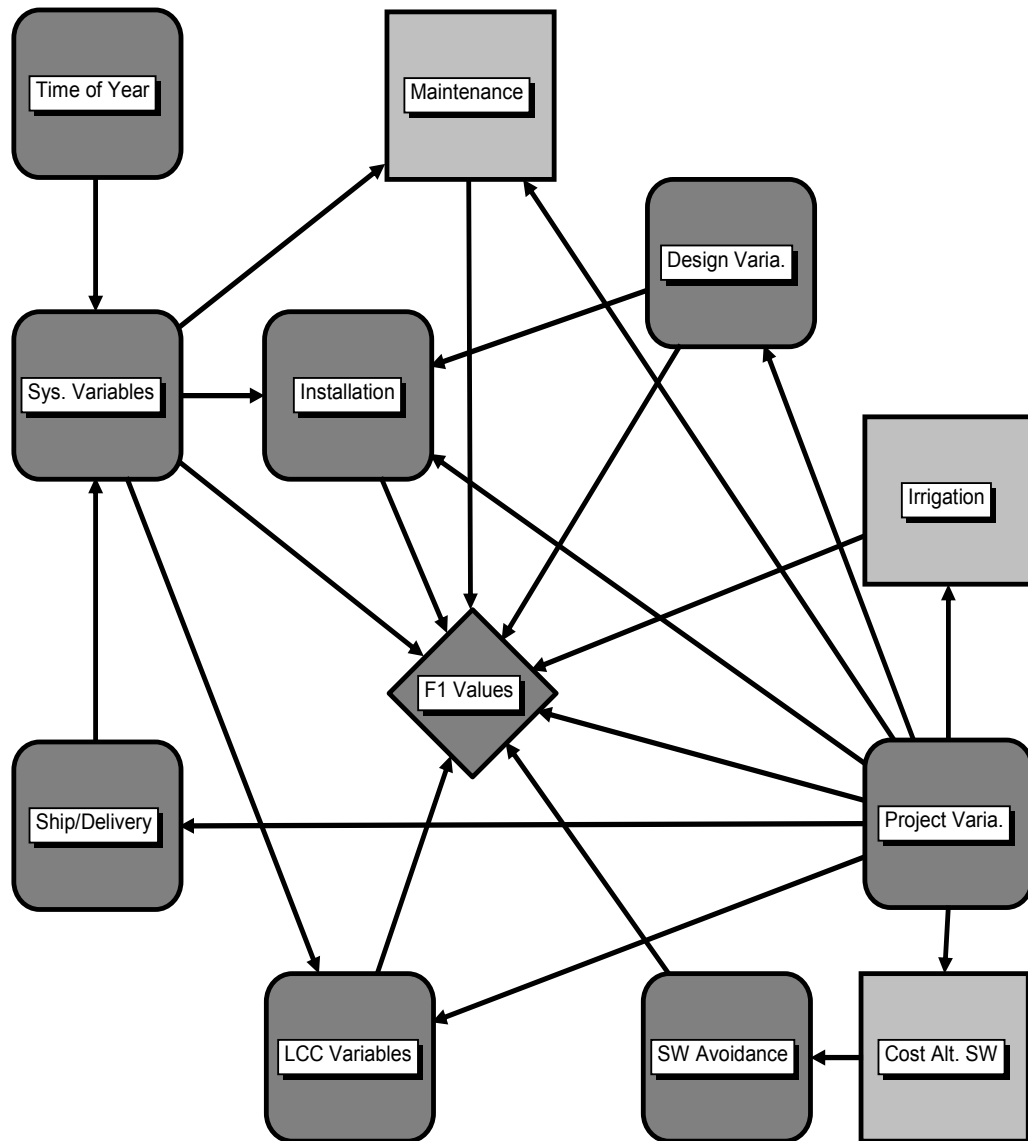


Figure 5.16 - Simplified influence diagram of cost Parameter F1

Each group of variables in Figure 5.16 is represented by a calculation node, since each node would in effect be a summation of the costs represented by each of its included variables. Finally, all the variables and groups thereof are connected with influence arcs to the payoff node, which would determine a value for a given green roof design based on both initial costs and long term costs over a set study period, as defined within the L.C.C. analysis. Even the simplified diagram remains a relatively complex web of interconnected factors, linked to a specific project, design, green roof system, and set of assumptions. It is a first step toward the

description of a methodology for determining green roof costs, which may also be used to compare systems one to another, and to a reference roof system. However, at this time, it is impractical to consider providing monetary values for each of the nodes included in these influence diagrams. It is recommended that some form of life cycle cost analysis be undertaken by a green roof designer before making final design decisions. Clearly, the time-consuming nature of this process indicates that a more rudimentary metric is needed to assist designers earlier in project development. Further, the influence diagrams in this section include a wide range of issues that transcend green roof system selection. The question cogent to the work of this dissertation is to determine which of these variables are relevant to green roof system selection, rather than to green roof design considered more broadly. Ideally, a rough indication of green roof system cost based on system depth or some other simple variable is needed.

In light of the cost estimates given by Jeff Sties, *Green Roofs for Healthy Cities* (2004a), Dunnett and Kingsbury (2004), and the U.S. Environmental Protection Agency (2006) in Section 3.6, a reasonable approximation of green roof costs cannot be generated based on their categorization as extensive or intensive, or any other convenient categorization. Even rules of thumb that state that green roofs are approximately 2 to 3 times more expensive than conventional roofing assume some agreement in the value of a base-case roof to which green roof systems may be compared. While consensus might be reached in a particular sector of the roofing market, for example, industrial buildings with low-slope roofs, it is impossible to extend rough cost comparisons from this sector to others, such as the residential, steep-slope market.

When faced with the absence of a convenient valuation of green roof cost, most designers will turn to the green roof industry to provide a general cost estimate for budgeting purposes. Worksheets such as that provided by Roofscapes, Inc. (2006) are helpful in this regard. The purpose of the influence diagrams presented in this section is to encourage green roof designers to investigate the ramifications of green roof selection as broadly as possible so they may derive the best budget estimate possible rather than relying only on numbers that reflect roof-area-based construction costs of the system in isolation. The situation of the project may prove far more relevant than a summation of green roof system component costs. Further, if L.C.C. analysis, even simplistic, can be applied, a payback period may be determined that makes the higher first costs of a green roof irrelevant. While arguably a rare occurrence, depending upon the financial situation of the owner and the length of time he or she expects to own the building, a green roof may be a logical investment and its higher first costs neglected in

decision-making. Or, as is more often the case, specific financial offsets based on policy initiatives or private donations may negate or offset the higher first costs of green roofing. Future versions of this framework would optimally include an advanced life cycle cost analysis tool, preferably one that could also account for the effects of environmental costs as discussed in Section 3.2.5. The L.C.C. tool would also highlight one of the most compelling reasons to install a green roof, namely the extension of the life of the underlying membrane. A placeholder for such a tool is represented by the grayed Parameter F1 in the final framework influence diagram.

5.9. Overall Framework

Figure 5.17 shows an influence diagram including all currently identified parameters. Gray parameters are those for which values can not yet be determined. This diagram is similar to Figure 5.1, except that a wider, and somewhat different, range of variables than originally contemplated have been identified as contributing meaningfully to green roof system selection. Climate and utility variables are incorporated, regulatory variables are deemed too project-specific to be useful, and many additional variables are included as described in each of the parameters A1 through F1. A list of these parameters is provided below the influence diagram in Figure 5.17.

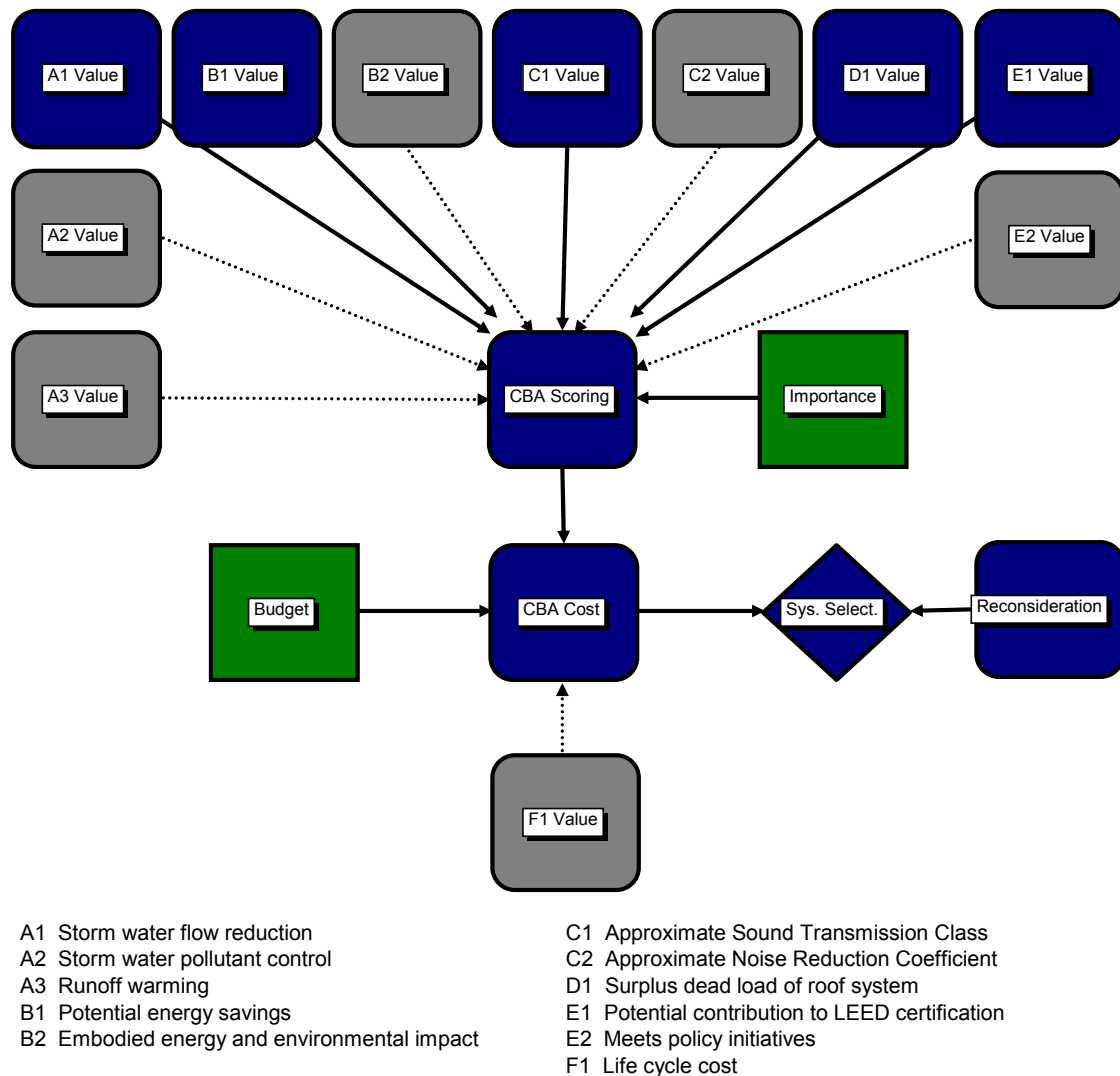


Figure 5.17 - Overall influence diagram of green roof system selection decision

To test the framework for acceptability, each user has to approach each parameter and attempt to quantify the difference between contemplated roofing systems using the methodology embedded therein. As with any other decision, there will often be gaps in the decision-maker's knowledge, particularly at any given time. That is one reason for including the "reconsideration phase" in the CBA analysis, to serve as a placeholder for any additional information that may either not be included in the parameters under review, or which may serve to refine their values or the importance assigned to the advantages of one system over others. For example, the designer may not have access to information about the mechanical equipment used in a particular project at the time of roof system selection. To find a value for Parameter B1, one of

the general categories of mechanical system performance may be used. As the building design develops, and more is known about the mechanical system, the reconsideration phase allows the roof designer to input more refined data and determine whether or not this will affect the outcome in terms of system selection. Likewise, the framework permits sensitivity analysis by allowing the designer to change one parameter's values across a range while holding the other parameters' values constant. In this way, one can test assumptions made during the process of assigning values. Reconsideration of changed values may also lead to an adjustment of the importance assigned to advantages represented by differences in these values. Changes in values or advantages or both may or may not impact the designer's decision. The framework permits an explicit tracking of this process, which can then be recorded as part of a project file and shared with stakeholders during the design phase, and again as questions arise during project execution.

Chapter 6 includes testing the framework for acceptability by assigning values to roof system types using the Choosing By Advantages (CBA) Tabular Method, determining the advantages of one or more systems over others, assigning importance to those advantages, tallying these importance scores, and deriving a recommendation. Cost is considered only after this process is complete, and only when necessary. Because the philosophy of CBA does not permit testing the framework in the abstract, green roof designers are asked to analyze a specific project using the framework, then to comment on its usefulness and applicability to green roof design situations they have encountered.

6. TESTING FOR ACCEPTABILITY

6.1. Interviewees' Design Processes

Interviewees were solicited based on the author's knowledge of their experience with green roofing and the location of their green roof practices within the Mid-Atlantic region. This narrow geographical area was chosen to allow for meaningful comparisons among green roof projects which shared similar rainfall patterns and other climatic characteristics. Of the six green roof designers invited to participate in the project, three completed both of the web-based surveys and one phone interview. The three sets of survey and interview responses summarized here were based on projects located in Northern Virginia. Project selection was left to the interviewee, who was asked in the questionnaires to "consider a green roof project with which you have been involved, particularly one on which you spent a considerable amount of design effort". All three respondents chose extensive green roof systems, which was not surprising based on the prevalence of extensive roofs in recent years.

The three interviewees signed and returned the Consent Form required by Virginia Tech's Institutional Review Board, found in Appendix B, prior to replying to the two web-based surveys entitled "Introduction, Process and Rationale Questionnaire" and "Framework Input Questionnaire", found in Appendices C2 and C3. Interviewees were instructed to complete the "Introduction" questionnaire first, then move on to the "Framework" questionnaire. This was done to avoid influencing the interviewees' open-ended discussion of their design processes in the first questionnaire with specific questions that revealed the parameters considered important to the author in the second questionnaire. Phone interviews were conducted after web survey results were received by the author. The interviews were between forty minutes and one hour in duration and generally followed the sequence of questions in the surveys with opportunities provided for the interviewee to elaborate on items of interest.

6.1.1. Interviewees' Experience with Green Roofing

Interviewee No. 1 is a registered landscape architect who has designed and overseen the installation of approximately 18 vegetated roofing projects for residential, commercial, industrial and institutional structures using a variety of delivery methods. He ordinarily becomes involved with green roof projects at the early conceptual stage, assisting the client with assembling an appropriate design team. He provides schematic design, construction documentation, and contract administration services, and frequently oversees maintenance for at least two growing

seasons after the vegetated roof is installed. He also offers design services for storm water harvesting and low-flow irrigation systems, and is becoming involved with designs incorporating renewable energy systems. He prefers to contract his services directly with the owner whenever possible rather than subcontract to another designer, but has consulted to architects and civil engineers, typically on new design-award-build construction projects, and has served as both prime contractor and subcontractor, primarily on design-build retrofit applications.

Interviewee No. 2 is a registered architect who has consulted to project architects on a number of vegetated roofing designs. One of his green roof designs has been implemented to date. His extensive research on vegetated roofing includes a trip to Germany to witness the manufacture and installation of green roof membranes, and he has lectured on the topic of green roofing to multiple groups. He observes that the industry trend for green roof system providers is to offer “one-stop shopping” to building owners, including design services, roofing membranes and vegetated roofing system components. While he appreciates that this delivery method is often necessary for these providers to remain in business, and acknowledges the benefit to the owner when the green roof supplier is the single point of responsibility for green roof warranty issues, he believes that the architect of record for the project should be involved in the green roof design process to ensure public safety and welfare, particularly in terms of the meeting of structural requirements, maintenance issues, and coordination with the building project as a whole.

Interviewee No. 3 is the president of a company that supplies products and services for green and reflective roofing systems, as well as rain water harvesting and irrigation systems, to building owners and architects. His company provides clients with a single source for design, detailing, materials, and project management services for vegetated roofing projects, including the roof membranes underlying the green roof components. Over thirty roofs have been installed by his company, with about 100 currently in various stages of design.

6.2. Framework Demonstration: Interview No. 1

6.2.1. Brief Description of Project

Project No. 1 is a 4,400-square-foot (410-square-meter) extensive green roof retrofit on an occupied building, six stories above grade, located in Alexandria, Virginia. The green roof has a 2% slope and is bounded by parapet walls with guard rails at 42 inches (1100 mm) above the roof surface. The green roof assembly consists of a mix of sedums pre-planted in one-by-two-

foot (300-by-600-mm) modular trays in 3 inches (75 mm) of growing medium. These are placed atop two 1 inch (25 mm) thick water retention mats laid over a product called “J-DRain”, which is a combined drainage mat, root barrier, and filter fabric layer, laid above an existing 0.160 inch (4 mm) thick two-ply atactic polypropylene (APP) modified bitumen membrane. Beneath the existing waterproofing, and predating the green roof installation, are a 5/8 inch (16 mm) thick gypsum fire protection board over two inches of rigid polystyrene supported by a 6 inch (150 mm) thick reinforced concrete roof deck.

6.2.2. Comparison of Design Process to Framework Process

The design process was initiated when the client approached the interviewee requesting a green roof that would meet a specific runoff reduction performance goal. The green roof system was chosen based on its ability to efficiently meet this performance goal using the best components available, according to the interviewee. The interviewee was leery of American vegetated roofing product manufacturers’ specific, and often untested, system performance claims, and preferred to use components previously tested in the European market.

6.2.3. Application of Framework to a Vegetated Roofing System Selection

For Project No. 1, it was possible to initially eliminate three of the five parameters from the decision. These are shown in gray rows in Table 6.1. The reference roof in this project was the existing system over which the new green roof components were laid, as described in Section 6.2.1. The reference roof assembly was assigned an R value of 15 h·ft²·°F/Btu (2.6 m²·K/W), a solar reflectance of 10%, and an infrared emittance of 70%. The R value was held constant for the green roof, since no insulation was added. Rather than estimate a higher R value to account for the thermal performance of the green roof, the solar reflectance value was artificially adjusted to account for the effects of the green roof according to the methodology described by Gaffin et. al. (2005) and discussed in Section 5.4.1.2. The difference between a green roof and the reference roof, when using the Department of Energy’s Cool Roof Calculator included in Parameter B1, was a savings of \$40 per year assuming a high “equivalent albedo” (Gaffin et al., 2005) of 85%, or \$26 per year assuming a low “equivalent albedo” of 70%. Due to these unimpressive savings, Parameter B1 was discarded as irrelevant. Detailed energy modeling was not performed as part of the design process, and therefore could not inform the roof selection decision. Further, because the green roof was only recently installed, there was no way to evaluate its impact on the building’s energy use. Acoustical performance was stated to

be irrelevant to the project's program, so Parameter C1 was ignored. Since the project was not LEED certified, Parameter E1 was also eliminated from the analysis.

Parameters A1 and D1 remained as the relevant criteria. The available dead load capacity of the existing roof structure for the superimposed green roof loads was 50 pounds per square foot (psf) (240 kilograms per square meter (kg/m^2)). According to the value function for Parameter D1, generic green roof Systems 1 through 4 as defined in Table 4.5 could have been accommodated, with a maximum loading of 41 psf (200 kg/m^2) for System 4 as estimated in Table 5.7. In the interviewee's opinion, the only feasible structural alteration would have been the addition of a carbon fiber mat to the top surface of the existing concrete roof deck. This modification would have required replacing the existing roof membrane which was still under warranty, and would have only netted an additional 5 psf (20 kg/m^2) of dead load capacity, just enough to support green roof System 5, which can weigh up to 54 psf (260 kg/m^2). This was not considered a reasonable tradeoff to the designer, so Systems 5 through 8 were excluded as viable choices and are shown in gray columns in Table 6.1.

The extensive green roof chosen by the designer fell within the depth range of System 3. Because expected runoff retention increases with system depth, it seems logical that System 4 would have been chosen in the absence of any other mitigating factors, as it optimized value for Parameter A1 and fell within the allowable dead loading restriction. The rationale leading to the choice of System 3 became clear during the phone interview. The green roof system was designed to retain 3 inches (75 mm) of water using a combination of two 1 inch (25 mm) thick retention mats, a proprietary drainage mat, and modular trays holding 3 inches (75 mm) of growing medium. The interviewee stated that this system, with a goal of 3 inches (25 mm) of retention, was designed to retain water from a one-year design storm. While the client would have liked to retain water from a two-year design storm, requiring the use of 5.2 inches (130 mm) of green roof media (which would have been classified as System 4), this was deemed impractical due to the placement of emergency overflow drainage scuppers 3 inches (75 mm) above the existing roof surface. The thicker system would have blocked these existing scuppers, and effectively would have required all of them to be raised to maintain the code-required secondary drainage system. For this reason, System 4 was excluded and is shown as a gray column in Table 6.1. The advantages of maintaining the existing emergency drainage system and the existing roof membrane afforded by using System 3 far outweighed the advantage of the additional runoff retention potentially provided by Systems 4 or 5. Since the

output of the framework was clearly a recommendation to choose System 3, and this choice was supported by mitigating factors in the actual design decision-making process, cost analysis was not performed. The interviewee stated that if an additional inch (25 mm) of growing medium had been added, the project would have exceeded the available budget. The city mandated a certain performance goal, and the designer chose the lightest system that met this goal, using what was in his opinion the highest-performing materials that fit the physical profile necessitated by the existing roof geometry.

6.2.4. Tabular Format Depicting Decision Situation

Table 6.1 shows the roof system selection decision situation for Project No. 1 using the tabular format described in *The Choosing By Advantages Decisionmaking System* by Suhr (1999) discussed in Section 4.4.4. Alternative roof systems are evaluated in light of parameters A1 through E1 identified in Chapter 5 of this dissertation. Gray rows and columns indicate parameters or systems excluded by their irrelevance or infeasibility to this design situation. Each intersection of row and column is subdivided into quadrants. The upper left hand corner shows the value assigned to that system by the value function within the applicable parameter. After these values have been assigned, the least preferred value for each parameter is underlined. Next, the difference, or advantage, of all the other systems as compared to the system with the underlined value is determined and placed in the lower left quadrant. The greatest advantage within each parameter is then circled. In Table 6.1, where multiple values are circled in one row, this indicates that all the circled systems all have an identical advantage over the least preferred system, based on the value function used for that parameter. Finally, the paramount advantage for the entire decision is determined and assigned a value of 100, which is placed in the lower right quadrant. All other circled advantages are ranked with a value between 100 and 0, respective to the paramount advantage.

In Project No. 1, assuming the exclusion of Systems 4 through 8, the paramount advantage shared by the reference roof and Systems 1 through 3 was the sufficiency of the existing building structure to support these systems without upgrades. The potential of System 3 to retain 150% more annual rainfall than a reference roof ranked as the second most important advantage, shown as “x”, where “x” is a value less than 100 and greater than 0. It was not necessary to precisely determine this importance value, nor that of the advantages of the reference roof and Systems 1 and 2 for Parameter A1, because the system with the greatest total importance of advantages, $100 + x$, was clearly System 3.

Table 6.1 - Tabular format results for Project No. 1

Project No. 1

FACTORS		ALTERNATIVES																	
		R (REF. ROOF)		1		2		3		4		5		6		7		8	
A1 SW RETENTION	Attributes:	<u>0.2</u>		0.4		0.45		0.5		0.55		0.6		0.6		0.7		0.9	
	Advantages:			100% more		125% more		150% more	x	175% more		200% more		200% more		250% more		350% more	
B1 POT. ENERGY SAVINGS	Attributes:	<u>0.44</u>		1		1		1		1		1		1		1		1	
	Advantages:			130% more, \$40/year	0	130% more, \$40/year	0	130% more, \$40/year	0	130% more, \$40/year	0	130% more, \$40/year		130% more, \$40/year		130% more, \$40/year		130% more, \$40/year	
C1 APPROXIMATE STC	Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
	Advantages:																		
D1 SURPLUS DL OF ROOF SYS.	Attributes:	1		1		1		1		1		<u>0</u>		<u>0</u>		<u>0</u>		<u>0</u>	
	Advantages:	Exist. structure sufficient	100	Exist. structure sufficient	100	Exist. structure sufficient	100	Exist. structure sufficient	100	Exist. structure sufficient	100								
E1 POT. CONTR. TO LEED CERT.	Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
	Advantages:																		
TOTAL IMPORTANCE:		100		100		100		100+x											
TOTAL COST:		Not Specified																	

Key:

<u>Value</u> (least preferred is underlined)	
Advantage (greatest is circled)	Importance of advantage

-  Gray rows - excluded parameters
-  Gray columns - excluded alternatives

6.3. Framework Demonstration: Interview No. 2

6.3.1. Brief Description of Project

Project No. 2 is an unconditioned garden shed in Fredericksburg, Virginia with a 4,000-square-foot (400-square-meter) vegetated roof in the rough shape of a barrel vault, with a maximum slope at the edges of 2.5:12. This maximum roof slope, at approximately 12°, falls within the definition in the *FLL Guideline* (2002) of a low-slope roof, i.e. “a roof gradient up to 15°” (p. 36). While the *FLL Guideline* does not specify whether the annual coefficient of discharge ψ_a applies exclusively to low-slope roofs or both low- and steep-slope roofs, it may be assumed that it applies at least to low-slope roofs, including the barrel vault in Project No. 2. The green roof assembly, in order from top to bottom, consists of sedums and other succulents in four inches (100 mm) of engineered growing medium comprised of expanded shale with a small percentage of fertilizer, a FamoRet membrane which combines a copper root barrier, drainage layer, and water retention layer in one, atop a torched-down Famobit membrane which serves as the waterproofing. The underlying structure is ½ inch (13 mm) thick pressure treated plywood decking atop 2-by-6 inch (50-by-150 mm) actual dimension solid wood tongue and groove siding.

6.3.2. Comparison of Design Process to Framework Process

As with Project No. 1, Project No. 2 was initiated by an owner’s request for a green roof. Like Interviewee No. 1, Interviewee No. 2 had several justifications for choosing a specific vegetated roofing system. He stated that “I used Famos system based on my knowledge of the system and the applicability to the project: extensive, additional weight could be accommodated in a wood frame, client was going to install system and plants, system was regionally available and could be easily adapted to a curved roof section.” Elucidation of each of these factors was provided by the discussion of the separate parameters under consideration by the framework, and is addressed in Section 6.3.3.

6.3.3. Application of Framework to a Vegetated Roofing System Selection

In Project No. 2, there was no reference roof to which green roof systems were compared; the client requested a green roof and grant money was obtained for that purpose. Energy and acoustical performance were not relevant to this non-insulated, unconditioned application, and the project did not involve LEED certification. Storm water retention was a main impetus of the project and drove the decision to install a green roof, since the green roof itself was funded

through a grant from the Environmental Protection Agency's Chesapeake Bay Program through the Virginia Department of Conservation and Recreation. Despite this focus, no specific storm water mitigation performance criteria were specified and therefore distinctions between green roof system types based on this parameter were not explicitly recognized.

The garden shed was viewed as a demonstration project incorporating several environmentally friendly technologies. The structure was made from wood harvested in a sustainable manner, with curved wood trusses made by Amish woodworkers. The entire structure was erected by unskilled volunteers. A structural engineer was consulted to determine if the structure could support the green roof, which was calculated to weigh 16 pounds per square foot (psf) (78 kilograms per square meter (kg/m^2)). The expected green roof loading was derived using a conservative assumption of one inch (25 mm) of standing water over the field of the roof, an unlikely scenario given the curved profile. A load allowance for the green roof of 16 psf (78 kg/m^2) fell within System 2, according to the estimated dead loads for green roof system types shown in Table 5.7 for Parameter D1. However, the growing medium used in the project was almost entirely composed of expanded shale, which according to the *FLL Guideline* (2002) weighs a maximum of 4 psf per inch (8 kg/m^2 per cm) of course depth, translating to 16 psf for 4 inches of media depth (78 kg/m^2 for 10 cm), the figure cited as the green roof load by Interviewee No. 2. Therefore, the green roof used in this project, while categorized as System 3 by its depth, weighed as little as a System 2 roof as defined within Parameter D1. This discrepancy may point out the conservative nature of the estimated dead loads in Parameter D1, especially with respect to engineered extensive green roof systems. The interviewee stated that it might have been possible to increase the weight of the green roof, allowing for a deeper profile and therefore a wider range of plant species, within the context of a wood frame structure. However, in this instance the species of wood used for some of the structural members was weaker than that typically specified, and volunteer labor was used to erect the structure, which might have lead to some inconsistencies in its construction. These two factors made a heavier system undesirable within the constraints of the wood frame construction selected. The importance of the advantage of allowing an additional structural factor of safety afforded by Systems 1 through 3, combined with the superior storm water load reduction performance of System 3 in Parameter A1, led to the decision to implement System 3. As with Project No. 1, there was no need to explicitly rank advantages using the tabular method. The framework pointed to a choice of System 3, and System 3, with a maximum media depth of 4 inches (100 mm), was in fact chosen by the designer.

While cost analysis is not required to make an initial system recommendation, cost constraints can potentially make a recommended system non-viable. In this case, cost had no impact on the choice of green roof system according to the interviewee, but perhaps affected the choice of detailing at the roof edges, which would have been an issue for any green roof system chosen for the project.

6.3.4. Tabular Format Depicting Decision Situation

The outcome of the tabular format applied to Project No. 2 was similar to that described in Section 6.2.4 for Project No. 1. The reference roof and Systems 4 through 8 were excluded for reasons explained in Section 6.3.3, and Parameters B1, C1 and E1 were disregarded as irrelevant. The paramount advantage was the sufficiency of the structure as designed, with the second ranking advantage the potential 25% improvement in roof runoff reduction expected with the use of System 3 as compared to System 1. System 3 was therefore suggested for selection.

Table 6.2 - Tabular format results for Project No. 2

Project No. 2

FACTORS		ALTERNATIVES																		
		R (REF. ROOF)		1		2		3		4		5		6		7		8		
A1 SW RETENTION		Attributes:	N/A		<u>0.4</u>		0.45		0.5		0.55		0.6		0.6		0.7		0.9	
		Advantages:					12.5% more		25% more	x	37.5% more		50% more		50% more		75% more		125% more	
B1 POT. ENERGY SAVINGS		Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
		Advantages:																		
C1 APPROXIMATE STC		Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
		Advantages:																		
D1 SURPLUS DL OF ROOF SYS.		Attributes:	N/A		1		1		1		<u>0</u>		<u>0</u>		<u>0</u>		<u>0</u>		<u>0</u>	
		Advantages:			Designed structure sufficient	100	Designed structure sufficient	100	Designed structure sufficient	100										
E1 POT. CONTR. TO LEED CERT.		Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
		Advantages:																		
TOTAL IMPORTANCE:				100		100		100+x												
TOTAL COST:		Not Specified																		

Key:

<u>Value</u> (least preferred is underlined)	
Advantage (greatest is circled)	Importance of advantage

-  Gray rows - excluded parameters
-  Gray columns - excluded alternatives

6.4. Framework Demonstration: Interview No. 3:

6.4.1. Brief Description of Project

Project No. 3 is a 8,000-square-foot (700-square-meter) extensive green roof located in Alexandria, Virginia on an existing condominium rooftop eight stories above grade. The green roof replaced an existing built-up roof, which was removed down to the underlying lightweight concrete substrate prior to the installation of the green roof. The green roof assembly comprises, from top to bottom, one inch (25 mm) diameter sedum plugs spaced at two plugs per square foot; three inches (75 mm) of engineered growing medium composed of 80% shale, 15% compost and 5% sand; geotextile filter fabric; and a two-layer waterproofing system and substrate. The waterproofing and substrate consist of an upper, integrated membrane which includes a copper root barrier, a water retention layer, and drainage channels, heat welded and torch applied to a lower 0.160 inch (4 mm) thick modified bitumen membrane of amorphous polyalphaolefin (APAO), heat welded and torch applied to a ½ inch (13 mm) gypsum thermal overlay board, adhered to three inches (75 mm) of isocyanurate insulation, adhered to a fiberglass reinforced base sheet mechanically attached to the existing lightweight concrete fill. The underlying, existing roof structure is, to the best of the interviewee's recollection, a six inch reinforced concrete deck.

6.4.2. Comparison of Design Process to Framework Process

The decision to implement a green roof on Project No. 3 was directly related to the availability of grant money. While such grants and other incentives are not formally included in the framework, they are addressed in Section 5.8. In this case, a grant from the National Fish and Wildlife Foundation supplied \$40,000 of the \$180,000 total green roof project budget, and covered overburden materials which would not have been included in a traditional roofing system, such as plants, growing media and other components necessary to support the vegetated roof. The system selected was chosen because it was the preferred system of the green roof designer. The reasons for this preference were, in the words of the designer, "all components are attached to the building providing superior wind ratings and all the components are included in the membrane which helps simplify installation and minimize labor costs". The weight of the system, at 25 pounds per square foot (psf) (120 kilograms per square meter (kg/m^2)), fell within the allowable structural capacity of 35 psf (170 kg/m^2), as verified by a structural engineer using x-rays of the existing structure. The designer also stated that the chosen system met the requirements of the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e. V. (FLL) and has been proven in Germany. In this case, a growing medium

depth of 3 inches (75 mm) was chosen because it fell within the project budget. The interviewee asserted that had money not been a controlling factor, a deeper system would have been considered.

6.4.3. Application of Framework to a Vegetated Roofing System Selection

A green roof was envisioned for Project No. 3 in the earliest stages of design because of the compromised water quality in the local watershed. Acoustical considerations and LEED certification were not relevant decision criteria according to the interviewee. Storm water retention was desired as an outcome of the installation of the green roof, but no specific performance goals were specified. A grant from the National Fish and Wildlife Foundation made the implementation of a vegetated roof economically feasible. Without it, a white reflective membrane roof would have been installed to replace the existing roof system, and this alternate membrane was used as the reference roof in the tabular format. The input data for the reference roof were based on a white roof with a solar reflectance of 80% and an infrared emittance of 80%, and an R value of $20 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$ ($3.5 \text{ m}^2\cdot\text{K}/\text{W}$) was assumed for all vegetated roof systems and the reference roof based on the use of 3 inches (75 mm) of isocyanurate insulation. The Department of Energy's Cool Roof Calculator generated a net savings relative to a black roof of $0.053 \text{ \$/ft}^2$ per year for the reference roof, a net savings of $0.047 \text{ \$/ft}^2$ per year for a green roof with an "equivalent albedo" of 70%, and a net savings of $0.058 \text{ \$/ft}^2$ per year for a green roof with an "equivalent albedo" of 85%. Assuming the higher albedo, a benefit of $0.005 \text{ \$/ft}^2$ per year for the use of the green roof in lieu of a white reflective roof, or an insignificant \$40 per year, was calculated. Assuming the lower albedo, the reference roof was preferred, but again, the difference was a negligible \$48 per year. The interviewee volunteered in the interview that even if there had been an appreciable reduction in energy needed to condition the building as a result of the green roof installation, this reduction would have only been experienced on the top one or two floors of the eight story building, a problem discussed by Alcazar and Bass (2005) in Section 3.2.4. For these reasons, the energy parameter B1 was ignored in the analysis.

The remaining parameters, A1 and D1, pointed to the selection of System 3 as designated in Table 4.5. This system had the greatest potential for storm water retention while still falling below the 35 pounds per square foot (170 kilograms per square meter) weight restriction prescribed by the structural engineer. The interviewee stated that it would have been nearly impossible to effect any structural upgrades to the project because condominium tenants

inhabited the space immediately below the green roof installation. The implemented system included 3 inches (75 mm) of media, which fell within the range of System 3, as defined by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e. V. (FLL). Weight restrictions would potentially have allowed 4 inches (100 mm) of media to be installed, which would have also fallen within the depth range of System 3. When the interviewee was questioned as to why a slightly deeper system was not used, he said it would have been, had the project budget not limited the quantity of media to 3 inches (75 mm). The quantity of engineered growing media used in extensive green roof systems is a significant factor in green roof cost, according to the interviewee. As with Projects No. 1 and No. 2, there was no need to numerically rank the importance of the advantages, as the ability to satisfy structural limitations was considered the most important advantage, and the ability to retain additional storm water is the next most important advantage. This advantage decreased in importance with a reduction in system depth, therefore the deepest system satisfying the restriction of system weight was selected. When cost was considered, the system suggested by the framework was feasible, with a slight downgrade from the maximum system depth to meet the project budget. Life cycle cost analysis was not performed formally for this project, but some generalizations were made by the interviewee comparing the cost of a vegetated roof to a conventional roof based on his past projects. He cited a 13 year payback period as the longest expected for a green roof in this type of application.

6.4.4. Tabular Format Depicting Decision Situation

The tabular format for Project No. 3 followed a similar pattern to that of Projects No. 1 and No. 2. Again, the advantage represented by the reference roof and Systems 1 through 3 meeting the existing structural dead load limit was added to the advantage of System 3 providing an estimated 150% more yearly runoff retention compared to the reference roof. System 3 therefore had the greatest total importance of advantages.

Table 6.3 - Tabular format results for Project No. 3

Project No. 3

FACTORS		ALTERNATIVES																	
		R (REF. ROOF)		1		2		3		4		5		6		7		8	
A1 SW RETENTION	Attributes:	<u>0.2</u>		0.4		0.45		0.5		0.55		0.6		0.6		0.7		0.9	
	Advantages:			100% more		125% more		150% more	x	175% more		200% more		200% more		250% more		350% more	
B1 POT. ENERGY SAVINGS	Attributes:	<u>0.91</u>		1		1		1		1		1		1		1		1	
	Advantages:			9.4% more, \$40/year		9.4% more, \$40/year		9.4% more, \$40/year		9.4% more, \$40/year		9.4% more, \$40/year		9.4% more, \$40/year		9.4% more, \$40/year		9.4% more, \$40/year	
C1 APPROXIMATE STC	Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
	Advantages:																		
D1 SURPLUS DL OF ROOF SYS.	Attributes:	1		1		1		1		0		<u>0</u>		<u>0</u>		<u>0</u>		<u>0</u>	
	Advantages:	Exist. structure sufficient	100	Exist. structure sufficient	100	Exist. structure sufficient	100	Exist. structure sufficient	100										
E1 POT. CONTR. TO LEED CERT.	Attributes:	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
	Advantages:																		
TOTAL IMPORTANCE:		100		100		100		100+x											
TOTAL COST:		Not Specified																	

Key:

<u>Value</u> (least preferred is underlined)	
Advantage (greatest is circled)	Importance of advantage

-  Gray rows - excluded parameters
-  Gray columns - excluded alternatives

6.5. Green Roofing System Design Tools Used by Interviewees

Interviewee No. 1 used the green roof system manufacturer's guidelines to determine how much storm water could be retained by various components of the green roof system, since the client approached him requesting a system that would retain 3 inches (75 mm) of rainwater. The "J-DRain" system was expected to retain $\frac{3}{4}$ inch to 1 inch (19 to 25 mm) of water, the two retention mats another $1\frac{1}{2}$ inches (38 mm) combined, and the 3 inches (75 mm) of growing medium the remaining $\frac{3}{4}$ inch (19 mm). When discussing structural loading, and the differences of opinion in the industry regarding the classification of retained water on green roofs as a dead load or a live load, Interviewee No. 1 said that he included the weight of water held within the system as part of the dead load, as this was the most conservative approach. Interviewee No. 2 used a rule of thumb weight representing one inch (25 mm) of standing water per square foot of roof area in his structural load calculations. No other design tools or rules of thumb were mentioned.

6.6. Green Roofing System Design Tools Desired by Interviewees

Interviewee No. 1 stated that he would benefit from a green building network to help assemble a design and construction team for green roof projects. Interviewee No. 2 made suggestions for useful online tools including a list of locally available membrane types, climate-specific media depth and plant species recommendations, sources for green roof accessories such as vents, details for conditions such as gutters and roof edges, region-specific green roof system costs per square foot, and green roof case study projects. Interviewee No. 3 envisioned a chart comparing green roof systems in terms of their waterproofing membrane type, system thickness, weights, methods, and industry approvals.

6.7. Interviewees' Obstacles to Green Roof Implementation

Interviewee No. 1 felt that the greatest obstacle faced in project implementation was the permitting process, which centered around the semantics of allowing the installation of a green roof above two existing roof membranes without the new green roofing materials qualifying as an entirely new roofing system.¹ There was also some difficulty with deciding whether the green

¹ This issue related to the code restriction that prohibits re-roofing over more than two existing roof membranes as elaborated in Section 3.5.2.7. In this case, the regulatory agency was inclined to consider the green roof components as a third superimposed roofing system, but was eventually convinced by the designers that, since the existing second layer of waterproofing would remain and would continue to serve as the waterproofing under the new green roof, the green roof components did not constitute a third "roof".

roof project ought to be considered a roof renovation or a building improvement, each of which required different permitting protocols.² All three interviewees considered cost as a constraint in their designs. They were limited in their choices by the project budget to some extent as all three projects were subsidized in whole or in part by a fixed sum of grant money. Interviewee No. 3 offered that while the higher first costs of green roofs as compared to conventional roofs are always a barrier for owners to overcome, life cycle cost analysis is helpful in justifying these systems.

6.8. Interviewees' General Recommendations to Green Roof Designers

Interviewee No. 1 stressed the need to clearly and thoroughly identify the client's programmatic needs at the earliest stage possible. He said these goals were very frequently well established prior to the project's inception, since many clients have researched green roofing long before contacting a green roof expert. His clients most often seek high-performing systems, in terms of reduction of energy use and extension of roof life, with low or no maintenance requirements. Interviewee No. 2 urged designers to consider vegetated roofs not only as building systems but also as elements of the larger landscape, and recognized the unique potential of green roofs to effectively integrate these two realms.

6.9. Study Limitations and Framework Critiques

6.9.1. Limitations of the Survey and Interview Instruments

It proved difficult to enforce the request to the interviewees to answer both web surveys using the same project. This may have occurred because each survey was accessed through a separate web address, and hence potentially at a separate time, by the interviewees. Another reason for this confusion could have been that the more specific framework survey asked technical questions that could perhaps have best been answered using a project different from the one used to answer the first survey, and the interviewees had no opportunity to return to the first survey to change their responses. The resulting lack of alignment between the questionnaires was resolved in the phone interviews without complication by re-asking the project-specific questions in the Introductory, Process and Rationale Questionnaire with respect to the project used to answer the Framework Input Questionnaire.

² The permitting body ultimately considered the green roof project a roof renovation, but required a structural engineer's evaluation.

6.9.2. Framework Critiques and Suggestions by Interviewees

Critiques of the decision-making framework were garnered in the course of explaining the applicable parameters to the interviewees in the context of various survey questions. This method was used in lieu of a formal review of all of the framework parameters to avoid lengthy explanations of value functions to interviewees in cases where certain parameters did not influence their decisions. Interviewee No. 1 did not look highly upon the use of the Department of Energy's (DOE) Cool Roof Calculator as a measure of potential savings effected by various roof assemblies. He looked forward instead to the availability of a database for green roof energy performance, especially one tailored to a small geographical area, the creation of which is a goal he hopes to achieve in his own practice. He also pointed to the variability of microclimates found on specific roof sites as a barrier to wholesale implementation of generalized calculators predicting the thermal behavior of vegetated roofs. The DOE Cool Roof Calculator was not applied to Project No. 2 since the green roof covered unconditioned space. However, the general premise behind energy parameter B1 was explained to Interviewee No. 2 in the course of conversation. He appreciated the concept of "equivalent albedo" and agreed that some proxy measure would be useful to account for the cooling effects of evapotranspiration and shading afforded by vegetated roofs. For Project No. 3, because many of the parameters were excluded from the analysis, and others were limited by project-specific constraints, no explicit critiques of the framework were evidenced in the interview. However, as was mentioned in the other two interviews, it was clear that in Project No. 3 the advantage represented by the designer's experience with, and confidence in, a particular system or family of vegetated roof systems overrode many other potential advantages of less familiar systems as enumerated in the framework. This conclusion was not surprising given the potential legal liability incurred in designing such systems. The need to wisely allocate design time and effort also motivates professionals to simplify the design process by choosing solutions they have used before, and with which they have a greater familiarity. Designing and administering projects involving new technologies, or at least technologies new to the client, requires the design professional to take on a degree of risk. Interviewee No. 3 explained that within the designer's palette of well-known green roof systems, there is room for some tailoring to specific project requirements and prescribed performance goals.

6.9.3. Accommodation of Uncertainty in the Framework Tests

In this section, sensitivity and uncertainty analysis of the values of the six examined parameters are discussed in light of the three interview cases. For Parameter A1, Storm water retention,

the actual degree of storm water retention was not the critical factor, but instead, deeper systems were intrinsically valued over shallower ones. In other words, even if the curve of the value function for Parameter A1 were shifted upward or downward on the y-axis, or the values thereon changed slightly, the ordinal relationship of systems would likely remain unchanged. For Parameter B1, Potential energy savings, the results of the Cool Roof Calculator, even when varying the “equivalent albedo” of the green roof from a low of 0.7 to a high of 0.85, were unimpressive and negligible, causing the results to be discarded. Parameter C1, Approximate Sound Transmission Class, was not relevant to the three interview cases, so sensitivity analysis was not performed. For Parameter D1, Surplus dead load of roof system, weights were assumed with a fairly high degree of confidence for each of the green roofs evaluated. Since structural design is by its nature a conservative endeavor, the designers interviewed used the maximum expected load of the green roof systems in their decision-making, making sensitivity analysis, at least in the form of varying these loads, not entirely appropriate. The vagaries of Parameter E1, Potential contribution to LEED certification, were not examined since none of the tested projects were LEED certified. The value function represents the probability of the green roof’s contributing to the LEED certification of the overall project. The only way to evaluate the sensitivity and uncertainty of this parameter will be to track a series of projects incorporating green roofs through the LEED certification process to determine the actual credits earned, the probable impact of the green roof on the earning of those credits, and the impact of potential credits on the decision to implement one of several types of green roofs. This detailed analysis is beyond the scope of this dissertation. Finally, cost was not, and in fact should not, be addressed within the framework at this time. It is a highly project-specific parameter and involves factors extrinsic to the specific roof selection question.

6.9.4. Limits of Generalizability

Because several parameters were excluded from the analysis in all three interviews, a full test of the acceptability of the decision-making framework for vegetated roofing system selection was not accomplished. Further testing will be necessary to determine whether all of the parameters and corresponding value functions are useful in the context of various different projects. Future verification will also determine whether the elimination of many framework parameters and the subsequent narrowing of the decision evidenced in the test cases are or are not representative of the framework’s general functioning. While it is difficult to make gross generalizations from three demonstration projects, these projects did highlight a strength of the framework, namely that it does not unnecessarily clutter a decision situation with irrelevant

categories, but rather narrows in quickly to the issues that make a difference in a particular design decision.

6.10. Summarized Comparison of Design Process to Framework Process

The framework's functioning was effectively compared with the designer's implicit selection process in the context of three green roof design projects. The framework proved sufficiently flexible to accommodate the simplicity or complexity of the actual decision situation in each case. Parameter A1, Storm water retention, did favor deeper systems over shallower, and all vegetated systems over all reference roofs, and was relevant to the roofing system selected in all three projects. Parameter B1, Potential energy savings, proved to be irrelevant in all three surveyed projects, due to the inclusion of insulation in the roof assembly, the small size of the green roofs, and the nature of the project itself, in the case of the garden shed. Results of the analysis suggested that this parameter does not favor green roofs over typical reference roofs, particularly white reflective roof membranes, in any substantive way on conditioned, insulated buildings. Parameter C1, Approximate Sound Transmission Class, was not found relevant to any of the projects discussed by the interviewees. Parameter D1, Surplus dead load of roof system, proved critical to the decision in all three cases, since structural alterations were not deemed practical. Parameter E1, Potential contribution to LEED certification, was not tested since none of the projects applied for or received LEED certification. The decision-making framework did not expressly address cost in the three projects because it was possible to defend the selection of each green roof system type in the absence of this information. As demonstrated in the three interviews, other mitigating parameters made the selection possible without using the project budget as a determining factor, except to slightly limit the quantity of green roof medium used within the range of System 3 in the case of Project No. 3.

In comparing the decision-making process reflected in the framework to that discussed by the designers, it is clear that the parameters currently defined within each overarching category may be replaced or augmented by more project-specific metrics as they apply. For example, the need to satisfy a particular, project-specific performance requirement such as retaining 3 inches (75 mm) of water, as was prescribed in Project No. 1, may be a simpler metric of a sufficient green roof system than the general coefficients used within Parameter A1. Additionally, there are other factors within the system selection decision that are more difficult to quantify, but ought to be included in future iterations of the framework. One such factor that was mentioned in all of the interviews is the familiarity of the designer with a specific vegetated roofing system

or systems. While this partiality might be viewed as an impediment to making an unbiased decision based on quantifiable parameters, the comfort level of the designer and owner with a particular product or family of products may well impact the ultimate success of a green roof project through less explicit means. These might include smoother permitting, scheduling, and delivery, better installation and detailing, and familiarity with the ongoing performance issues and maintenance needs of the completed roof, all due in some part to lessons learned in past projects using the same or similar systems, and to the local availability of both the system and the labor force needed to install it. Moreover, there are parameters that can not be realistically anticipated by a generalized framework, but that profoundly impact the system selected. An example from Project No. 1 was the height of the existing overflow scuppers that limited the depth of the superimposed green roof system. These must be included by the designer as limiting criteria that affect the system selection decision situation in tandem with the parameters identified by the decision-making framework.

7. CONCLUSIONS AND DISCUSSION

7.1. Comparison of Framework Findings to a Previous Green Roof Survey

A comparison of the findings from the surveys and interviews conducted in this dissertation with the results of a survey conducted by Jennifer Strauss Hendricks (2005) illuminates the need for a decision-making framework for vegetated roofing system selection. Hendricks surveyed 240 architects and building owners, all of whom were members of the Building Owners and Managers Association (BOMA), in the Chicago and Indianapolis metropolitan areas about their perceptions of the risks and benefits of green roofing. The overall response rate was 39.7%, with the highest response rate from Chicago architects (52.7%) and the lowest response rate from Chicago building owners (30.5%). Though they reflected opinions of designers and owners in a different region of the United States, findings from Hendricks' study legitimate the results of the initial demonstration of the decision-making framework and help to place these results in the context of the broader building industry. Hendricks' study also revealed flaws in designers' and building owners' rationale that may lead to avoidance of green roof technologies. Examples include a lack of recognition of the storm water retention and energy savings benefits of green roofing, a lack of knowledge about modern lightweight growing medium, and a failure to recognize the increased waterproofing membrane life afforded by green roofs. These misperceptions are addressed in the following discussion. Finally, a review of Hendricks' survey results demonstrates the danger of weighing factors that are not related to specific and accurate information about various roofing systems and thus supports the adoption of Choosing By Advantages methods in the framework employed in this dissertation.

Hendricks reported that both architects and building owners surveyed in Chicago and Indianapolis considered storm water management benefits an important incentive to green roof implementation, as shown in Figure 7.1, and architects ranked storm water runoff 4 out of 5 on a scale of importance as a decision-making factor in building design, as shown in Figure 7.2.

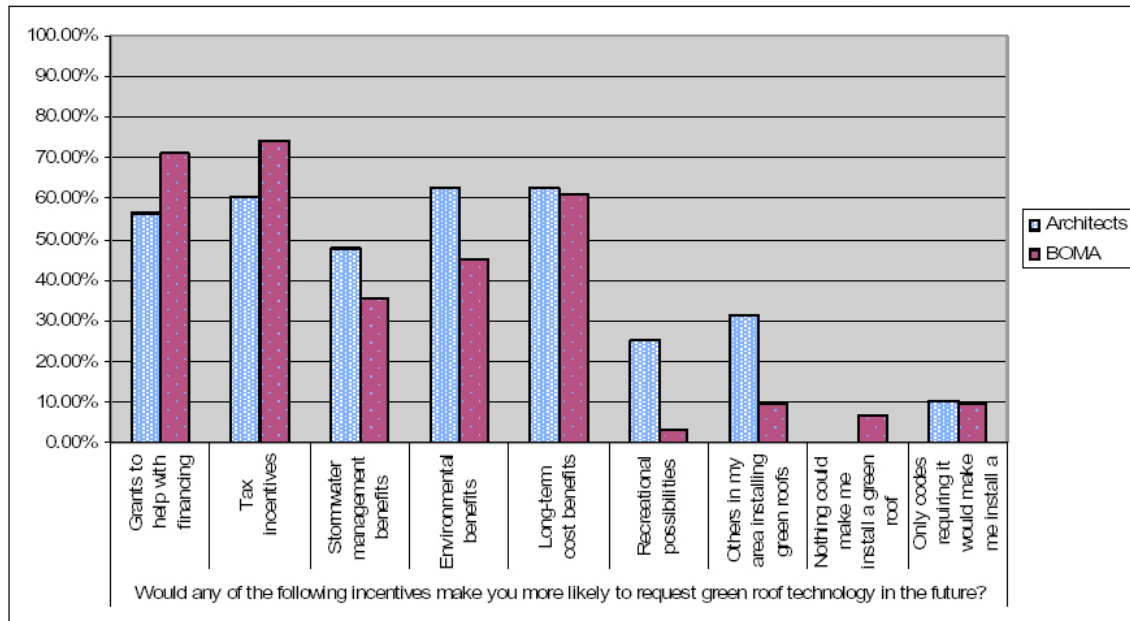


Figure 7.1 - Incentives [to requesting green roof technology in the future] (Hendricks, 2005, p. 65), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Oct. 15, 2007)

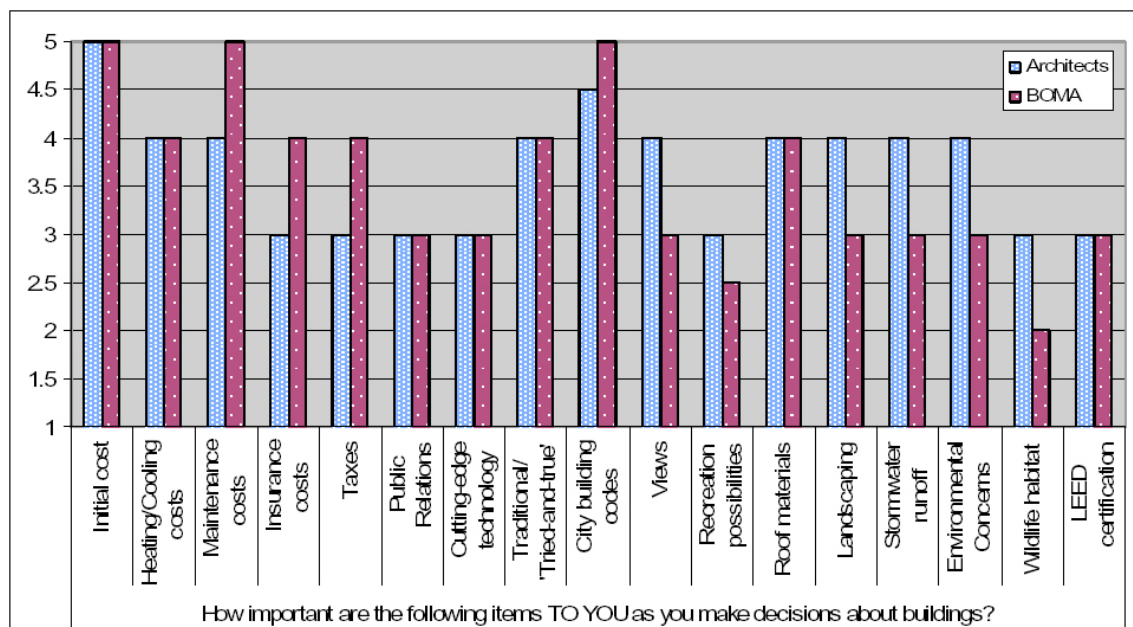


Figure 7.2 - Importance (median values) 5= very important, 1= not important (Hendricks, 2005, p. 63), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Oct. 15, 2007)

Despite this, fewer than 30% of building owners believed reduced storm water quantity was a benefit to society afforded by green roofs versus traditional roofs, as shown in Figure 7.3, and only slightly over 10% of building owners saw reduced storm water fees as a benefit of green roofs to the individual building owner, as shown in Figure 7.4.

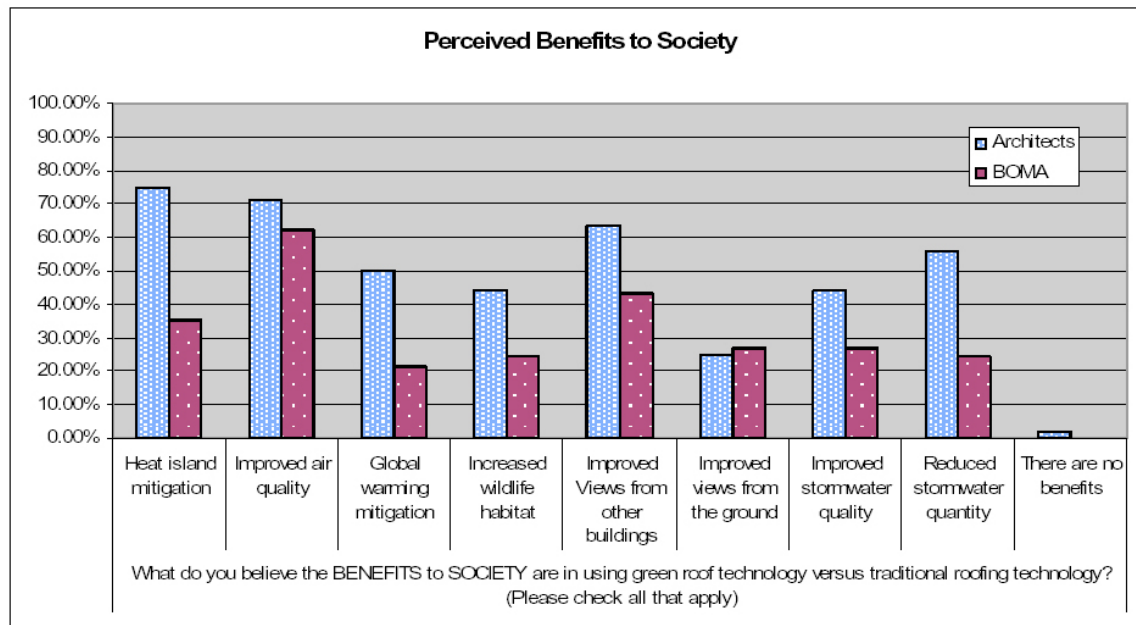


Figure 7.3 - Perceived benefits to society (Hendricks, 2005, p. 62), permission to use granted by:
Jennifer Sprout, Green Roofs for Healthy Cities (Oct. 15, 2007)

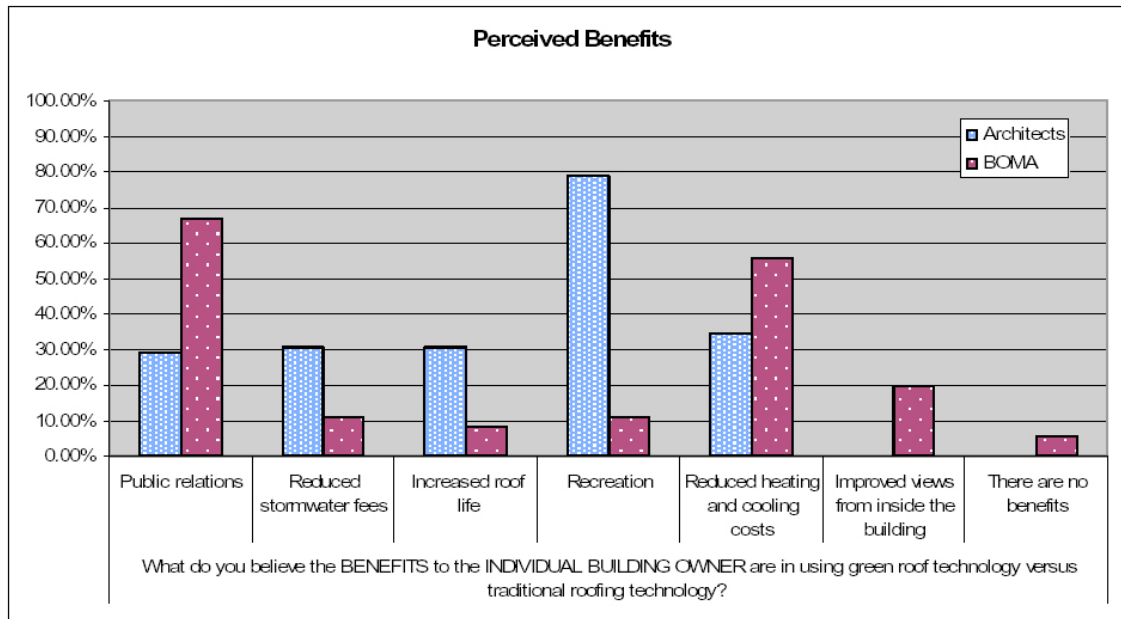


Figure 7.4 - Perceived benefits to building owner (Hendricks, 2005, p. 62), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Oct. 15, 2007)

This disconnect points to the importance of including a decision-making factor such as Parameter A1 that estimates the percentage of annual runoff reduction expected when implementing various green roof systems.

Relative to energy savings, Hendricks showed that only about one third of architects and one half of building owners surveyed considered reduced heating and cooling costs to be a benefit to the individual building owner of green roofing, as shown in Figure 7.4. Hendricks found this surprising since energy savings are a widely-publicized advantage of green roofing systems. In the decision-making framework developed in this dissertation, the potential heating and cooling cost savings attributable to a green roof are estimated using the Department of Energy's Cool Roof Calculator as a proxy for more sophisticated modeling tools. The fact that these savings proved negligible in the three interview projects makes it imperative to replace this proxy measurement with value functions derived from a growing body of data obtained by monitoring of existing green roof installations. Improved value functions would give building owners a better idea if significant energy savings can be expected on their projects. Hendricks also observed that reduction of the heat island effect and mitigation of global warming were not named as societal benefits of green roofs by a majority of building owners surveyed, as seen in

Figure 7.3. The framework for green roofing system selection does not explicitly account for the reduction of the urban heat island effect except in the context of LEED certification. While it would be desirable to more accurately quantify energy savings on a per-project basis as well as assign value to the broader thermal effects of green roofs on their surroundings in future iterations of the framework, at present it appears that neither reduction of energy use for building thermal conditioning nor mitigation of urban heat islands are parameters that typically factor prominently in an owner's decision to implement a green roof.

Hendricks did not list noise abatement as an advantage of green roofs, so there were no data presented in her paper reflecting architects' and building owners' perception of this benefit. Likewise, this issue was not raised within the three interview projects, and based on a review of the literature, acoustic concerns seem to be relevant only to a fairly small and isolated number of green roof installations, notably those constructed in close proximity to airports.

The structural question raised in Parameter D1 did prove to be an important issue for building owners in particular in the Hendricks study. She observed that while cost was considered the most important consideration in building design decision-making, as shown in Figure 7.2, concerns about weight and system failure far outranked cost as owners' barriers to green roof execution, as shown in Figure 7.5.

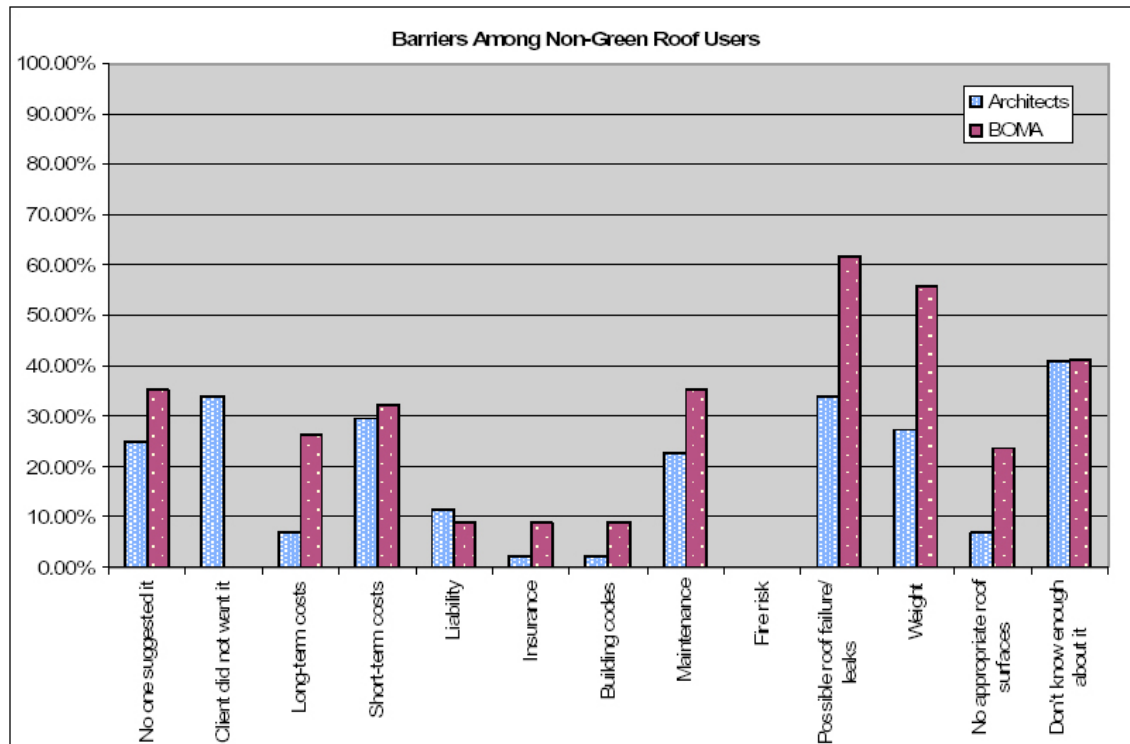


Figure 7.5 - Perceived barriers to green roof implementation (Hendricks, 2005, p. 64), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Oct. 15, 2007)

Hendricks found this result disappointing in light of the modern advances in growing media which have supported increasingly light green roof assemblies. As evidenced by the interviews in this dissertation, there were in each case several green roof system types that could have been chosen without exceeding the available structural capacity of the existing roof deck. Perhaps concerns about system weight in Hendricks' study were a result of owners' previous exposure to intensive roof gardens, including past examples that have failed, and their lack of familiarity with newer extensive systems. It is not surprising that barriers like roof weight and possible roof failure, issues relating to the potential legal liability of a building owner, featured so prominently in Hendricks' survey, especially since the questions were not anchored to specific information about lightweight extensive green roofs in comparison to traditional roofs.

A minority of the architects and none of the building owners in Hendricks' study had been involved with any Leadership in Energy and Environmental Design (LEED) certified building projects, yet two thirds of the architects responded that they were "somewhat or very likely" to design a green roof in the next five years, and 19% of the building owners had considered

implementing a green roof. Hendricks suggested that experience with the LEED certification process was not necessarily a prerequisite for interest in green roofing. None of the interview projects in this dissertation involved LEED certification, and it may be surmised that green roofs will more often than not be implemented on projects where LEED is not a factor, at least in the near future. Further testing of the framework will be necessary to see whether Parameter E1 has a measurable influence on the type of green roof system selected.

The difference in the cost of green roof system types was a factor in all three interview projects, limiting the depth of growing medium selected. As shown in Figure 7.2, initial costs, heating/cooling costs and maintenance costs were given high importance values by both building owners and architects as a decision-making variable in Hendricks' survey. Figure 7.6 shows the perceived costs of green roof technology to the building owner.

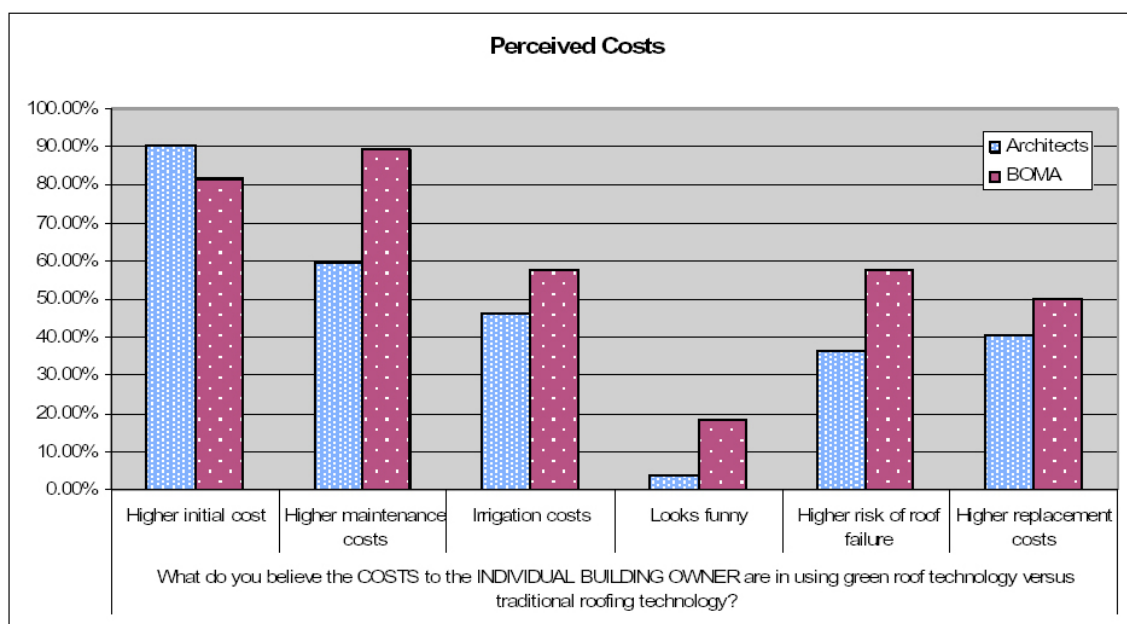


Figure 7.6 - Perceived costs to building owner (Hendricks, 2005, p. 61), permission to use granted by: Jennifer Sprout, Green Roofs for Healthy Cities (Oct. 15, 2007)

Hendricks argued that since a majority of survey respondents viewed green roofs as having both higher initial and maintenance costs when compared to traditional roofs, this result combined with the high importance assigned to these parameters suggested a significant barrier to green roof implementation. Hendricks asserted that while nearly half of survey respondents believed green roofs have higher replacement costs than traditional roofs, this belief did not take

into account the extended life of roof membranes afforded by green roofs, which actually reduce replacement costs in the long term. Until a large number of green roofs have sufficient and successful tenure in North America, demonstrating their purported ability to double or triple roof membrane life as compared to traditional systems that leave roof membranes exposed, this benefit may be difficult to defend. The barrier represented by higher initial costs was acknowledged by all the interviewees in the decision-making framework surveys, and was surmounted only by supplementing the project budget with grant money. Life cycle cost analysis, which would have likely reflected the reduced replacement costs of green roofs, was alluded to in one case but did not strongly influence the decision to implement a green roof.

Finally, a parameter mentioned in the interviews conducted in this dissertation but not specifically defined in the framework for vegetated roofing system selection also featured prominently in the Hendricks study. Hendricks' survey respondents ranked "Traditional/'Tried-and-true'" above "Cutting edge technology" as a desirable characteristic, as shown in Figure 7.2. Similarly, designers interviewed in this dissertation stated that specific vegetated roof systems were chosen based on their proven performance in the German market, and the designers' personal familiarity with them. Clearly all green roof systems are not created equal in the minds of designers, and some systems are more "tried-and-true" than others within the larger assemblage of available systems. As a greater number of green roofs are installed in North America, vegetated roofing systems will gradually move away from their current "cutting edge" status and join other roof technologies, such as single-ply roof membranes, which were once considered revolutionary and are now commonplace.

Hendricks concluded in her study that there was a lack of fit between building owners' and architects' interest in and intentions regarding green roofing technology and the actual demonstrated characteristics and benefits of these systems. She called for education of both groups about the "real monetary and physical costs and benefits to the individual" (p. 66) to permit green roofs to become a viable choice. The decision-making framework for vegetated roofing system selection begins to provide this enlightenment by eschewing the ranking of conceptual parameters such as those shown in Figure 7.2 and replacing them with measures of green roof performance compared with one another in the context of specific projects.

7.2. Identification of Gaps in the Body of Knowledge

Gaps in the current knowledge base regarding vegetated roofing are identified through an examination of the literature relevant to the system components of vegetated roofs identified in Chapter 2 and to the evaluative categories identified in Chapter 3. Many of these gaps are also identified in Chapter 5 as attributes, design variables and parameters excluded from the framework, but appropriate for further study. Additional research questions were derived by testing the framework for acceptability through interviews with green roof designers, as elaborated in Chapter 6. Finally, the comparison of the framework findings with Hendricks' (2005) survey research in Section 7.1 uncovers barriers to green roof implementation that might be dealt with through future inquiry. In some cases, these research questions have been answered in part by previous studies, but in all cases there is a need for replication, elaboration, and extension of results. The following series of tables summarizes these research questions and indexes them to various sections of this dissertation, wherein they are described in greater detail. Secondary queries are shown indented under primary research questions.

Table 7.1 - Research questions concerning green roof system components

Section	Research Question
2.1	Are a broad range of plant types, including indigenous species, appropriate for (semi-intensive) green roofs?
2.1	How does the type of vegetation used affect runoff attenuation in green roof assemblies?
2.2	Can standards be developed to guide the selection of growing medium in North America? How do cost and availability of materials, site hydrology, and climate affect this selection?
2.5	Can standards for root penetration resistance be developed for North American green roof products?

Table 7.2 - Research questions concerning storm water

Section	Research Question
3.1.1	Can the storm water management performance of green roofs be compared with that of more traditional storm water BMPs?

Section	Research Question
3.1.1	Can green roofs provide the effective peak flow rate control necessary to prevent flooding?
3.1.1 & 5.3.1.5	How do temporal and climatic factors such as time of year, interval between storms, intensity and duration of storms, moisture content of growing medium prior to storms, and relative humidity affect the capacity of green roofs to retain and delay storm water?
3.1.1 & 5.3.1.5	How do architectural factors such as: roof slope; distance between drains; type of green roof system; depth, water retention and drainage characteristics of green roof medium; and type and variety of vegetation affect the success of green roofs as storm water management devices?
3.1.1	Can a useful measure of performance be developed to quantify the performance of green roofs in common storm water calculations?
3.1.2 & 5.3.1.6	What are the pollutant removal capacities of green roofs? To what degree do green roofs reduce or increase nitrogen and phosphorus loadings and concentrations in roof runoff?
3.1.2	What is the appropriate initial nutrient content for green roof medium where reduction of nutrient pollution is desired?
3.1.2	How does green roof system configuration (e.g. proprietary system type, medium depth, medium type, planting strategy, and plant mix) affect runoff volume and contaminant control?
3.1.3 & 5.3.1.6	What is the effect of green roof runoff temperature on stream warming? How do the size, depth, and plant and growing medium properties of the green roof, and the characteristics of the site, watershed, and climatic region affect the impact of roof runoff on stream warming? How do density, height, and other plant characteristics affect the efficiency of shading on green roofs? How does the degree of shading affect the warming of roof runoff? What is the impact of heat transfer from green roof medium to roof runoff on the warming of that runoff?
3.1.3.4	Is the effect of green roofs on stream warming significant in areas adjacent to riparian buffer zones, in cold water stream areas, in urbanizing rural watersheds, or in any combination of these areas?

Table 7.3 - Research questions concerning energy

Section	Research Question
3.2, 3.2.3 & 5.4.1.4	How does weather, in terms of ambient temperature, solar radiation, snow cover, rainfall, wind speed, and relative humidity, affect green roof thermal processes?
3.2.1, 3.2.3, 3.2.4 & 5.4.1.4	How does the moisture content of green roof medium affect its thermal conductivity and the overall thermal performance of green roof assemblies?
3.2.1	How do the characteristics of the building underlying a green roof, including its construction and usage characteristics (e.g. the differential between internal set point temperature and outside temperature), affect green roof thermal processes?
3.2.2	How, and to what degree, do green roofs affect the efficiency of mechanical cooling systems, particularly those with components located on the roof?
3.2.2	How, and to what degree, do green roofs affect the temperature of outdoor ventilation air at rooftop intake locations?
3.2.2	How, and to what degree, do green roofs affect the efficiency of rooftop photovoltaic arrays?
3.2.2	How, and to what degree, do green roofs extend the life of underlying waterproofing membranes? How do average roof temperatures and the magnitude of temperature swings as influenced by green roofs affect waterproofing membrane life?
3.2.3	How effective are green roofs as a passive cooling strategy? Can nighttime ventilation of building interiors improve the thermal efficiency of green roofs used as passive cooling devices?
3.2.3	Can models of green roof energy performance be incorporated into whole-building energy simulation software packages? How might these models be made increasingly accurate? Can sensitivity analysis of heat and moisture parameters improve the predictive power of green roof thermal models?
3.2.3	Can green roofs ameliorate the increasing heat island problem in urban areas?
3.2.3	Can ventilation at a green roof surface reduce localized high humidity caused by evapotranspiration?

Section	Research Question
3.2.3	Can green roofing reduce light levels at adjacent building surfaces as compared to white, reflective roofing strategies?
3.2.3 & 5.4.1.4	What is the effect of roof insulation on green roof thermal performance? How does this vary in a roof design incorporating tapered rigid insulation?
3.2.3 & 5.4.1.4	What are the effects of green roof system type (ranging from extensive to intensive) and growing medium depth on green roof thermal performance?
3.2.3	How do plant characteristics such as foliage density (LAI) and height affect green roof thermal performance?
3.2.4	Can, and should, an equivalent R-value, or measure of thermal resistance, be assigned to green roof systems?
3.2.4.	Can a heat transfer rate, or Q-value, be assigned to green roof systems?
3.2.4	What is an appropriate "equivalent albedo" for various green roof systems?
3.2.4	What is the relationship between Bowen ratio and soil moisture content for a green roof? What are observed Bowen ratios for green roofs of various types in various environmental settings?
3.2.4 & 5.4.1.4	What is the effect of solar radiation on green roof thermal performance, and can this effect be approximated using an "equivalent absorbance" factor?
3.2.4	How do peak loading conditions affect the potential for energy savings attributable to green roofs?
3.2.4 & 5.4.1.4	How does building geometry, expressed in terms of roof-to-envelope ratio, floor area, and number of stories, affect the potential for energy savings attributable to green roofs? How many stories beneath the roof are affected by the thermal performance of green roofs, and to what degree?
3.2.5	How do production issues contribute to reducing the environmental impact of green roofs?
3.2.5	How do manufacturing issues contribute to reducing the environmental impact of green roofs?
3.2.5	How do transport issues contribute to reducing the environmental impact of green roofs?

Section	Research Question
3.2.5	How do application issues contribute to reducing the environmental impact of green roofs?
3.2.5	How is waste reduced by re-utilization of green roof materials?
3.2.5	Does using non-proprietary specifications reduce the embodied energy of green roofs by encouraging the use of local materials and the development of local green roof industry?
5.4.1.4	What are the sensitive parameters in green roof energy performance?
5.4.1.5	How does the thermal mass of intensive green roof systems contribute to their thermal performance?
6.9.2	Can databases for green roof energy performance be developed for small geographical areas? How will these databases account for project-specific microclimates found on roofs?
7.1	Can the value function in “Parameter B1 Potential energy savings” be replaced with value functions derived from data obtained by monitoring existing green roof installations?
7.1	Can future versions of the framework more explicitly assign value to the broader thermal effects of green roofs on their surroundings?

Table 7.4 - Research questions concerning acoustics

Section	Research Question
3.3	How do plants and their roots affect the acoustic properties of growing media?
3.3	How does water content affect the acoustic properties of growing media?
3.3	How does organic content affect the acoustic properties of growing media?
3.3 & 5.5.1.5	To what degree do various green roof assemblies block sound transmission?
3.3 & 5.5.1.6	To what degree do various green roof assemblies dampen ambient noise atop roofs?
5.5.1.5	How do roof penetrations affect a green roof's acoustical performance?
5.5.1.5	How does the roof assembly underlying the green roof system affect a green roof's acoustical performance?

Section	Research Question
5.5.1.5	What are the frequency-specific acoustic resistances of various plants and growing media?

Table 7.5 - Research questions concerning structure

Section	Research Question
5.6.1.5	Can generic weight estimates of green roof systems be improved using more specific information about engineered media products and plant types?
5.6.1.5	How does differentiation within a green roof design affect the localized weight of systems at various locations on a roof, and the strategies used to accommodate this weight?
5.6.1.6	How does the methodology used to calculate live loads impact green roof system type selection and the ability to occupy the roof?
5.6.1.6	What are the most effective methods of protecting green roof systems from wind uplifting pressures and wind scour?
6.5	What is an appropriate methodology for calculating the weight of water temporarily retained within a green roof system? Should this water be considered a live load or a dead load?

Table 7.6 - Research questions concerning compliance

Section	Research Question
3.5.1.1	Which states, municipalities, public and private organizations in North America offer direct financial incentives for the use of green technologies including green roofs? Which of these are tied to the meeting of Leadership in Energy and Environmental Design (LEED) certification criteria? Which of these are tied to the meeting of energy-conserving properties? Which of these are tied to wider environmental, fiscal, or social agendas?
3.5.1.2	Which municipalities implement indirect financial incentives such as storm water fee reduction?
3.5.1.3	Which municipalities consider green roofs as "green spaces", or the equivalent of German "ecological compensation measures"?

Section	Research Question
3.5.1.4	Which municipalities offer density bonuses such as floor area ratio increases for the use of green roofs? What are the conditions of these bonuses?
3.5.1.4 & 7.1	What is the effect of mandating LEED certification for certain building types on the implementation of green roofing? What is the nature of the correlation between LEED certification and green roof implementation?
3.5.1.4	What are the effects of the Clean Water Act and its 1987 Amendments on green roof implementation?
3.5.1.5	What additional strategies for encouraging green roof implementation have been used, and with what degree of success?
3.5.2	What code-related issues including those concerning structural soundness, life safety, and fire safety affect the implementation and selection of green roof systems? Which of these are related to the degree of accessibility of the roof, and how?
3.5.3	How do green roofs in general, and different green roof system types in particular, satisfy criteria measured by the LEED rating system?
3.5.3 & 5.7.1.5	To what degree do green roofs contribute indirectly to criteria measured by the LEED rating system?
6.9.3	Can additional LEED-certified project or projects incorporating a green roof be tracked through their development to determine the actual LEED credits earned, the probable impact of the green roof on the earning of those credits, and the impact of potential credits on the decision to implement one of several types of green roofs?

Table 7.7 - Research questions concerning cost

Section	Research Question
3.6 & 5.8	How do the project-specific factors itemized in Section 3.6 and Section 5.8 contribute to the first costs and life cycle costs of green roof systems?
3.6.1	Are green roofs effectively incentivized through their use as roof garden space?
3.6.1	Are green roofs effectively incentivized through their use as an alternate form of storm water quality and quantity management?
3.6.1	Are green roofs effectively incentivized through their capacity to minimize land use?
3.6.2	How do the assumptions embedded within life cycle cost analyses of green roof systems affect the results of these analyses?

Section	Research Question
5.8	Can a methodology be developed, such as that diagrammed in Figure 5.16, to determine green roof and reference roof costs based on a web of interconnected factors linked to a specific project, design, green roof system, and set of assumptions? Will this methodology prove more effective than estimates based on cost per unit area, or summations of the costs of green roof components?
5.8 & 6.7	How does the use of life cycle cost (LCC) analysis affect the impact of first cost on the decision to implement a green roof?
5.8 & 6.7	In what percentage of cases are the higher first costs of green roofs offset or negated by policy incentives or private donations?
5.8	Can an advanced LCC analysis tool be developed to account for the environmental costs of roof systems?
7.1	What are the longevities of green roofs compared to the longevities of traditional roofs in North America?

Table 7.8 - Research questions concerning the implementation and future development of the framework

Section	Research Question
5.9	How will updating and refining value functions affect the outcomes of the framework?
5.9	How will performing sensitivity analysis on the parameters within the framework affect outcomes?
5.9	How will changing the values of parameters affect the importance assigned to the advantages of different systems, and hence affect the outcomes of the framework?
6.9.4	Are all the parameters and value functions incorporated within the current framework useful in the context of various different projects?
6.9.4	Are the elimination of many framework parameters and the subsequent narrowing of the decision evidenced in the test cases in this dissertation representative of the framework's general functioning?
6.10 & 7.1	Can future versions of the framework accommodate the familiarity of the designer with a specific vegetated roofing system or systems? How might the advantages represented by this factor be expressed in a quantifiable manner?

Section	Research Question
7.1	Can future versions of the framework include a factor accounting for the success of specific vegetated roofing systems in European markets, and the designer's preference for such systems? How might the advantages represented by this factor be expressed in a quantifiable manner?

Table 7.9 - Research questions concerning the design process

Section	Research Question
6.6	Can green building networks be established to help designers assemble a design and construction team for green roof projects?
6.6	Can an online tool or tools be developed to offer region-specific green roof information to roof designers as itemized in Section 6.6?
6.6	Can a chart be developed indexing green roof systems according to waterproofing membrane type, system thickness, weight, installation method, and industry approvals?
6.7	How can the permitting process for green roof projects be streamlined?
6.9.2	In how many instances, and in what ways, have green roof systems contributed to litigation involving design professionals?

7.3. Contributions of the Framework to the Design Process

The framework for vegetated roofing system selection does not provide suggestions for the proper specification, design and detailing of green roof systems. The intent is rather to assist designers in determining which generic type of green roof system is most appropriate for a specific project. However, it would be remiss not to address the general trepidation of some members of the building industry toward green roof systems, and to offer suggestions gathered from the literature, case studies, and interviews to help demystify the green roofing design process and reduce its risk. Following a discussion of potential liability in vegetated roofing design and ways to mitigate it, the capacities of the framework to allow designers to rapidly evaluate alternatives and to document design decisions are explained. These capacities may themselves be considered additional risk-reduction measures.

7.3.1. Professional Liability in Vegetated Roofing Design

The roof designer's concerns regarding professional liability are not unfounded given the roof's position as a building's first line of defense against the elements. Herbert (1989), in a text entitled *Roofing: Design Criteria, Options, Selection* gives two telling statistics; first, that "over 50 percent of post-construction problems can be attributed to roofing or related systems" (xiii), and second, that "approximately 65 percent of all lawsuits brought against architects during one recent period originated with roofing problems" (3). While these statistics are somewhat dated, the explanation Herbert gives for these phenomena in the 1980s, namely the introduction of a large number of new roofing technologies in a brief period of time, can be compared to the situation facing the designers of vegetated roofs. Larry Waldron lectured at the Mid-Atlantic Chapter Meeting of the Roof Consultants Institute (RCI) in Richmond, Virginia, on May 6, 2004 about the risks inherent in designing and specifying vegetated roofing systems, and offered suggestions for mitigating this risk. Waldron has extensive experience in the roofing and waterproofing industries and has owned his own roof consulting firm. He has also served as an expert witness in legal trials. While he expressed an understanding of and advocacy for the environmental benefits of vegetated roofing as well as respect for their proven implementation in Europe, he also expressed reservations about its rapid, widespread, and perhaps premature application in the United States. Waldron's concerns are presented in the following sections, interwoven with a discussion of how these concerns are addressed within this dissertation.

7.3.1.1. The Unique Characteristics of Vegetated Roofs

Larry Waldron (personal communication, May 6, 2004) stated that the design of green roofs is specialty work, and supported this statement with an account of the ways green roofs differ from traditional roofs. In the 1960s, dead level roofs covered with coal tar pitch were commonplace in the United States and ponding water was considered acceptable in some instances (Patterson & Mehta, 2001). Waldron explained that many of the vegetated roofs built during that time period in the U.S., which were frequently classified as partially-planted plaza decks located over parking garages or other underground structures, were waterproofed with virtually water-impregnable coal tar pitch. Since the health hazards of coal tar to roofing installers has become widely understood, this system has fallen out of favor (Patterson & Mehta, 2001), and along with it, dead level roofs. The prevailing wisdom, as exemplified and codified in the model building codes, now suggests that no water be permitted to remain on the surface of roofs. This wisdom is behind requirements to provide positive drainage at all locations on a roof, has created the ubiquitous $\frac{1}{4}$ "-per-foot (2-percent) slope requirement at low-slope roofs on new

construction, and has necessitated the provision of overflow drains in the event that the primary drainage mechanism fails. Waldron questioned why the roofing industry is so quick to embrace green roofing, a system that has as its chief goal the retention of water on the roof. He raised the concern that so swift a reversal, without an understanding of its ramifications, may lead to a significant number of green roof failures. Concerns associated with the provision of positive drainage are addressed in this dissertation in the discussion of code requirements, particularly in Sections 3.5.2.6 and 3.5.2.7 in which green roof designers are encouraged to provide positive drainage even where it is not strictly required by code, as in some reroofing applications. Additionally, Karen Liu (2004) has observed that the residence time of retained water on a green roof is fairly short, ranging in her tests from 4 to 95 minutes. This finding, while it requires replication, would tend to minimize concerns related to ponding water on properly designed green roofs.

Because green roofs do retain water, albeit briefly, Waldron insisted that green roofing is not truly roofing, it is waterproofing. An explanation of this distinction is found in the introductory paragraphs of Chapter 2 of this dissertation. Waldron stated that it is absolutely necessary for a roof consultant contemplating the design of a green roof to locate an expert who is intimately acquainted with the design issues and redundant detailing employed in the waterproofing trade. He suggested that green roof designers should attempt to partner with expert suppliers who have the European contacts and experience to assist with the design process. He also asserted that design professionals should partner with a team of specialists, including structural and electrical engineers and plant and soil experts. These statements were echoed by the reports of the surveyed interviewees in this research, as elaborated in Sections 6.1.1, 6.2.2, and 6.4.2, who also either personally spent time in Germany learning about green roof systems there, as was the case with Interviewee No. 2, or regarded systems and suppliers with European experience more highly than those without, as was the case with Interviewees No. 1 and No. 3.

7.3.1.2. *Historical Green Roof Failures and their Causes*

Larry Waldron (personal communication, May 6, 2004) painted a rather grim picture of the past failures of green roofing systems, citing examples of taproots penetrating roof membranes in search of water, thus creating leaks. He explained that some plant roots aggressively seek moisture, which is often found at intersections and penetrations, the weakest links in roofing systems. While there is no substitute for careful design and detailing, nor for roof observation

during installation, the use of FLL-certified protective layers is one way to reduce the risk of leaks due to root penetrations. The FLL test procedure discussed in Section 2.5 of this dissertation requires roof membranes, barriers, or coatings to remain puncture-free for a period of two or four years, depending upon the test conditions. Waldron also emphasized the importance of maintaining the integrity of the roof drainage system below the green roof. He cautioned that some types of filter fabric employed to keep growing medium from reaching and clogging the drainage system may itself become clogged and virtually watertight, causing the green roof to become waterlogged. This concern was also addressed in texts by Osmundson (1999) and Dunnett and Kingsbury (2004) as discussed in Sections 2.3 and 2.4 of this dissertation. Among other suggestions, Waldron offered a conservative solution to the problem of maintaining the integrity of the waterproofing: divorcing the green roof assembly from the underlying waterproofing membrane. This idea is commonly manifested in the use of modular tray systems such as the GreenTech system implemented at the Woodward Academy's Jordan N. Carlos Middle School Campus art building shown in Appendix A.

7.3.1.3. *Practical Suggestions for Risk Reduction*

In addition to those strategies promulgated by Larry Waldron in his presentation, other conference participants at the RCI Mid-Atlantic Chapter meeting held on May 6, 2004 suggested practical means of reducing the risk of green roof failure. One suggestion was to include monitoring and quality assurance of the green roof installation in the roof's cost along with performance of an electric field vector mapping (EFVM) survey at job closeout to assure the owner that the roof is leak-free at completion. Such strategies are often offered to the owner of a green roof project to lessen anxiety about potential leaks, and to ensure that the designed and specified system is properly installed. Chris Eichorn (2002) gave a succinct description of EFVM, a non-invasive leak detection technology common in Europe. According to Eichorn's report, EFVM is performed by creating a low-voltage electrical field at the roof surface using a loop of uninsulated wire attached to an electrical pulse generator. The roof structure, insulated from the roof surface by the membrane and often other layers such as insulation, acts as a second electrical field. A technician carrying two electrodes attached to a potentiometer surveys the roof for leaks by positioning the electrodes within the electrical field created on the roof surface. Any breaches in the membrane cause a directional change on the potentiometer, allowing the technician to pinpoint their location, even in the case of holes too small to be detected visually. The advantages of this system when compared to traditional methods of leak detection are considerable. It can be performed either before or after the installation of green

roof layers, without any damage to those layers. It avoids the potential hazards of the traditional flood test, which include possible damage to the roof substrate if a defect is present in the membrane, and unlike flood testing, it can be performed on sloped assemblies. It precisely locates holes in the membrane, which other methods fail to do. Its main limitation is its incompatibility with some waterproofing membranes, such as EPDM and aluminized coatings, due to their high electrical conductivity. This technology, when widely accepted in North America, may help alleviate the worries associated with the notorious propensity of historical green roofs to leak.

7.3.1.4. *Risk Reduction through Informed Design*

The framework for vegetated roofing system selection alerts the designer to potential issues that may develop during the design, execution, and lifespan of a green roof. Because it incorporates lessons learned from an accumulated body of constructed designs, it becomes a tool to mitigate the risks inherent in the adoption of an innovative technology. While storm water, acoustical, and energy performance are important benefits of green roofs, structural considerations and regulatory implications, along with their corresponding costs, are often perceived as barriers to green roof implementation., as discussed in Section 7.1. By focusing on potential barriers in the early stages of design, the framework can help designers choose appropriate systems and avoid complications in the construction document and contract administration phases of green roof projects.

The areas identified within Section 3.5.2, Code Review, are particularly useful in the attempt to avoid pitfalls experienced in past projects. The influence diagram shown in Figure 3.11 provides a summarized list of topics to be researched by designers beginning a green roof design. Broadly, these include issues related to the viability of a reroofing strategy, the dead load of the roof system, the occupation of the roof, the possible regulatory influence of additional parties with a vested interest in the project, the provision of adequate drainage, and the mitigation of fire risk. Combined with appropriate and conservative specification and detailing, examination of project-specific requirements in these areas is a positive step toward minimizing the occurrence of design errors and omissions, and encourages early and essential dialog among the green roof designer, the other members of the project team, and the officials regulating the work.

7.3.2. Efficient Evaluation of Alternatives

The framework for vegetated roofing system selection allows designers to rapidly investigate the implications of several different green roof system choices early in the design process, and to give their clients feedback about the advantages inherent to each of these systems. In the programming stage, giving the owner choices of different media depths allows brainstorming about the possible use of the space. For example, the author is currently working with a group of university educators who would like to employ a range of green roof systems on an existing academic building. One of the roof levels of the building is ideally suited to a small intensive system surrounded by a larger semi-intensive system based on the roof's structural capacity, its low exposure to wind load, its accessibility for plant upkeep, and the desire of the faculty to involve students in planting the roof as part of the pedagogical approach of the science curriculum. A higher roof level on the same building is less accessible and much larger, and as such may be better suited to a shallower extensive system with lower cost and fewer maintenance and irrigation requirements. The framework will be used to demonstrate the performance of these various system types in a collaborative process involving the roof consultant, project architect, structural designer, green roof suppliers, and the university's representatives.

7.3.3. Demonstrating and Documenting Decisions

Defending the performance of green roof systems is also important when convincing possible donors of their benefits, and in obtaining grant money to support green roof implementation efforts. Additionally, offering alternatives often empowers owners and allows them to experience more control over the choices made in the design process. In a situation where an unfamiliar technology like vegetated roofing is undertaken by a building owner for the first time, full understanding and acceptance of the expected range of performance of that technology are crucial to avoiding the misunderstandings which can potentially escalate into accusations if perceived project goals are not met. For example, if a building owner or user expects to grow certain plant types in green roof media, this intention should be discussed early in the planning stages, as different media depths support different categories of plant life, and conditions atop a roof are quite different than those on the ground. Realistic expectations for maintenance, irrigation, and plant appearance, as well as the time necessary for plant establishment based on different initial planting strategies, should be discussed. For instance, a low-maintenance extensive green roof planted with varieties of sedum may be allowed to go dormant during parts of the year and turn brown with no damage to its viability, but the owner needs to be informed

about the aesthetic consequences of this choice. If this outcome is not acceptable or desirable, a deeper system with some form of irrigation will most likely be recommended. Additionally, owners may be disappointed to learn that it may take two or three years for plant coverage to approach completion. It is far better to address these expectations early in the design phases than during construction or after project completion. It is important for the design professional to be able to show the client the implications of various options prior to their installation, especially since many clients have no previous direct experience with vegetated roofing technology. Because the framework offers a built-in methodology for recording the assumptions of the analysis and the importance assigned to the advantages of different systems, there is a persistent record of both the choices made by members of the project team and the justifications for these choices.

7.4. Future Development and Dissemination of the Framework

The evolution of the decision-making framework for vegetated roofing system selection will continue with efforts to address the most significant issues identified in this dissertation. For example, since a detailed review of the value functions comprising each parameter was not conducted in the survey and interview process, this will be undertaken by presenting the research in peer-reviewed journal articles and conference proceedings. Elaboration of the framework will focus on widening the scope of design parameters within which green roof and traditional roof systems may be compared. Attention will also be paid to improving the sophistication and accuracy of each parameter using enhanced value functions derived from ongoing North American green roof studies. Comments made by interviewees indicate the usefulness of region-specific recommendations which could be incorporated as subsets of the larger framework. Specific strategies for future development and dissemination of the framework in the professional and academic realms are discussed in the following sections.

7.4.1. Discovery: Ongoing Research Agendas

The author is planning to remain involved with a green roof study commenced by a graduate student in the College of Architecture and Urban Studies. The graduate student has constructed a ten-by-ten-foot (3-by-3-meter) green roof test plot to be filled with the same vegetated assembly planned for the Biology/Vivarium building currently being constructed at Virginia Tech. The study will include an evaluation of the thermal conditions throughout the green roof section and an analysis of the quantity, flow rate, and pollutant concentrations and loadings of runoff from the test plot. Additionally, she plans to instrument and monitor a green

roof and adjacent control roof atop the ideally-located Seitz Hall, home to the Virginia Tech Biological Systems Engineering department. The focus of the author's portion of the project will be similar to that of the Biology/Vivarium project, namely the monitoring of energy and storm water management performance of the green roof as compared with a reference roof.

7.4.2. Learning: The Framework as a Pedagogical Model

Plans are ongoing at Virginia Tech's College of Architecture and Urban Studies (CAUS) to incorporate the framework for vegetated roofing system selection and other similar decision-making tools into an interactive, computer-based design assistance program interfacing with computer-aided drafting software. This will allow various emerging technologies, including green roofing, to be integrated into a whole building design. The frameworks embedded in the design assistance program will help to structure the decision-making that naturally occurs during the design process, and will aim to make these decisions more visible to the program's user, especially to users engaging a new technology for the first time. This approach benefits designers as it provides a means of tracking decisions made during the design process, and of confirming that these decisions were made with the benefit of information specific to the project. The studio instruction model in place at the CAUS provides an ideal forum for the testing of the framework in a quasi-practice setting, particularly in terms of the framework's capacity to quickly evaluate a series of design scenarios. In a related effort, the framework for vegetated roofing system selection and its underlying methodology were presented to master's and doctoral students in a Design Research Methods course taught by the author at Virginia Tech in the fall of 2007 to spark interest in the continuing development of this and other decision-support frameworks as both research agendas and teaching tools within the college's graduate programs in architecture.

7.4.3. Engagement: Professional Activities, Continuing Education Offerings and Publication

The author has recently undertaken a green roof consulting opportunity at a university in southwest Virginia which will enable her to test many of the assumptions of the framework and apply it to a specific project. In light of the discussion of risk inherent in green roof design in North America, she has enlisted the aid of a green roof supplier familiar with vegetated roofing technology both in the project area and in Germany at the inception of the project, which is currently in the feasibility study phase.

There are numerous opportunities for the development of courses introducing the framework for vegetated roofing system selection to architects, landscape architects, roof consultants, and other practitioners. Because these designers are often required by state licensing agencies or professional organizations to earn continuing education credits, there is a ready audience for such an offering, and Virginia Tech provides both the venue and the support for the delivery of continuing education courses. Additional opportunities will be sought to present findings at conferences where practitioners actively seek training relative to vegetated roofing; the author has already delivered one such talk at the Greening Rooftops for Sustainable Communities Conference in Washington D.C. in May of 2005, and another at the Roof Consultants Institute's Mid-Atlantic Chapter Meeting in August of 2007.

Initial findings collected from the case studies and the general structure of the framework have been presented in a paper entitled "A Framework for Decision-Making in Vegetated Roofing System Design" published in the *Proceedings of the 3rd Annual Greening Rooftops for Sustainable Communities Conference* held in Washington D.C. in 2005, and in a paper entitled "A Decision-Making Approach to Green Roof System Design" published in *Interface*, the journal of the Roof Consultants Institute, both co-authored by Elizabeth Grant and James Jones. Papers will be submitted to additional journals upon the completion of this dissertation with the goal of reaching a wider audience. Future publications will include the development and refinement of the framework and the testing for acceptability undertaken since the first two publications.

Through the author's roles as adjunct instructor, green roof consultant, and architect, she will continue to seek opportunities to test the decision-making framework for vegetated roofing system selection in design situations faced by architects in current practice, ideally in cooperation with students and faculty at Virginia Tech in the context of design exercises or research investigations, or both. Through these activities, the author and her colleagues may both inform designers and learn from their experiences in an ongoing effort to connect the realms of discovery, learning, and engagement with architectural practice.

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