A DECISION-MAKING FRAMEWORK FOR VEGETATED ROOFING SYSTEM SELECTION

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ABSTRACT

Design frequently involves making tradeoffs to obtain the "optimal" solution to a design problem, often using intuition or past experience as a guide. 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 needed. This research comprises the creation of a framework diagramming the decision process involved in the selection of vegetated roofing systems. Through literature review, case studies and interviews with experts, the available knowledge is captured and organized to determine the critical parameters affecting design decisions. Six important evaluative categories are identified and parameters within these categories 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 framework is demonstrated and compared with green roof designers' decision-making processes and conclusions are drawn regarding its effectiveness.

KEYWORDS

vegetated roof, green roof, decision support system, decision-making framework, Choosing By Advantages

1. INTRODUCTION

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. This research constitutes the first step in an 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 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 reference roof may be defined as either the existing roof or a non-vegetated roof that would most likely be implemented in lieu of a green roof. 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. 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

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research and data collected from green roof sites in North America, and from applicable industry rules of thumb. 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 framework also identifies gaps in the available knowledge that demand further investigation.

This paper includes a discussion of the methodology employed in the decision-making framework, a description of the framework's organization, an elaboration of the parameters by which green roofs are evaluated, a demonstration of the framework's operation, and conclusions about its acceptability as a means of mapping the decision-making process.

2. DECISION-MAKING METHODOLOGY

Most complex decisions cannot be made based on purely quantifiable metrics. The selection of vegetated roofing systems includes both quantifiable and qualitative factors that must be incorporated in satisfying the objective of maximizing the positive influence of a building project on the environment. In addition, the outlook and priorities of the person or persons making the decision must be made explicit in the decision analysis. Two decision-making methodologies suitable for application to green roof system selection are described below.

2.1 The Environmental Evaluation System, or Battelle Method

The Environmental Evaluation System (EES), or Battelle method (Dee, Baker, Drobny, Duke, Whitman, & Fahringer, 1973) allows incorporation of intangible criteria as well as quantifiable indices of performance by rating a system according to various categories. A hierarchical checklist is developed, divided into categories, components, and parameters. For each alternative solution, each environmental quality parameter is rated on a cardinal scale and then translated to environmental impact units (EIU) using "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. Next, each parameter is weighted based on its relative importance. 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 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 1. The higher the EI, the more desirable the project.

EQUATION 1. Environmental Index Calculation

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

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, 1989, p. 138).*

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 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 the geographical and physical context of the building project and the priorities of the stakeholders in the decision.

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. The benefit 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 selection, the process of assigning weight factors to parameters is replaced with a method based on the Choosing By Advantages Decisionmaking System described below.

2.2 The Choosing by Advantages (CBA) Decisionmaking 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 CBA system simplifies, clarifies and unifies the art of decision-making and organizes it into three areas: Sound Decisionmaking, Congruent Decisionmaking, and Effective Decisionmaking. Different types of decisions call for different CBA methods, based on their complexity. The authors chose the CBA Tabular Method outlined in this paper, which lies within the Sound Decisionmaking area of CBA, based on its appropriateness for the vegetated roofing system selection decision.

For complex decisions, the CBA 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 for the Tabular Method 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 Suhr (1999) describes differs from traditional "Weighting-Rating-and-Calculating" (WRC) methods including the Battelle method because it involves weighing advantages of alternatives, rather than weighing factors or attributes of those alternatives. While he emphasized 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 methods 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 can be 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. CBA does not view cost differences between alternatives directly as advantages, but rather as symbolic representations, or abstractions, of advantages. This methodology may be incorporated in future versions of the decision-making framework, but was not employed in this research.

3. ORGANIZING AND MAPPING THE FRAMEWORK

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 roofs. It is therefore necessary to limit the number of parameters by which green roofs are evaluated to a reasonable number. The existing literature on green roofing and six case study projects located in Baltimore, Maryland, Hazleton, Pennsylvania, Chicago, Illinois, Dearborn, Michigan, Toronto, Ontario, and Atlanta, Georgia, were evaluated to determine key design factors for inclusion in the framework for vegetated roofing system design (Grant & Jones, 2005). The case study projects were selected to represent a range of building types, locations, and design considerations. The six main evaluative categories and their constituent parameters shown in Table 1 were selected based on their importance to green roof designers and owners, their frequent discussion within the literature, their significance in the case study projects, the 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. Items appearing in gray cells indicate parameters which were deemed worthy of further consideration, but for which no adequate evaluative criteria currently exist.

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. However, many of these factors are incorporated indirectly within the reviewed parameters.

To define the attributes within each of these parameters for a range of possible roof systems, a set of values is calculated using eight generic vegetated roofing system types as identified in the *FLL Guideline for the Planning, Execution and Upkeep of Green-Roof Sites* (2002) (*FLL Guideline*). Using these predefined system types simplifies the framework and eliminates the need to identify proprietary systems. Rather than vary each green roof sub-system variable (e.g. 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

TABLE 1. 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					

TABLE 2. Annual average rainwater retained by roof system types (adapted from FLL, 2002, p. 37).

	Roof System Type	Substrate Depth		Plant Type	Annual Coefficient of Discharge ψ_a	Y (Fraction of annual average rainwater retained)
		(in)	(cm)			
	RR	—	—	—	0.80	0.20
Extensive	1	0.8 to 1.6	2.0 to 4.0	moss-sedum	0.60	0.40
	2	>1.6 to 2.4	>4.0 to 6.0	sedum-moss	0.55	0.45
	3	>2.4 to 4.0	>6.0 to 10.0	sedum-moss-herb	0.50	0.50
	4	>4.0 to 6.0	>10.0 to 15.0	sedum-herb-grass	0.45	0.55
	5	>6.0 to 8.0	>15.0 to 20.0	grass-herb	0.40	0.60
Intensive	6	>6.0 to 10.0	>15.0 to 25.0	lawn-perennial-small shrub	0.40	0.60
	7	>10.0 to 20.0	>25.0 to 50.0	lawn-perennial-shrub	0.30	0.70
	8	>20.0	>50.0	lawn-perennial-shrub-tree	0.10	0.90

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 described in Table 2 represent a sufficient range of differentiation among possible green roof system types and accommodate practically all possible green roof systems available in North America.

3.1 Parameter A1: Storm Water Retention

The green roof system types, depths, and corresponding annual coefficients of discharge ψ_a shown in Table 2 are drawn directly from the *FLL Guideline*. 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. A gravel area on a green roof can be compared 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.

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* 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 1971 to 2000 for the major cities closest to the six case study projects examined in this research were reviewed. 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. Clearly, the FLL's coefficients should be used as a rough estimate only because North American weather patterns and hence water retention rates for each system may vary substantially from their German counterparts. 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. Further, the potential evapotranspiration (PET) in each project location should be considered in determining specialized coefficients for various roof system types.

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.

3.2 Parameter B1: Potential Energy Savings

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, but these have limited application. Until a simplified modeling tool becomes widely available, green roof energy performance needs to be estimated by fairly sophisticated energy analysis models, often attuned to a specific region's weather data and requiring significant time, money, and expertise to construct.

Perhaps the most useful thermal characteristic 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 is useful as a single-number attribute that can help give an early estimate of potential energy savings attributable to a green roof. This may be achieved by implementing a 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. The 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 (Oak Ridge National Laboratory, 2004). 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.

The project-specific inputs to the Cool Roof Calculator 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:

EQUATION 2

Highest netting option in net savings ($\$/\text{ft}^2$ per year) over a black roof = 1

EQUATION 3

Lower netting option(s) in net savings ($\$/\text{ft}^2$ per year) over a black roof = ratio of net savings of lower netting option(s) ($\$/\text{ft}^2$ per year) divided by net savings of highest netting option ($\$/\text{ft}^2$ per year)

For example, if a green roof netted 0.50 $\$/\text{ft}^2$ per year over a black roof, and a conventional roof also under consideration netted 0.10 $\$/\text{ft}^2$ 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. 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.

3.3 Parameter C1: Approximate Sound Transmission Class

Since data determining the approximate sound transmission class (STC) of green roofs are nearly nonexistent, a proxy scale based loosely on 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), 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. 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. Surface mass is defined by Stein and Reynolds (1992) for walls as "the weight of the wall per square foot of surface area" (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, but since the growing medium is typically the heaviest component of green roof systems, its surface mass is used to represent that of an entire system of a given depth.

Stein and Reynolds (1992) give STC values for lightweight concrete masonry unit (CMU) walls which align well along a logarithmic scale with the small number of acoustic values reported by Minke and Witter for green roof substrate. Lightweight CMU has a similar surface mass to green roof media, based on the reported wet densities of the medium in the six case study projects investigated, permitting the use of STC ratings of lightweight CMU as an approximation of a green roof system of similar depth. Table 3 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

TABLE 3. Acoustic rating based on system type.

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

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

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

[3] Value taken from Minke and Witter (1983)

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

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. In the right two columns of Table 3, acoustic ratings and numeric ratings are assigned to these STC values. 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 (1992, p. 1400). 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.

After these many necessary transformations, it is possible to create a value function relating roof system type to acoustic performance as shown in Table 3. 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.

To use this value function, the designer must first decide whether the roof deck for the project in question already 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. A cutoff for the approximate acoustic value of the roof deck is arbitrarily set at STC 42, above which the addition of a green roof is considered acoustically extraneous. Designers are cautioned to consider the reference roof's actual performance when ultimately deciding the importance of the acoustic advantage of one green roof over the other, or over the reference roof.

3.4 Parameter D1: Surplus Dead Load of Roof System

The dead load capacity of a roof structure may or may not be precisely defined at the time the roof system is selected. 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. The added weight of larger plants on intensive green roof systems as compared to extensive systems must also be accommodated. ASTM has developed *E2397-05 Standard Practice for Determination of Dead Loads and Live Loads associated with Green Roof Systems*. Roofscapes, Inc., a leading provider of a range of green roof system products, references this standard in its model specifications for each green roof type. The Roofscapes 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.

The *FLL Guideline* also includes reference values for design loads for a broad range of green roof components. 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 10 psf per inch of course depth (20 kg/m^2 per cm of course depth) may be assumed as a logical maximum, since this is the highest load cited for drainage and vegetation support courses. 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 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 4. While somewhat arbitrary, this distinction permits

TABLE 4. 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[1]	59
2	2.4	6.0	16[2]	78
3	4.0	10.0	27[3]	130
4	6.0	15.0	41[4]	200
5	8.0	20.0	54[5]	260
6	10.0	25.0	68[6]	330
7	20.0	50.0	206[7]	1030
8	>20.0	>50.0	>208[8]	>1040

[1] (Roofscapes, Sept. 2006a)
[2] (Roofscapes, Sept. 2006a)
[3] (Roofscapes, Sept. 2006b)
[4] (Roofscapes, Sept. 2006b)
[5] (Roofscapes, Nov. 2006a)
[6] (Roofscapes, Nov. 2006b)
[7] Heaviest media at 10 psf per inch (20 kg/m^2 per cm) plus 6 psf (30 kg/m^2) for plants based on FLL system description
[8] Heaviest media at 10 psf per inch (20 kg/m^2 per cm) plus 8 psf (40 kg/m^2) for plants based on FLL system description

the use of load data for systems currently available in North America where possible, and substitutes the conservative estimate generated from the German standards everywhere else.

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/m^2), translating to a weight of 5.8 to 6 psf per inch (11.3 to 14 kg/m^2 per cm). Intensive roofs, with depths greater than 6 inches (150 mm), are expected to weigh between 59 and 199 psf (290 to 970 kg/m^2). The expected dead load of the reference roof must also be estimated for the sake of comparison. Low-slope roofs with pavers or ballast, and steep-slope roofs with slate or clay tiles, must support considerable weight which may equate to that of an extensive green roof system.

The value function for Parameter D1 assigns a value to each roof system, including the reference roof, as follows:

EQUATION 4. Roof structural capacity calculation.

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

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.

The purpose of this value function is to alert the designer to the fact that green roofs are usually 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 capacity to determine what is possible. In some cases, the extra weight of certain 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.

3.5 Parameter E1: Potential Contribution to LEED Certification

Parameter E1 assigns value to green roofs based on the likelihood that they will contribute to the earning of points within the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program. 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 known until the project has been evaluated by the USGBC, the framework assigns values in areas where green roofs potentially contribute to the earning of points, or toward the goal rewarded by a LEED 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 a LEED credit, and where their benefits are most widely accepted.

The relevant credits as they appear in the LEED-NC 2.2 guidelines are as follows: Sustainable Sites (SS) Credit 5.1: Site Development: Protect or Restore Habitat; SS Credit 5.2: Site Development: Maximize Open Space; SS Credit 6.1: Stormwater Design: Quantity Control; SS Credit 6.2: Stormwater Design: Quality Control; and SS Credit 7.2: Heat Island Effect: Roof (USGBC, 2005).

The first two credits, SS Credit 5.1 and SS Credit 5.2, give credit for the use of a vegetated roof provided that 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. SS Credit 6.2 also explicitly mentions the use of vegetated roofs as one way to "reduce imperviousness and promote infiltration thereby reducing pollutant loadings" (USGBC, 2005, p. 21). While clearly green roofs do absorb more rainfall than traditional roofs, current 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 expected 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, 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. 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.

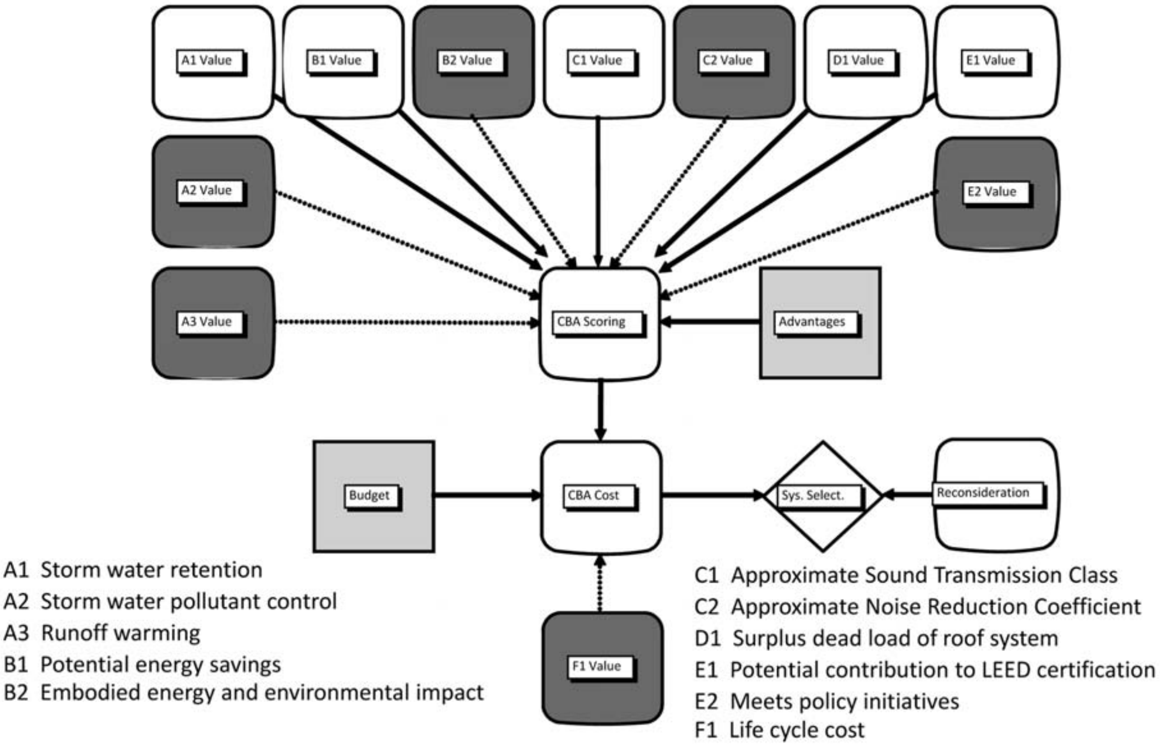
3.6 Cost

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. Green roof designers should investigate the ramifications of green roof selection as broadly as possible so they may derive the best budget estimate 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 life cycle cost (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 less important. 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 L.C.C. analysis tool, preferably one that could also account for the effects of environmental costs. The L.C.C. analysis tool would also highlight one of the most compelling reasons to install a green roof, which is extending the life of the underlying roof membrane by protecting it from ultraviolet radiation, internal stresses caused by thermal cycling (Scholz-Barth, 2001), and external mechanical damage caused by foot traffic and other impacts. A placeholder for such a tool is represented by the gray Parameter F1 in the influence diagram of the framework shown in Figure 1.

3.7 Overall Framework

Figure 1 shows an influence diagram including all parameters identified in this research to date. Dark gray parameters are those for which values cannot yet be determined.

FIGURE 1. Influence diagram of green roof system selection decision.



A1 Storm water retention
A2 Storm water pollutant control
A3 Runoff warming
B1 Potential energy savings
B2 Embodied energy and environmental impact

C1 Approximate Sound Transmission Class
C2 Approximate Noise Reduction Coefficient
D1 Surplus dead load of roof system
E1 Potential contribution to LEED certification
E2 Meets policy initiatives
F1 Life cycle cost

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 why the "Reconsideration Phase" from the CBA Decisionmaking System is included in the framework to serve as a placeholder for any additional information that may either not be incorporated 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. 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.

4. TESTING FOR ACCEPTABILITY

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. The results of one interview are summarized as follows for the sake of illustration.

4.1 Brief Description of Project

The project is a 4,400-square-foot (410-square-meter) extensive green roof retrofit on an occupied building, six stories above grade, located in an urban area in the Mid-Atlantic. 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 attactic 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 (50 mm) of rigid polystyrene supported by a 6-inch (150-mm) thick reinforced concrete roof deck.

4.2 Application of Framework to Vegetated Roofing System Selection

For this project, it was possible to initially eliminate three of the five parameters from the decision. These are shown in gray rows in Table 5. The reference roof in this project was the existing system over which the new green roof components were laid, as previously described. 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 unimportant 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.

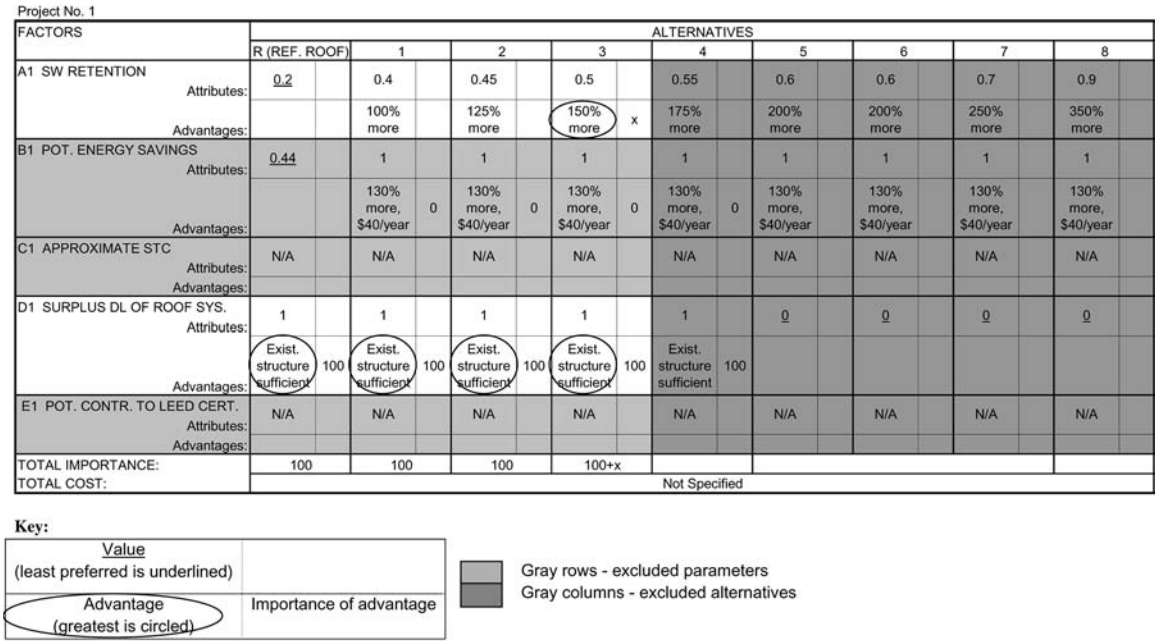
Parameters A1 and D1 remained as the relevant criteria. The available dead load capacity of the existing roof structure for the superimposed green roof loads was 50 pounds per square foot (psf) (240 kilograms per square meter (kg/m^2)). According to the value function for Parameter D1, generic green roof Systems 1 through 4 as defined in Table 2 could have been accommodated, with a maximum loading of 41 psf (200 kg/m^2) for System 4 as estimated in Table 4. Systems 5 through 8 were therefore excluded as viable choices and are shown in gray columns in Table 5.

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 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 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 location 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 5. 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 System 4. 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. However, the interviewee stated that if it had been practical to add an additional inch (25 mm) of growing medium, 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.

4.3 Tabular Format Depicting Decision Situation

Table 5 shows the roof system selection decision situation for Project No. 1 using the tabular format described in *The Choosing By Advantages Decision-making System* by Suhr (1999). Alternative roof systems are evaluated in light of parameters A1 through E1. Gray rows and columns indicate parameters or systems excluded by their irrelevance or infeasibility

TABLE 5. 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:	0.2		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:	0.44		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		0		0		0		0	
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:

Value (least preferred is underlined)	
Advantage (greatest is circled)	Importance of advantage

▨ Gray rows - excluded parameters

▨ Gray columns - excluded alternatives

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 5, 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.

5. CONCLUSIONS AND DISCUSSION

5.1 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 roof, or the nature of the project itself, as in the case of one green roof located over unconditioned space. 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.

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 the example project discussed in this paper, 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 cannot be realistically anticipated by a generalized framework, but that profoundly impact the system selected. An example from the project presented in this paper was the location of the existing overflow scuppers that limited the depth of the superimposed green roof system. These parameters must be included by the designer as limiting factors that affect the system selection decision situation in tandem with the parameters identified by the decision-making framework.

5.2 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.

Additionally, 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 paper 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.

5.3 Demonstrating and Documenting Decisions

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 green roof space. The framework can be used to demonstrate the performance of these various system types in the context of a collaborative process.

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. 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.

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