A Decision Support System for Construction Materials Selection using Sustainability as a Criterion

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Abstract: Traditionally, materials selection for the design and construction of facilities has been based on economic and technological considerations, given the desired life span of a facility and the program of requirements and codes it must meet. In design environments where ecological, health, and ethical impacts are increasingly important, often the only way to choose from many different material alternatives is by relying on unquantified professional judgment or past experience. A new method is needed for evaluating the tradeoffs between material alternatives within the context of specific projects. The method should allow comparison of not only the technical performance and costs of materials, but also the immediate and long-term impacts their use has on the finite supply of natural resources and the ongoing needs for those resources by society. Together, these impacts comprise a measure of the sustainability of materials and should be given consideration during materials specification.

In this paper, a definition of sustainability with respect to construction materials is developed, a methodology for evaluating construction materials based on sustainability is presented, and a conceptual framework for a decision support system to assist the materials selection and specification process is described. The new method will facilitate the approval and integration of more sustainable materials into future facility designs by helping designers quantify how they compare to materials already permitted under existing codes. As the tradeoffs between novel and currently-accepted materials are made explicit, better material selections can be made which will enhance overall project sustainability.

Introduction

Sustainability as a concept is probably most widely known in relation to sustainable development. The United Nations World Commission on Environment and Development has defined sustainable development as “development which meets the needs of present generations without compromising the ability of future generations to meet their own needs” (WCED 1987). Inherent in this concept is the assumption that human development will not decline or cease but rather continue to progress, albeit at a pace which can be sustained by the ultimately finite resources of the earth. Thus, sustainability is a system state marked by stability, where changes to the system remain constrained so as to maintain the stability of the system into the foreseeable future.

Sustainability is important for designers, engineers, and others involved in the construction of new facilities, because the facilities we construct have a huge impact on the environment of which we are all a part. Not only do these facilities make use of natural resources for their construction and leave man-made footprints in the ecological environment which surrounds us, but built facilities also serve as our interface to the natural environment, protecting us from the elements and meeting the needs of humanity

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for shelter, status, and other functions. As the designers and constructors these facilities, we hold the power to make built facilities more sustainable, so that they meet the needs of society without compromising the needs of others or jeopardizing the future survival of humanity on earth.

The primary objective of this research is to make facilities more sustainable by improving how materials for the facility are selected during conceptual design, and to encourage the specification of innovative materials which may be more sustainable than their traditional counterparts. To achieve this objective, a comprehensive list of the attributes of sustainability relevant to construction materials has been compiled for use in comparing materials. Second, a methodology for evaluating materials sustainability has been developed, using the list of attributes and based on a rational actor decision model. Finally, a framework for a Sustainability Decision Support System (SDSS) has been developed based on the methodology for evaluating sustainability, which can assist project decision makers in the task of selecting and specifying materials. In implementation, the SDSS will be capable of providing sustainability indices for both individual materials within the context of the conceptual design as well as for the design as a whole after individual materials have been combined in the conceptual design. A prototype SDSS is under development and will be used to validate the methodology and demonstrate proof of concept.

In this paper, a definition of sustainability is developed for the task of construction materials selection. A new methodology for comparing and selecting material alternatives is discussed which is based on the definition of sustainability. A conceptual framework for a Sustainability Decision Support System (SDSS) is presented which could be implemented to automate the selection methodology. The paper concludes with a summary of the contributions and applications of the research, and future research prospects in this area.

Sustainability with Respect to Construction Materials

Three general objectives serve as a framework for implementing sustainability in construction materials selection. In selecting materials, we should strive to:

1) Minimize the consumption of matter and energy, while
2) Maintaining some reasonable degree of human satisfaction and
3) Causing minimal negative environmental impacts.

The first goal, minimization of matter and energy consumption, is based on minimization of entropy gain as well as intergenerational equity objectives. Consumption processes inherently involve increasing the entropy of materials and energy, rendering them less adaptable for future use (Roberts 1994, Rees 1990). By subjecting materials and energy to consumption processes, we generally decrease their potential utility to future generations. In other words, we use them up. Therefore, consuming as little matter and energy as possible, or “doing more with less,” is a fundamental objective of sustainability and of sustainable material selection (ibid.). Examples of choosing materials to minimize consumption are selecting materials with minimal packaging or using materials made by local manufacturers to minimize transportation energy expenditure.

Doing more with less relates as well to the second goal of sustainable material selection: maximizing human satisfaction. In achieving sustainability in construction, tradeoffs must ultimately be made between human satisfaction and resource consumption. Nonetheless, human satisfaction as an objective is important: people will not accept the measures necessary to change the state of the world unless they are satisfied as a result of those changes. Thus, maintaining human satisfaction and satisfying human preferences is a sustainability objective along with minimizing resource consumption. Economics also ties into the human satisfaction component of sustainability – within the current paradigm of economics-driven society, no owners are likely to be satisfied unless their economic interests are protected. Examples of objectives for selecting materials which improve human satisfaction are minimizing cost, ensuring human comfort and safety, and edifying the human spirit (e.g., Day 1990).

Finally, minimizing negative environmental impacts as a result of construction materials use is an important objective of sustainable material selection, since the environment consists of ecosystems whose ongoing health is essential for human survival on earth (e.g., Goodland 1994, etc.). Sustainability of the human race requires that ecosystems be protected and preserved in a respectable state of health, by maintaining biodiversity, preserving adequate habitat for species, and minimizing pollution and environmental destruction. Ecosystem survival is essential for human survival, since ecosystems serve as the ultimate source of raw materials for all human activities. Construction materials which minimize negative environmental impact are those which are created with non-polluting manufacturing processes, whose raw components come from stable ecosystems and are sustainably harvested, and which are reusable or recyclable.

Thus, a measure of sustainability for material selection includes consideration of the level of resource consumption, the degree to which human satisfaction is achieved, and the net level of negative environmental impacts. These three global objectives for design and construction sustainability serve as the basis for evaluating construction materials in terms of their sustainability.

Evaluating the Sustainability of Construction Materials

The fundamental contribution of this research is the generation of a scientific and rational methodology for comparing and selecting construction materials based on the doctrine of sustainability. To achieve this contribution, research efforts have been focused on constructing an applied definition of sustainability based on the sustainability literature, developing a set of metrics of sustainability with respect to materials using the definition, and adapting the metrics into a approach for comparing material alternatives to assist the selection process.

In the following sections, the research approach used to develop the selection methodology is discussed, the resulting selection methodology is described, and a conceptual framework for a decision support system based on the methodology is presented. A taxonomy for classifying the attributes of sustainability into the categories of technology, ecology, economics, and ethics is also presented, and examples of sustainability indicators which can be used to evaluate materials are shown.

A Taxonomy for Sustainability Attributes

Built facilities are created using technology. In order for a facility to be sustainable, it must be created using sustainable technology. Sustainable technologies are "environmentally benign and largely composed of renewable, reusable or recyclable materials" (Carpenter 1994, p. 1). They are respectful of the limitations of the systems in which they exist, and are sensitive to the health of ecosystems. Thus, the first way in which materials selection can contribute to sustainability is by providing the building blocks for sustainable technologies. In selecting sustainable materials with respect to technology, the goal is to maximize performance while minimizing negative impacts to the systems in which the technology exists. An important attribute which can be used to measure the contribution of a material to sustainable technology is the degree to which the material meets requirements for technical performance, given its intended use. Other technology-related indicators include life span, reliability, recyclability, and resistance to damage or decay.

Ecological impacts are especially relevant to sustainability, since all human activity occurs within the context of natural ecological systems and ultimately depends on those systems for raw resources to meet human needs (Norton 1994). Hence, maintaining the integrity of those systems to ensure that resources continue to be available for human use is a central goal of sustainable development (Carpenter 1994). Materials selection can play a key role in achieving ecological sustainability if it is done in such a way as to minimize adverse impacts on natural environmental systems as a result of using the materials. In particular, this means selecting materials which minimize environmental degradation over the whole life cycle of the material, from initial extraction of raw components from the environment, to eventual disposal or recycling of the material. Also important is minimizing the total amount of energy consumed and entropy gained in the preparation of the material for its anticipated use, and eliminating waste by reusing or recycling materials. Total embodied energy of the material is a primary attribute of the ecological sustainability of materials. Other indicators include amount of pollution generated over the life of the material as a result of its use and availability of environmentally sound disposal options.

Economic sustainability is based on the ease with which feasible alternatives for limited natural resources can be found, and the costs to society of developing those alternatives (Norton 1994). The pricing of goods in the free market is a reflection of those social costs and the importance which society as consumers of those goods assigns to their availability. Built facilities are made more economically sustainable through minimizing the total life cycle cost of projects by selecting material components with the lowest life cycle costs. The principal indicators of economic sustainability are a material's life cycle costs, including costs of manufacture, transport, assembly, maintenance, and disposal or recycling.

Ethical concerns are at the central core of sustainability. Sustainability is a system state which, because it exists within the constraints of the limited resources of the system, is maintainable into the foreseeable future. With respect to the earth and its human inhabitants, the primary goal of sustainability is the equitable distribution of the resources of the earth, such that the needs of humans are adequately met. In addition to meeting the needs of currently existing humans, sufficient stocks of resources must be maintained, invested, or transformed such that future generations can adequately meet their own needs (Daly & Cobb 1994).

The implications of ethical sustainability for construction materials selection are thus related to the wise use of natural resources. Specific goals are minimization of the use of unnecessary materials, selection of materials only from renewable or substitutable sources, and using those materials at a rate no greater than the renewal or substitution rate of the stock. Attributes associated with ethical sustainability include degree to which using the material represents depletion of natural resources, reusability of the material, and substitutability of the material with respect to nonrenewable resources (after Norton 1994).

Research Approach

A list of indicators has been compiled from the literature and professional practice which can be used to measure the sustainability of construction materials. A representative list of potential indicators is shown in Figure 1. Each indicator is listed according to its relationship to the three global objectives of sustainable construction. A sensitivity analysis is currently under way using project case studies, to determine the correlation of each indicator with the sustainability of materials. While the current selection methodology uses all the indicators shown in Figure 1, it is desirable to define the “boundaries of sustainability” in terms of each indicator, and to determine the relative contribution of each property to the sustainability of a particular material. The sensitivity analysis will achieve these goals.

Factor	**Resource Consumpt'n**	**Environmt'l Impact**	**Human Satisfaction**
Scope of harvest	•	•	•
Existence of harvest infrastructure	•	•	
Accessibility of raw materials	•	•	
Availability of material	•		
Abundance of raw materials	•	•	•
Degree of processing required	•	•	
Degree to which material is renewable	•	•	
Life cycle cost			•
Life span under conditions of projected use	•	•	•
Maintainability	•	•	•
Reusability	•	•	
Harvester efficiency/effectiveness	•	•	
Recyclability	•	•	
Degree to which material contributes to local economy			•
Amount of transport required	•	•	
Resilience of ecosystems on harvest site		•	
Degree to which material detracts from resource base	•	•	
Toxicity		•	•
Degree to which material incorporates recycled mat'ls	•	•	•
Market pricing of comparable resources			•

Availability of environmentally sound disposal options		•	•
Symbiotic effects of materials matched to bioregion		•	•
Appropriateness of material choice			•
Resistance to potential damage or decay	•		•
Technical performance of material	•	•	•

Figure 1: Attributes which Influence the Sustainability of Construction Materials

As noted in the discussion of sustainability of materials, consideration of the context of use is essential to determine the sustainability of anything. For example, whereas using ice blocks as a construction material might be sustainable in Antarctica, it would probably not be so in Nigeria. While in this example the importance of context may seem to be obvious, context should be a critical consideration for all project decision making, since even projects located on neighboring sites will have different end users, different specific site characteristics, and may have many other differences as well. For example, one site may include the habitat of an endangered species, or require access for disabled persons, while neighboring sites may not.

To deal with the necessity of including contextual considerations in the sustainability comparison of materials, the research approach has included collection of methods used in current practice for estimating the project-specific minimum requirements for each of the sustainability indicators in Figure 1. In addition, a separate set of contextual considerations has been developed as a heuristics base to facilitate site-specific feasibility and appropriateness testing of each material choice. A sample of these heuristics is shown in Figure 2.

Heuristic	**Resource Consumpt'n**	**Environmt'l Impact**	**Human Satisfaction**
Material <x> does not require more than <threshold> consumption of energy for transportation to site.	•		
Site preparation for material <x> requires no more than <threshold> square units of vegetation clearing.		•	
Material <x> does not exceed <threshold> offgassing requirements for users of this facility.			•
Material <x> does not use more than <threshold> packaging in shipment.	•	•	
Material <x> does not cost more than <threshold> per unit.			•

Figure 2: Selected Heuristics for Evaluation of Selection Appropriateness

These context modifiers are necessary to make the material sustainability ratings for each project unique, since specific values such as transportation requirements from supplier to site always change from project to project. The heuristics database serves to identify the values which need to be calculated. Threshold values can be set by the decision maker. In addition, algorithms are available in the literature to determine the truth of each heuristic. For example, several techniques have been developed to assess the energy requirements of various transportation modes with respect to distance and terrain, and can be used to determine how much energy would be expended to move a particular material to a given site from the supplier's warehouse (e.g., Edwards et al. 1994; Greene 1994).

A Rational Actor Approach to Materials Selection: The Selection Methodology

The goal of this research has been to develop a way to choose materials according to their sustainability, so that more sustainable materials can be selected for building facilities. The selection methodology developed here is based on Simon's "Rational Actor" model of decision making. The rational actor model has three phases: determine the set of all possible choices, analyze all of the potential consequences of each choice, and choose the best alternative based on the attractiveness or utility of its most probable outcome (Simon 1983). This model is based on the presumption that human decision makers, given full knowledge of all possible consequences of all possible alternatives, will select the alternative with the highest likelihood of resulting in the most desired outcome.

In our approach to materials selection, the rational actor model has been modified to reduce the number of alternatives which must be considered at one time. First, all material alternatives which are clearly infeasible for the intended application are initially pruned from the database of all materials, based on classifications of materials according to Construction Standards Institute (CSI) Divisions. For example, if the element under consideration is a structural beam, materials such as sheet rock, glass, and ceramic tile are automatically pruned from the set of possible alternatives under consideration, since none of these materials fall under the CSI structural divisions. This "pruning" approach is used rather than allowing the user to select feasible materials from the whole set because users tend to overlook alternatives which might be unfamiliar to them but which are nonetheless feasible.

The second modification involves replacing probabilities used in the original rational actor approach with user weightings of the importance of each sustainability attribute. Rather than using utility of outcome multiplied by the probability of occurrence, our model uses a composite measure of sustainability, based on all the sustainability indicators in the database multiplied by user weightings of the importance of each sustainability attribute. Maximizing sustainability is the objective of the methodology, and is analogous to maximizing utility in the original rational actor methodology.

User weightings have been included in the selection methodology because the method is intended to supplement, not supplant, human judgment in developing a design for a facility. Weightings are also included because acceptability of the final design to the project parties remains the ultimate design criteria; no laws currently exist to force sustainable design, and therefore any designer who wishes to have his or her designs implemented must first ensure that they are acceptable to the owner. By incorporating user weightings into the selection process, the methodology gains greater acceptability to the user who supplies the weightings, and a customization of the sustainability of the final design product can occur.

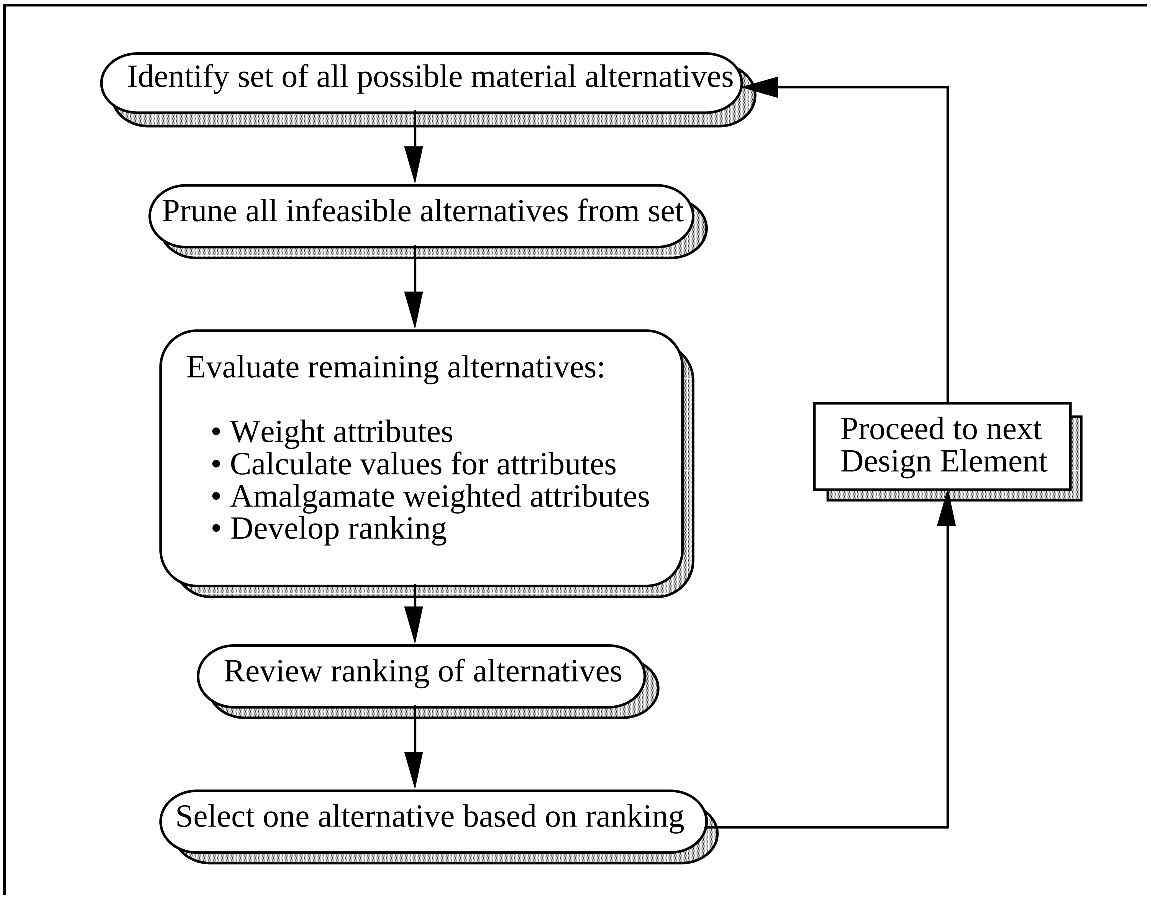

Figure 3: Materials Selection Methodology

The methodology for materials selection is shown in Figure 3. The first step in the methodology is to generate the set of all possible alternatives which are available for selection. In the material selection process, this comprehensive set of alternatives includes all construction materials currently on the market. The second step involves reducing the complete set of alternatives by eliminating those alternatives which are clearly infeasible for the application. This pruning may be done using technical performance thresholds or other heuristics (see Figure 2), and should result in a subset of alternatives, all of which would be feasible choices for the intended application.

The third step in the methodology is to evaluate the feasible alternatives such that a ranking can be developed according to the utility of the material for the intended application. First, the decision maker weights each attribute of sustainability according to the subjective importance or utility which that attribute holds for the decision maker. Then, values for each of the sustainability attributes are determined for each material from manufacturer information and other sources, and a normalized value between zero and one is calculated for each attribute value. Examples of sustainability criteria which would be calculated for each material are shown in Figure 1. After weights have been established and values calculated for each attribute for a particular material, the weights and normalized values are multiplied and summed to create an index of subjective utility for that alternative.

When the indices of utility have been calculated for all feasible alternatives, a ranking is developed by sorting the alternatives according to utility value. The alternative with the highest utility value is the recommended alternative. The decision maker may then either select the highest ranked alternative, or choose another alternative from the set based on professional judgment. The selection process then proceeds to the next design element.

A Decision Support System for Construction Materials Selection

Figure 4 shows a conceptual framework for a Sustainability Decision Support System (SDSS) to automate the methodology for assisting sustainable materials selection. To use the system as depicted in the conceptual framework, the user first provides a list of the conceptual design elements of a facility (broken down by CSI Division), along with values for relevant parameters describing the conceptual design and the decision making context. The system uses the conceptual design and decision making parameters, along with material selection heuristics from the internal Knowledge Base, to generate a list of feasible materials from the Materials Database for each design element.

After a set of feasible materials has been generated for each design element, the Value Extractor module queries the user to obtain weightings for the attributes of sustainability, based on the user’s system of values. Values for the sustainability attributes are calculated for each feasible material choice by the Sustainability Index Calculator. Then, the user’s weightings are amalgamated with the attribute values for each potential material and sorted by the Amalgamator Module, resulting in a relative ranking of the feasible materials for each element. The material with the highest ranking is recommended by the system.

The user reviews the system's recommended choice for each element, and selects a material for each design element based on professional judgment and/or the system's recommendation. As materials are selected by the user, the SDSS provides an internal check using the knowledge base to detect any potential conflicts between material choices. The set of recommended materials for each element is modified automatically as materials are selected for design elements which may lead to constraints in the options available for other elements.

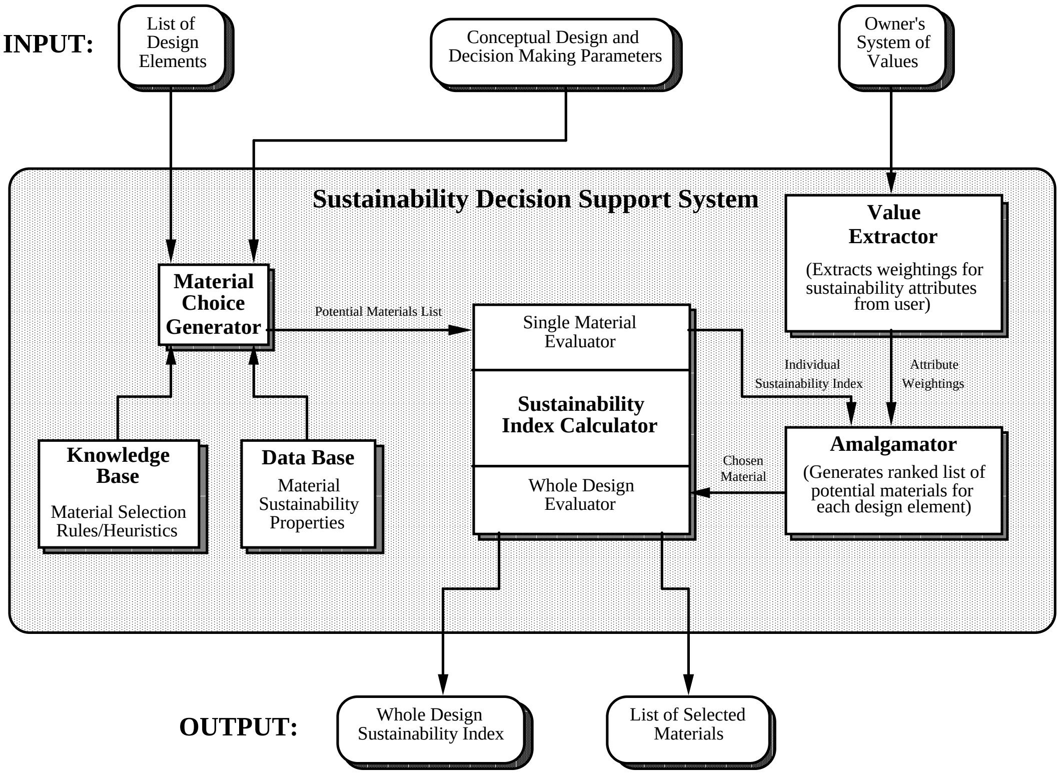

Figure 4: SDSS Conceptual Framework

When materials have been selected for each design element, the Sustainability Index Calculator provides a composite index of sustainability for the whole design[*], based on the materials selected. If desired, the user can continue to generate alternative designs by experimenting with other combinations of materials. After each design is generated, a composite index of sustainability is calculated for that combination of materials. The user may elect to generate a printout of the list of selected materials and sustainability indices if desired.

Preliminary Results and Future Research

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[*] Currently, the composite index of sustainability is based on a summation of the sustainability indices of the individual components, although research is continuing to develop other methods for assessing the sustainability of entire designs.

The research team is currently in the process of developing a prototype SDSS system to demonstrate the concept of the selection methodology, and is continuing to supplement the knowledge and data bases which support the SDSS system. The primary strengths of the conceptual SDSS framework are its modularity and expandability. Since the components of the framework are modular, each may be developed independently, and data may be added as it is acquired to supplement the knowledge and databases. The SDSS prototype system is still in the conceptual phases of development, and as such has not been tested to determine the limitations of the SDSS concept.

Future modifications to the SDSS could include integration of the materials selection framework into a comprehensive automated design system or expansion of the system to design of artifacts other than built facilities. Extensions which could be made within the SDSS framework include adding design generation capabilities to the system, more extensive modeling of the interactions between materials choices for each design element, and the capacity to automate knowledge acquisition as new projects are encountered.

Benefits, Contributions, and Applications

It is hoped that the SDSS concept will lead to better project decision making by enabling more detailed consideration of a larger number of materials alternatives, evaluated in terms of their sustainability. The capacity of the system to compare materials using multiple attributes with user-specified weightings should force decision-makers to explicitly consider the effects of their previously-implicit weightings on the outcome of the project, and thus make choices which result in more sustainable project design and implementation. The ability to quickly simulate the sustainability outcomes of alternative designs may encourage greater industry acceptance of innovative materials technology.

Potential applications of this research may include extending the methodology to materials selection tasks in other disciplines such as manufacturing and mechanical engineering, as well as using the SDSS shell for supporting other construction decision-making tasks such as process and equipment selection. The materials sustainability evaluation methodology may also be useful within a larger model to determine overall project sustainability for construction projects.

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