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## **1.0 Introduction**

The development of a model for evaluating the sustainability of construction materials is proposed. This model will be incorporated into a computer-based decision support system to facilitate the selection of materials for construction projects, using sustainability as the primary decision criterion. The system will be capable of taking into account the decision maker's system of values in recommending materials for the project design elements during the conceptual design phase of construction projects.

### **1.1 Problem Statement**

Traditionally, materials selection for the design and construction of facilities has been based to a significant degree on economic and technological considerations, given the desired life span of the facility and the program of requirements it must meet. While issues such as environmental impact and resource efficiency are becoming increasingly important to parties involved in construction projects, often the only way to choose from many different material alternatives is by relying on unquantifiable professional judgment or experience (Rosen & Bennett 1979). No systematic methods currently exist to evaluate and compare construction materials against one another, in the context of their intended application with respect to their life cycle, from extraction and processing to eventual disposal. A new scientific and replicable method is needed for evaluating the sustainability of construction material alternatives. The new method should not only consider the technological and economic factors involved in materials choices, but also the immediate and long-term impact of the selection on the finite supply of natural resources and the ongoing needs for those resources by society. Together, these impacts comprise a measure of the level of sustainability of a project and should be given due consideration during materials selection.

### **1.2 Research Objectives**

The primary objective of this research is to develop a scientific and replicable method for evaluating the sustainability of construction material alternatives, in the context of their intended use within a project. To achieve this global objective, several sub-objectives will be met. First, a comprehensive list of the attributes of sustainability relevant to construction materials will be compiled from the literature and case studies. Second, a methodology for evaluating materials sustainability will be developed and tested, based on the comprehensive list of attributes. Finally, a framework for a Sustainability Decision Support System (SDSS) will be developed based on the methodology for measuring sustainability, which can assist project decision makers in the task of selecting and specifying materials. 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 will be developed and used to validate the methodology and demonstrate proof of concept.

## **2.0 Background and Existing State of Knowledge**

The following sections provide background to the problem of comprehensive evaluation of construction materials. First, some common definitions of sustainability are examined, then the state of the art in materials selection technology is presented in terms of technological, ecological, economic and ethical attributes. The section concludes with a discussion of how the proposed research relates and will contribute to the existing state of knowledge.

### **2.1 Sustainability: Some Definitions**

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 that meets the needs of the present 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 remain constrained so as to maintain the stability of the system into the foreseeable future.

#### **2.1.1 Technology**

In modern developed countries, the interface between human activity and the natural environment is technology. While rampant industrial development has been identified as a "root cause of global environmental decline" (Rees 1988, p. 274), some analysts believe that continued economic growth resulting in new technology development is the only feasible way to achieve a sustainable society without broad transformations of culture and human behavior (Olson 1994). Thus, the first category of sustainability attributes relates to technology and its innovative and appropriate use.

#### **2.1.2 Ecology**

While much debate exists over the economic, ethical, and policy implications of sustainable development (Rees 1988), there is general agreement that one of the most important issues for sustainable development is careful stewardship of natural resources, both renewable and nonrenewable (e.g., Gardner 1989; Pearce 1988; Lozar 1993). The Canadian National Task Force on Environment and Economy has expressed an interpretation of sustainable development which is almost entirely resource-based, writing that "sustainable development is...development that ensures that the utilization of resources and the environment today does not damage prospects for their use by future generations" (1987). Since the initial source for all physical resources is the natural environment, protection of environmental quality is also a critical factor of sustainability. Thus, the second category of sustainability attributes consists of ecological indicators.

### **2.1.3 Economics**

A third critical element of sustainable development is economic growth. While sustainability is sometimes used to refer to the behavior of closed systems which have zero growth (Brown, et al 1987), most sources agree that in order to realistically implement policies of sustainability, economic growth is essential, particularly in developing countries (Rees 1988, etc.). Especially in attempting to motivate corporate change in a highly competitive, profit-based industries like construction, every new idea must show promise of economic benefit to find acceptance. Even small increases in costs can pose considerable risk, sometimes resulting the loss of market-share to a competitor or even bankruptcy. Thus, any attempt to motivate consideration of environmental or long-term resource conservation issues must be accompanied by assurances that change toward sustainability does not necessarily mean economic disadvantage. The concept of sustainable performance, as developed by Kinlaw (1992), addresses the competitive reality of corporate environments by showing that incorporating sustainability into company strategies can lead to many economic advantages, including waste reduction, increased market share of eco-conscious consumers, and reduction of environmental liability.

### **2.1.4 Ethics**

Finally, issues such as environmental liability and conservation of resources for intergenerational equity extend sustainability into the sphere of ethical and social impacts. Along with consideration of ecological and economic impacts, the social and ethical impacts of changing technology and its effects on the human habitat must be considered in any evaluation of sustainability (Henderson 1989; 1994). Therefore, the fourth category of sustainability attributes relates to social and ethical impacts.

### **2.1.5 Composite Measures of Sustainability**

While no specific measures of sustainability have been documented in the literature for construction materials selection, composite measures have been developed to evaluate the sustainability of agriculture activities (e.g., Conway & Barbier 1988; Faeth 1993) and fish and timber harvests (Brown, et al 1987). In addition, various authors have identified a broad range of indicators of sustainability, which together cover the technological, economic, environmental and social/ethical dimensions of sustainability (e.g., Brown, et al 1987; Corson 1994; Brown, Flavin & Wolf 1988; Cramer & Zegveld 1991; Henderson 1989; Hunt, Sellers & Franklin 1992). In particular, Corson identifies twelve indicators of sustainability for measuring the ecological and socioeconomic sustainability of communities and nations, as follows: (1) natural resources and environment; (2) transportation; (3) economy; (4) socioeconomic equity; (5) social environment; (6) population; (7) health; (8) education; (9) culture; (10) recreation; (11) political participation and involvement; and (12) government stability and effectiveness (Corson 1994).

One of the most difficult problems in developing a composite measure of sustainability is developing indices with commensurable units, especially when comparing areas as diverse as economic value with ecological impacts with technological

performance. Some efforts at quantifying sustainability have taken the approach of costing natural resources in terms of economic indicators such as net present social value (Mikesell 1992) or natural capital stock (Pearce 1988). Other researchers have developed composite accounting methods in terms of quality of life (discussed in Henderson 1989; Henderson 1994). Other potential ways of combining disparate indicators are by common numerical scaling of indicators followed by amalgamation, described in detail in (Corson 1994; Elliott 1981; Hobbs 1985).

## **2.2 Materials Selection: State of the Field**

Using the four general classifications of sustainability attributes identified above (technology, ecology, economics and ethics), this research will develop a comprehensive metric for evaluating the sustainability of building materials to be used in materials selection and specification. Before examining the potential contributions of this research to the existing state of knowledge, existing methods for measuring material attributes in each of the four general categories above will be examined.

### **2.2.1 Technology**

Construction materials technology has changed rapidly in recent years, with significant changes including increased reuse and recycling of construction and demolition waste materials like timber, steel and concrete (e.g. Brown & Bassett 1988), improvements to traditional products such as fiber-reinforced concrete and plastic-reinforced wood (e.g. Plevris & Triantafillou 1992), and development of completely new technology such as geotextiles (Richardson 1988). While use of innovative materials is growing, many designers and contractors are reluctant to try materials which are not yet "tried and true," particularly in civil engineering projects where public funding is involved and where failure could mean the loss of many human lives. Building codes and other regulatory restrictions impose further limitations on the use of recycled or innovative materials, often taking years to catch up to changes in materials technology. Finally, the sheer number of potential materials available to designers and contractors makes optimization of material choices a nearly impossible task.

Particularly in the field of mechanical engineering design, many databases exist which describe engineering materials in terms of their physical and performance properties. In particular, the American Society for Testing Materials (ASTM) has made enormous progress in the last thirty years toward the standardization of material specifications according to uniform testing standards designed to establish reliable measures of material properties (Divitci 1970; Li & Ho 1989). Examples of some physical properties according to which materials are typically rated are modulus of elasticity, endurance limit, density, and yield strength.

Material properties databases are managed using various computerized techniques, including knowledge-based expert systems (Iwata 1989), integrated design requirements-material properties multivariate analysis systems (Bengtson, et al 1991), management information systems (Newley 1992), component modeling systems (Brooks, et al 1992), and concurrent selection/component design systems (Karandikar & Mistree, 1992). Common problems with systems to assist in materials selection include lacking

the capacity to explain the rationale behind the system's recommendations, and the capability to alert users to potential misuses of materials or gaps in the database (Hossain & Barry 1992).

### **2.2.2 Ecology**

Quite a few attempts have been made to describe materials in terms of their impacts on the environment. For example, one reference guide on engineering materials developed at the Center for Resourceful Building Technology presents a listing of sources for materials which contain recycled materials or are low in embodied energy (Loken, et al 1994). However, there are often significant environmental tradeoffs to be considered in trying to choose the "optimal" material for a given application. For example, the benefits of recycling materials, such as conserving landfill space and reducing demands on virgin resources, are sometimes overshadowed by increased energy expenditures required for collection and reprocessing (Scarlett 1991, Scott 1992).

Often, environmentally benign materials are technologically unavailable at the time of materials selection (Bjerklie 1993). Even when ecologically sound alternatives to traditional building materials can be found, their use often presents conflicts with other parameters for materials selection, especially economic considerations. Typically the initial cost of using recycled materials is higher than for virgin materials. And sometimes otherwise sound alternative materials present the same bad features as the traditional materials they replace. As one architect pointed out, "recycled carpet made from old plastic soda bottles still gives off the same toxic gasses that regular nylon carpet does" (Paul Bierman-Lytle, quoted in Bjerklie 1993).

A variety of materials selection technologies have been developed specifically to assist designers with environmental issues. Design tools range from indexed sourcebooks such as the *Guide to Resource-Efficient Building Materials*, which lists "green" materials and their properties, to computer-based information systems such as the Forest Resource Information System, which offers a computerized database on the characteristics and potential uses of thousands of virtually unknown tropical species of wood. However, these systems usually provide only facts related to each material's characteristics, and rely on human judgment to compare alternatives in the context of the intended use.

### **2.2.3 Economics**

Methods for comparing materials on an economic basis are extremely well-developed. The entire field of construction estimating involves pricing various alternatives for materials, labor and equipment and selecting the best alternatives based on price (given an acceptable level of performance, of course). Construction estimators have at their disposal elaborate guides to pricing such as the annually-updated Means *Construction Cost Data* and *Walker's Building Estimator's Reference Book*, as well as customized corporate databases of historical pricing information from previous projects. Estimators must consider factors like installation time, availability, potential liability, and reliability, all of which contribute to the level of economic risk undertaken by the

contractor in agreeing to complete the project. Computerized systems for project estimating include software like Timberline, by \$\$\$ Corporation.

#### **2.2.4 Ethics**

Comparing materials in terms of ethical tradeoffs is considerably more difficult than making technological, ecological, or economic comparisons. Ethical considerations are often embedded within contradictions between environment and economy. For example, is it worth the excess cost to purchase recycled materials and protect virgin natural resources, or is cost a more important consideration? Issues such as quality of life, inter- and intra-generational equity, and stewardship of resources are often discussed in the literature on sustainability, but are difficult to define and even more difficult to implement (e.g., Henderson 1994; Elgin 1994; Corson 1994).

Ethical issues are wide-ranging in impact, involving not only those who design, build and use facilities but also those who are affected by the opportunity costs of providing resources for their construction or space for the wastes generated by their disposal. And in the competitive and sometimes cut-throat environment of construction, such issues often get lost among the shuffle of performance, time, and economic considerations. If ethical tradeoffs are considered at all, they are generally taken into account in the early planning stages of the project, and depend greatly on the priorities and value system of the owner as conveyed to the project design and management teams.

### **2.3 Relation of Proposed Research to Existing State of Knowledge**

This research will provide a methodology for calculating an index of sustainability for construction materials, in the context of their intended application and with respect to the whole life cycle of the materials, from extraction and processing of their raw components to eventual reuse, recycling or disposal. This research is unique in attempting to develop a multi-attribute evaluation method for construction materials based on the complete doctrine of sustainability. While systems such as those discussed in Section 2.2 exist to support material selection for individual criteria (usually performance and cost), no model exists for evaluating materials in terms of sustainability in its entirety. All four of the parameters of sustainability must be considered in the context of each individual design and decision-making environment in order to select the most appropriate materials for each of the facility's design elements.

The methodology for calculating the sustainability of individual materials will be incorporated into a computer-based framework for a Sustainability Decision Support System to be used for selecting materials for an entire facility. The system will assist the user by accessing a database of construction materials and their sustainability properties and generating a listing of suggested materials for each design element of the facility. The user will then contribute weightings for the attributes of sustainability such that an index of sustainability for each material can be calculated by the system. Thus, the system will be capable of incorporating the user's individual value system into its ranking

of the list of materials choices for each design element. The interactive graphical user interface will allow the user to manipulate variables representing the weights given to each attribute in the model of sustainability, thus providing a quantified representation of how important the user feels each variable is to the decision at hand. No materials selection system which currently exists provides the capability to accommodate the user's system of values in the system's recommendations.

After providing the user with a ranked list of suggested materials for each design element, the system will assist the user in choosing a material for each element by checking for conflicts with the conceptual design and previously selected materials. When materials for the whole design have been fixed, the system will provide an overall index of sustainability for the design as a whole, to allow comparison with other alternative designs. In this manner, the designer can quickly simulate many possible material combinations and designs, and select based on overall sustainability.

### **3.0 Proposed Methodology**

The following sections of this proposal describe the proposed methodology to be used to execute the research described above. First, the role of each module in the SDSS conceptual framework will be explained and the progression of data through the system will be described. Next, a description of the plan of work is presented, with a detailed discussion of the tasks to be completed in the implementation of this research. Included are a proposed schedule for the execution of the project is shown, and a description of the scope of each project task, along with a listing of deliverables at each step. Finally, the criteria for evaluating the success of the project are described, and the expected contributions of the research are presented.

#### **3.1 SDSS Conceptual Framework**

The conceptual framework for a Sustainability Decision Support System which will be developed as part of this research consists of six internal modules (Knowledge Base, Materials Database, Material Choice Generator, Sustainability Index Calculator, Value Extractor, and Amalgamator) plus a graphical user interface to the user. A diagram of the framework system is shown in Figure A, and a flow chart of the user's path through the materials selection process using the SDSS is shown in Figure B.

First, the user provides a list of the design elements of a facility (broken down by CSI Divisions) and values for relevant parameters describing the conceptual design and the decision making environment. 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. Values for several descriptive parameters representing the sustainability of the individual material are calculated for each feasible material choice for each element by the Sustainability Index Calculator.

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 representative parameters of sustainability, based on the user's system of values. Then, the user's weightings are amalgamated with the parameters of the sustainability index for each potential material 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 elements which may lead to constraints in the options available for other elements.

When materials have been selected for each element, the Sustainability Index Calculator provides a composite index of sustainability for the whole design. The user may continue to generate alternative designs by experimenting with other combinations

of materials if multiple evaluations are required. After each design is generated, a composite index of sustainability is generated for that combination of materials. The user may elect to generate a printout of the list of selected materials and sustainability indices if desired.

### **3.2 Description of Work**

The following sections describe the plan of for the proposed research. The scope and proposed methodology for each activity are presented, and the contributions of each activity to the research are discussed. The plan of work is divided into four general phases: Data Acquisition, Model Development, SDSS Prototype Development, and System Testing and Documentation. Figure C shows a projected schedule for the research as described below. Figure D contains a brief description of the scope of each activity in Figure C, along with deliverables expected to result from each activity and the allocated time for each task.

The schedule shown in Figure C is a proposed schedule only. The researcher reserves the right to modify the proposed schedule as necessary to ensure that this research produces a valid contribution to the body of knowledge, with well-documented results. In addition, the researcher reserves the right to add to the scope of work for each task shown in Figure D, as necessary or as time permits.

#### **3.2.1 Phase I: Data Acquisition**

The research will begin with a comprehensive review of the current literature on sustainability and sustainable development, along with a survey of existing materials selection technology in the areas of materials databases, cost estimating, construction management, and architectural and civil engineering design (Activity 1). The review of the literature will be an ongoing activity throughout the first three phases of research. From the background materials generated by the literature review, a comprehensive list of indicators and attributes of sustainability will be compiled which might be relevant for materials selection (Activity 2). A type of project to be used to demonstrate the framework will also be selected at this time, based on data availability. As time and resources permit, interviews with construction and design experts may be conducted to verify the completeness of the list of indicators.

The list of sustainability indicators and attributes will be used to guide the development of the materials database (Activity 3). The materials database will contain values for the sustainability attributes and indicators of each construction material in the database. Information for the database will be compiled from existing databases, textual sources such as *Sweet's Catalogues*, and life cycle analysis of the materials from a multilevel systems perspective. Life cycle analysis will include, but not be limited to, estimating the total embodied energy in the material at all phases of the life cycle,

recyclability and reusability of the material, durability, and resistance to decay and degradation.

A knowledge base of material selection heuristics will be compiled from literature resources and supplemented by interviews as needed (Activity 4). The knowledge base will be used within the system to constrain the extraction of alternatives from the materials database by the Choice Generator, to check for conflicts between selected materials, and to assist the Sustainability Index Calculator in determining a sustainability index for whole designs. Case studies of conceptual facility designs and sustainability parameters for existing projects will be compiled during the last six weeks of Phase I (Activity 5). The case studies will serve to provide the data required for the scaling of sustainability attributes and validation of the model of sustainability to be developed during Phase II.

### **3.2.2 Phase II: Model Development**

Phase II will begin with the statistical analysis of the materials data and case studies gathered during Phase I, and the development of appropriate scales for each attribute and indicator of sustainability (Activity 6). All sustainability attributes of the materials will be scaled, and amalgamation theory will be used to develop a theoretical model of sustainability for individual materials (Activity 7). The model will include the attributes of sustainability and weightings extracted from the user's system of values as variables. The output of the model will be a numerical index of sustainability, based on the user's input of relative valuation of the attributes of sustainability.

Part of the collection of case studies compiled in Phase I will be analyzed to provide data points from which a theoretical model of whole design sustainability will be developed using statistical regression (Activity 8). To allow the case study information to be useful for curve-fitting, an estimation of the overall sustainability of each project will be made by evaluating the completed project along the dimensions of technology, economics, and environmental impact using existing techniques as described in Section 2.2, Materials Selection. The model will subsequently be validated by comparing its calculation of sustainability against an estimation of the sustainability for the rest of the construction case studies, evaluated using existing techniques as described above.

Phase II will conclude with an evaluation of potential computing environments for possible use in the prototype SDSS system and the preparation of functional specifications for each module in the SDSS (Activity 9). The functional specifications will serve as the conceptual framework for development of future systems, and will guide the coding of the prototype system modules in Phase III.

### **3.2.3 Phase III: SDSS Prototype Development**

Phase III of the research will involve creating a prototype system to demonstrate the conceptual framework for a Sustainability Decision Support System. The system will be driven by the theoretical models of individual material and whole design sustainability developed in Activities 7 and 8 of Phase II. Using the functional specifications from

Activity 9, each module in the SDSS described in Section 3.1 of this proposal will be coded using the selected computing tools.

Phase III will begin with the coding of the Material Choice Generator module (Activity 10), the Value Extractor module (Activity 11), and the Amalgamator module (Activity 12). The Material Choice Generator will utilize an inference engine to select feasible material choices from the materials database for each element of the specified conceptual facility design, constrained by selection heuristics from the knowledge base and the parameters of the conceptual design and project decision environment. The Value Extractor module will serve to determine appropriate weightings for the attributes of sustainability via the user interface. Several systems for extracting weights may be developed, including a graphical module which allows the user to directly manipulate weights, a query module which infers weightings from user responses to a series of questions designed to evaluate tradeoffs which the decision maker is willing to make, or a neural network-based module which "learns" the decision maker's value system by imitating decisions made by the user.

Similarly, if time permits, several modules may be developed for amalgamation, to allow the user to select the module which is most helpful for particular situations. The Amalgamator module will serve to combine the values for the sustainability attributes of a particular material with the user's relative valuation of those attributes, to arrive at a sustainability index for that material which can be ranked relative to the indices for other feasible materials. The amalgamation and value extraction processes will be based on existing multivariate decision theory (c.f.g. discussions in (Elliott 1981), (Hobbs 1985)).

Concurrently with the coding of the other modules, the Sustainability Index Calculator module will be created (Activity 13), which calculates values for parameters representing the sustainability of individual materials based on the material's attributes and the design context in which it is being considered. This set of parameters, when amalgamated with the user's value weightings, represents the sustainability of each individual material, and is based on the model of sustainability for individual materials developed in Phase II. The Sustainability Index Calculator also serves to calculate the Whole Design Sustainability Index for the final set of materials selected for the conceptual design by the user, based on the theoretical model of whole design sustainability developed in Phase II. The Whole Design Sustainability Index is determined using the Sustainability Index calculated for the material selected for each design element, along with the conceptual design and decision making parameters originally supplied by the user.

Phase III concludes with the development of the interactive user interface (Activity 14) and coding of the necessary software interfaces between the modules of the SDSS (Activity 15). The user interface will provide templates for entering conceptual design and project environment information, as well as feedback capabilities for reporting the ranking and sustainability indices for individual materials. The user interface will support the user in selecting appropriate materials for each design element, and will permit monitoring of the Choice Generator and Sustainability Index Calculator modules. The interface will also permit printing of the list of selected materials and design elements, along with the composite sustainability index for the whole design.

Completion of all activities in Phase III of the research will yield a working SDSS prototype.

### **3.2.4 Phase IV: System Testing and Documentation**

Phase IV will begin with thorough validation (Activity 16) and user testing (Activity 17) of the SDSS prototype which was completed in Phase III. Validation will include testing to determine that the materials recommended by the system for each design element correspond with the most sustainable materials as determined by the theoretical model of sustainability for individual materials, as developed and validated in Activity 7. If time and resources permit, the system may be field-tested in real or simulated design scenarios. The case studies collected in Activity 5 will also be used to test the prototype system.

Concurrent with user testing, a User's Guide to the SDSS prototype will be developed (Activity 18). Ongoing documentation of the research (Activity 19) will be completed, and the resulting documentation will be incorporated into the preparation of the doctoral dissertation of the researcher (Activity 20). The submittal and defense of the dissertation will mark the end of Phase IV of this research.

### **3.3 Project Evaluation**

The success of this research will be evaluated against the following three goals, based on meeting the objectives as described in Section 1.2, Objectives:

- 1) A comprehensive listing of attributes of sustainability for materials selection is developed from the literature and case studies
- 2) A methodology for calculating the sustainability of individual construction materials is developed and validated
- 3) A framework for a Sustainability Decision Support System is developed, and a prototype SDSS is implemented as proof of concept.

### **3.4 Expected Contributions of the Research**

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. Moreover, 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 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. Finally, this research will provide a means for assessing the completeness of current project documentation procedures, and will identify any gaps in information which should be filled in documentation of future projects.

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 efforts such as process and equipment selection. The materials sustainability evaluation model may also be useful within a larger model to determine overall project sustainability for construction projects.

Future research in this area could include integration of the SDSS framework into a comprehensive automated design system. 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 acquire knowledge as new projects are encountered.

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