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Impact of Sustainability Perceptions on Optimal Material Selection in Construction Projects

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ABSTRACT

As more owners seek to develop sustainable buildings, the construction industry is adapting to new requirements in order to meet owner's concerns. Material selection is an area where designers and contractors can have a significant impact on the green certification of a building. Objective factors such as design and cost considerations play a role in the selection of materials. However, there may be subjective factors that could also impact the selection. This paper explores the potential impact of sustainability perceptions in an optimization model that can be used to help decision makers to select materials. The objective of the model is the maximization of the number of material-related LEED-based credits. A survey of design and construction students and practitioners is undertaken to capture the subjective factors. A framework for green material selection is proposed to indicate the effect on the optimal choice of materials due to the factors considered.

INTRODUCTION

Buildings have an enormous and significant impact on the environment since they are responsible for a large portion of carbon emissions (Keysar and Pierce 2007, Yudelson 2008, Gonzalez and Navarro 2006) and use a considerable number of resources and energy [Pulselli et al 2007]. Additionally, the bad quality of indoor environments in office buildings may affect the health of employees, reducing their productivity [Ries et al 2006]. Green building movement emerged to mitigate the impact of buildings on the environment and to improve the building construction process, bringing significant economic, financial, social, and environmental benefits [Wang et al 2005, Thormark 2006, Ross et al 2006, Edwards 2003, Kats 2003, Ries et al 2006, Muse and Plaut 2006, Baker 2006]. To realize such benefits it is not only necessary to select wisely the appropriate technologies, but the right materials [Wang et al 2005, Moeck and Yoon 2004].

Selecting inappropriate materials may preclude the achievement of the desired sustainability goals. Sustainability goals may be achieved by considering factors such as environmental impacts, economic impacts, customer requirements and market demand [Ljungberg 2007]. The Leadership in Energy and Environmental Design (LEED) rating system is a widely applied rating system used to determine the level of accomplishment of environmental factors. The LEED rating system encourages the use of materials extracted, processed, and manufactured regionally [USGBC 2008]. The LEED system also promotes the use of materials with high recycled content, rapid renewable periods, responsible harvesting management, low-emitting contaminants, and proper solar reflectance index. In addition to environmental factors, market demand is also a factor considered for the achievement of sustainability goals. Market preferences may be determined using an instrument to validate consumer's preferences of product sustainability. Preferences are measured through visual features and the metaphysical aspects of products and help capture subjective characteristics [Lurie and Mason 2007]. Subjective characteristics associated with sustainable products include low raw material consumption [Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009], low reparability (i.e. time between repairs is high) and highly prolonged lifetime [Ljungberg 2007, Mora 2007], buildability [Dammann and Elle 2006], safe to use [Zhou 2009, Mora 2007, Ljungberg 2007], highly satisfying to the user [Ljungberg 2007], something the public needs [Glavic and Lukman 2007], resource use efficiency [Glavic and Lukman 2007], and trend braking [Ljungberg 2007] among others. As a result, if a building wants to earn the LEED points associated to the previously described standards and accomplish sustainability goals, a complex and comprehensive material selection process is required.

The material selection problem has been addressed with the support of analytical tools such as multiobjective optimization [Sirisalee et al 2004, Ashby 2000], ranking methods [Jee and Kang 2000, Chan and Tong 2007], index-based methods [Holloway 1998, Giudice et al 2005], and other quantitative methods [Farag 2002]. However, the current green building literature lacks of a method that helps decision makers to select the appropriate materials in order to optimize the sustainability in products. The criterion for optimizing sustainability in products considers not only environmental impacts, economic impacts, and customer requirements but also market demand [Ljungberg 2007]. Therefore, to help decision makers with the selection of appropriate materials, this study applies a mixed integer optimization model that maximizes the number of material-related credits reached under a modified version of the LEED system [Castro-Lacouture et al 2009]. The model incorporates the design, and budget, constraints previously considered in Castro-Lacouture et al 2009 and includes an additional market preference constraint. The market preference constraint is determined by using an instrument of consumer perception of product sustainability to measure consumer's attitudes. In other words, the instrument determines a consumer's attitude parameter as an input for the optimization model. Under budget constraints, the model guides decision makers towards a detailed plan that describes the choice of materials and their extent of use, allowing them to include preferred materials, and design parameters. The model can also be used to show purchasability intentions towards sustainable products which may impact the LEED credits obtained due to market preferences.

INSTRUMENT OF CONSUMER PERCEPTION OF PRODUCT SUSTAINABILITY

Consumer's perception of product sustainability is examined by developing and testing a measurement instrument of product sustainability based on the creativity measurement instrument developed by Horn and Salvendy 2006. The model shows the process of how consumers retrieve information about a product and compare this information to a set of sustainability criterion in order to determine the level of material sustainability. Sustainability is defined as the subjective judgment of a product to enhance well-being, give satisfaction to the user, and conserve resources in economically viable, safe and healthy ways for consumers [Glavic and Lukman 2007]. To be a sustainable product, the product must be judged as socially and creatively rewarding for all stakeholders for the short and long term future [Glavic and Lukman 2007]. From this definition, four dimensions of product sustainability were derived. The quality dimension measures the product's capability to satisfy customer requirements. The functionality dimension measures the usefulness of sustainable materials. The user appeal dimension measures the arousal impact of the product sustainability. Finally, the resourcefulness dimension measures the product characteristics associated with sustainability.

The four dimensions of product sustainability are measured using an instrument which includes 12 items (see Table 1). The adjective pairs (*P1*-*P12*) used to measure the quality, functionality, user appeal, and resourcefulness dimension items deployed for this instrument were based on derived associated wording in subjective characteristics derived from previous studies [Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009, Ljungberg 2007, Mora 2007].

Table 1. Sustainability measurement instrument

Sustainability dimension	Item number	Product sustainability measurement item
Quality	*P1*	extraordinary-ordinary
	P2	reliable-unreliable
	P3	durable-temporary
Functionality	*P4*	functional-unusable
	P5	useful-impractical
	P6	helpful-worthless
User appeal	*P7*	attractive-unattractive
	P8	beneficial-detrimental
	P9	satisfied-disappointed
Resourcefulness	*P10*	resourceful-wasteful
	P11	efficient-inefficient
	P12	innovative-common

In order to test the four-dimensional instrument and to better understand the factors that could influence product sustainability perceptions, a web-based survey was conducted among design and construction students and practitioners. The survey presented a brief definition of sustainable products and a two-dimensional image of a specific construction product. The subject was instructed to first examine the product image and description and to think about the product sustainability. Then the subject was asked to mark responses that best describe the specific product shown on the survey. The subjects were asked to evaluate the overall sustainability of the specific product and mark a sustainability score on a 7-point Likert scale (1=extremely not sustainable, 2=not sustainable, 3=slightly not sustainable, 4= neither not sustainable nor sustainable, 5=slightly sustainable 6=sustainable, 7=extremely sustainable) to the questions asked. The questions included were each of the adjective pairs in Table 1. For instance, one question asked respondents if a sustainable product should be resourceful or wasteful on the 7-point Likert scale. Approximately half of the measurement items were reversed to reduce response bias.

After collecting the responses to the survey, the instrument of consumer perception of product sustainability can be validated and the number of dimensions of product sustainability can be determined. Once the instrument has been validated, a product sustainability score can be given to materials to account for product sustainability and the overall weighting of importance of subjective characteristics. The addition of the sustainability score as a measure of consumer's attitudes completes the data input module to optimize product sustainability.

OPTIMIZATION MODEL FOR SUSTAINABLE MATERIAL SELECTION

The optimization model considers that buildings are comprised of systems like wood finishes, floors, walls, windows, and roofs. Each system is built using a specific set of materials classified in categories such as adhesives and sealants, paints and coatings, carpets, roof materials, permanently installed woods, and temporally installed woods. One particular system can be built using materials from different categories. Thus, the cornerstone decision in the model is the extent of use of materials to build each system while maximizing the chances for a green certification such as LEED. For instance, if the floor system area to be covered is 1000 m2, then the right combination of materials must be selected. A possible recommendation from the model is to buy 1000 m2 of floor wood w1 or to buy 600 m2 of floor wood w1 and 400 m2 of floor wood w2. However, this selection decision cannot be taken without considering the criteria for optimizing product sustainability which consists of environmental impact of materials, design requirements, available budget, and market demand [Ljungberg 2007].

The optimization framework shown in Figure 1 supports the decision maker in the complex process of material selection. The data input module collects information on the available materials, their price, and environmental properties such as recycled content, volatile organic compounds (VOC) content or emission factor, reflectance index for roof materials, place of origin, renewable period and forest certification for woods, and urea-formaldehyde content.

The data input module also includes the design parameters, which define the system size, the subset of suitable materials to build the system, and the minimum and maximum fraction of the system than can be built using those materials. For instance, consider that suitable materials for the floor system are woods *w1*, *w2*, *w3*, *w4*, *w5*, and *w6*. The designer knows that at least 20% of the floor area, but no more than 40%, must be built using either wood *w1*, *w2*, or *w3*; a half of the system must be built using wood *w4;* and at least 20% but no more than 30% of the system must be built using either wood *w5* or *w6* (see Table 2). In this case, the optimization model selects the right type of woods while meeting the designer criteria.

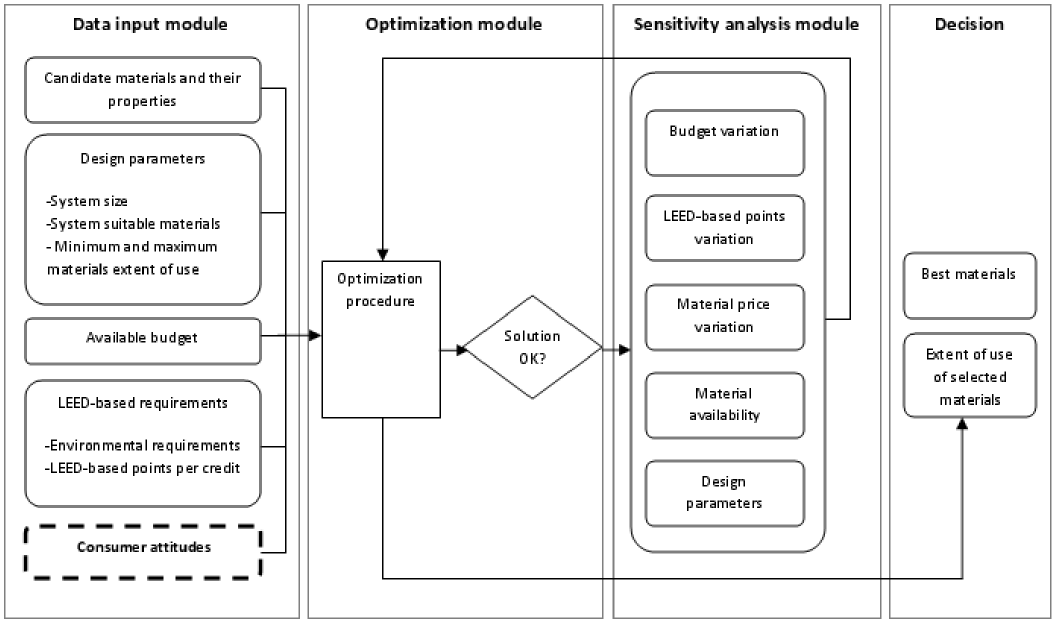

Figure 1. Optimization model framework

A sustainability score measured by consumer attitudes is also included as a data input. The attitudes were captured in the instrument of consumer perception of product sustainability and an overall score was given to each construction material. As a result, the score not only reflects how users actually perceive a product to be sustainable but also what criterion is involved which may affect purchase intentions. Criteria such as easy to build with, safe to use, highly satisfying to the user, and something the public needs may be difficult to measure but through visuals can be assessed and help capture market preferences.

Table 2. Floor system design criteria

Material	Lower bound*	Upper bound*
w1	20%	40%
w2		
w3		
w4	50%	50%
w5	20%	30%
w6		

*100%=total area

In addition to allocate a budget for material purchasing, the decision maker defines the LEED-based credit parameters in the data input module. A description of the LEED-based requirements is provided in Table 2. Those requirements are included in the optimization model as constraints. Figure 2 shows a graphical representation of the constraints associated with the accomplishment of credits 6 and 7 from the materials and resources area (see Table 3). If the total cost of rapidly renewable (RR) wood-based materials is greater than 2.5% of the total material cost, then the variable z_1 takes the value of 1, indicating that the LEED credit 6 is accomplished. In this case, the auxiliary term takes the value of zero and the inequality holds. Conversely, if the variable z_1 takes the value of 0, then the LEED-based credit 6 is not accomplished and the auxiliary term takes the value of *G* (a conveniently large number). A similar mechanism is used for other LEED credits considered in the model.

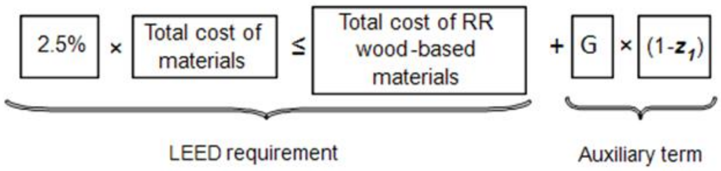

Figure 2. Operation of LEED-based constraints

Once all the data input is entered, the optimization module builds the model that maximizes the number of LEED-based points awarded through credit accomplishment (see Table 3). Mathematically, the model's objective is to maximize the number of *z* variables that take the value of 1, indicating the credit accomplishments. The output of the optimization model is a detailed selection of the best materials and their extent of use for each system in the building. A detailed description of the optimization model can be found in Castro-Lacouture et al 2009.

Finally, the optimal solution is used in the sensitivity analysis module, where the solution robustness is evaluated by measuring the impact on credit accomplishments due to changes in the budget, LEED-based points, material prices, material availability, and design parameters. This sensitivity analysis enriches the decision maker information, supporting the final decision.

DISCUSSION

A number of studies on properties of sustainable materials have been carried out, indicating the use of objective as well as subjective measures in defining sustainable materials. Although the material selection problem has been approached by considering objective factors that may influence the decision-making process, subjective factors need to be considered as well. Visual features of materials may have an emotional impact on the user and on the user's appraisal of sustainability. Therefore, an instrument is needed to assess subjective characteristics in order to improve the current decision-making process by considering objective and subjective measures simultaneously.

The instrument of consumer perception of product sustainability to be deployed in this study can help assess subjective characteristics of sustainable materials and bring significant positive changes to the actual process of material selection in sustainable construction. Its usefulness lies in the opportunity to include in the decision-making process subjective characteristics associated with sustainable products. The assessment of subjective characteristics may help capture how users perceive a product to be sustainable and all the factors that may influence product sustainability. Therefore, suppliers can include in the material's image features typically associated with sustainable characteristics, reducing large data sets to simple visuals. Through sight and the highly developed skills of human perceptual senses, the benefits of visual information of a product could be realized. As a result, the process of materials selection may be simplified and accelerated. Visual features may broaden the capabilities of the decision-making process by allowing users to evaluate more data without being overloaded with information.

Table 3. LEED-based requirements

Credit	Area	Name	Intent	Description
7.2 Points: 1	Sustainable Sites	Heat Island Effect, Roof	Reduce heat islands	Use roofing materials having a solar reflectance index (SRI) equal to or greater than 78 for low-sloped roofs (≤2:12) or 29 for steep-sloped roofs (>2:12). These values must be used for a minimum of 75% of the roof surface.
4.1 Points: 1	Materials and Resources	Recycled Content - 10%	Increase demand for building products that incorporate recycled content materials, reducing impacts from extraction and processing of virgin materials.	Use materials with recycled content such that the content constitutes at least 10% (based on cost) of the total value of the materials in the project. Only include materials permanently installed in the project, except mechanical, electrical, plumbing components and specialty items such as elevators. The recycled fraction of the assembly (by weight) is multiplied by the cost of assembly to determine the recycled content value.
4.2 Points: 1		Recycled Content - 20%		Use materials with recycled content such that content constitutes an additional 10% beyond Credit 4.1 (total of 20%, based on cost) of the total value of the materials in the project.
5.1 Points: 1		Regional Materials, 10% Extracted, Processed & Manufactured Regionally	Increase demand for building materials and products that are extracted and manufactured within the region, supporting local economies and reducing the environmental impacts resulting from transportation.	Use building materials or products that have been extracted, harvested or recovered, as well as manufactured, within the same region of the project site for a minimum of 10% (based on cost) of the total materials value. Only include materials permanently installed in the project, except mechanical, electrical, plumbing components and specialty items such as elevators.
5.2 Points: 1		Regional Materials, 20% Extracted, Processed & Manufactured Regionally		Use building materials or products that have been extracted, harvested or recovered, as well as manufactured, within the same region of the project site for an additional 10% beyond Credit 5.1 (total of 20%, based on cost) of the total materials value.
6 Points: 1		Rapidly Renewable Materials	Reduce the use and depletion of finite raw materials and long-cycle renewable materials by replacing them with rapidly renewable materials.	Use rapidly renewable building materials and products (made from plants that are typically harvested within a ten-year cycle or shorter) for 2.5% of the total value of all building materials and products used in the project, based on cost.
7 Points: 1		Certified Wood	Encourage environmentally responsible forest management.	Use a minimum of 50% (based on cost) of wood-based materials and products, which are certified (e.g., Forest Stewardship Council's -FSC), for wood building components (e.g., structural framing and general dimensional framing, flooring, sub-flooring, wood doors, and finishes). Only include materials permanently installed in the project.
4.1 Points: 1	Indoor Environmental Quality	Low-Emitting Materials, Adhesives & Sealants	Reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.	All adhesives and sealants used on the interior of the building shall comply with the volatile organic compounds (VOC) limits provided in USGBC (2005) page 65.
4.2 Points: 1		Low-Emitting Materials, Paints & Coatings		Paints and coatings used on the interior of the building shall comply with the volatile organic compounds (VOC) limits provided in USGBC (2005) page 67.
4.3 Points: 1		Low-Emitting Materials, Carpet Systems		All carpet installed in the building interior shall meet the product requirements of the Carpet and Rug Institute's Green Label Plus program.
4.4 Points: 1		Low-Emitting Materials, Composite Wood & Agrifiber Products		Composite wood and agrifiber products used on the interior of the building shall contain no added urea-formaldehyde resins. Laminating adhesives used to fabricate on-site and shop-applied composite wood and agrifiber assemblies shall contain no added urea-formaldehyde resins.

Source: Castro-Lacouture et al (2009). Adapted from USGBC (2005).

The applied optimization model incorporates the objective and subjective measures to assist decision-making in materials selection. The instrument of consumer perception provides a preference factor resulting from the collection of massive amounts of subjective information in visual features of materials. In addition to the preference factor, other objective parameters are included to determine the optimal choice of materials to achieve sustainability goals.

As electronic environments increase, the range of construction materials expands overwhelming users with information and making the retrieving information process effortful. Therefore, it is necessary to understand the market of materials in order to help users benefit from all the information provided. The instrument to be deployed in this study may contribute to benefit the marketing of sustainable materials. By investigating the factors that influence user's perception of material sustainability and predicting user's attitudes, material databases could become valuable tools to assist in purchasability of sustainable materials in an ever-expanding range of options. The understanding of demand within building construction enhance consumer satisfaction contributing on how to make sustainable practices remain viable for the well-being of present and future generations.

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