MEASURING SUSTAINABILITY PERCEPTIONS OF CONSTRUCTION MATERIALS

A Dissertation
Presented to
The Academic Faculty

By

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In Partial Fulfillment
Of the Requirements for the Degree
Master of Science in Building Construction and Facility Management

Georgia Institute of Technology

August, 2010

MEASURING SUSTAINABILITY PERCEPTIONS OF CONSTRUCTION MATERIALS

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ACKNOWLEDGEMENTS

This accomplishment would have not been possible without the support of my advisor, Dr. Daniel Castro-Lacouture. He guided me with his outstanding professional knowledge, believed in me, always encouraged me to think positively, and taught me about research and life. I will always carry his lessons with me.

I also want to thank Dr. Javier Irizarry for his advice and helpful recommendations; Dr. Linda Thomas-Mobley for her professional expertise and invaluable teachings; Dr. Diana Horn for her guidance and assistance with the instrument design.

I thank my parents for their patience and unconditional love. Thanks to them I am a better person. I also want to acknowledge my sisters for their friendship, constant support, and for making my life happier. Finally, I thank all my family for always being there for me. I am very proud to have them in my life.

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SUMMARY

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 has been identified as an area where designers and contractors can have a significant impact on the sustainable performance of a building. Objective factors such as design considerations and cost constraints can play a role in the selection of materials. However, there may be subjective factors that could also impact the selection of materials. Building upon the potential impact of sustainability perceptions in an optimization model that can be used to help decision makers to select materials, this study defines and tests an instrument to identify and measure such perceptions. The purpose of this dissertation is to develop a conceptual instrument that measures the user-based assessment of product sustainability and validates decision-maker's perceptions in order to evaluate the contribution of subjective characteristics in materials selection. A survey of design and construction students and practitioners is carried out to capture the subjective factors included in the instrument. A Factor Analysis approach is used to refine and validate the measurement instrument and predict decision-makers' sustainability appraisal due to the factors considered.

CHAPTER 1

INTRODUCTION

1.1 Overview

The market for sustainable buildings is increasing since the construction industry has acknowledged they may mitigate the impact on the environment and bring significant economic, financial, social and environmental benefits (Ries et al. 2006, Wang et al. 2005, Thormark 2006, Muse and Plaut 2006, Baker 2006). To realize such benefits it is necessary to select materials which conform to sustainable principles (Abeysundara et al. 2009, Wang et al. 2005, Glavic and Lukman 2007). Selecting inappropriate materials may impact the performance of the building and preclude the achievement of the desired sustainability goals (Nassar et al 2003). Sustainability goals may be achieved by considering factors such as environmental impacts, economic impacts, customer requirements and market demand (Ljungberg 2007).

Traditionally, sustainability appraisals are based on life-cycle assessment (LCA) as a tool to quantify the environmental impact (Giudice et al. 2005, Ljungberg 2007, Abeysundara et al. 2009) and on the conception of triple bottom line (TBL) for measuring performance against economic, social and environmental parameters (Ljungberg 2007). However, the visual features and the metaphysical aspects of products may influence appraisals, market demand, and affect decision making in sustainable materials selection (Ljungberg 2007). Therefore, it would be helpful to create a tool to help suppliers measure the assessment of sustainable features from the perspective of decision-makers since emotional phenomena may account for different functions that arise in the decision making process (Schwarz 2000, Pfister and Bohm 2006).

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 products. Sustainable materials are materials with high recycled content (Mora 2007, Zhou 2009), low-emitting contaminants (Mora 2007, Glavic and Lukman 2007), rapid renewable periods (Glavic and Lukman 2007), high reused content (Mora 2007, Zhou 2009) and harm of contaminants free (Zhou 2009). In addition, sustainable materials are characterized as low consuming (Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009), low reparable and highly prolonged (Ljungberg 2007, Mora 2007), easy to build with (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), do more with less (Glavic and Lukman 2007), socially and creatively awarding (Glavic and Lukman 2007), and as trend braking (Ljungberg 2007) among others. As a result, if a building has to be built according to sustainable principles, a thorough process of selection of materials has to be performed.

1.2 Background

The material selection problem has been tackled with the support of analytical tools such as multi-objective optimization (Ashby 2000, Sirisalee et al. 2004, Zhou et al. 2009), 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 sustainable building literature lacks of a method that helps decision makers to select the appropriate materials by including all the factors that arise in the decision making process in order to optimize sustainability (Ljungberg 2007, Heijungs et al. 2010). The criterion for optimizing sustainability 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 proposes a method to capture subjective factors that arise in the decision-making process. The subjective factors used to describe sustainable materials will be assessed with the support of images. Visual features may broaden decision making capabilities by allowing a process of evaluating more data without overloading the decision maker (Lurie and Mason 2007). Through visual recognition and human's highly developed skills of perceptual senses, decision makers could reduce large data sets to simple visuals and enhance the decision making process since sustainability indicators are an important component (Heijungs et al 2010).

A number of studies have been developed to assess visuals' qualitative and subjective characteristics that may influence decision making. The scenic views that affect occupants' satisfaction in buildings (Li and Will 2005), the aesthetic of facades which affect perceived quality of buildings (Gifford et al. 2000), environmental aesthetics which influence urban landscape quality (Bernasconi et al. 2009), and product creativity that influences consumer evaluation of products (Horn and Salvendy 2006). However, there is no study of how sustainable features may influence decision making in materials selection. The assessment of sustainability perceptions among construction professionals may help determine how do decision-makers actually perceive a product to be sustainable and what factors are involved in the selection.

1.3 Research objective and scope

This study proposes a conceptual model of product sustainability assessment as a basis to develop an instrument to determine the key subjective factors that arise in the decision-making process of sustainable materials selection. By investigating the construction industry's perceptions of properties of sustainable products, the instrument may be used to assess product sustainability from the decision maker's perspective through examination of specific visual features. A survey of design and construction students and practitioners is carried out to test the instrument with evaluations of product sustainability using a modified version of the creativity tool (Horn and Salvendy 2006). A Factor Analysis approach is carried out to identify the most relevant features when evaluating sustainability by validating specific visual perceptions. The Factor Analysis determines the number of sustainability dimensions which explain the variance in perceptions. The tested instrument of product sustainability may help suppliers determine how decision makers perceive sustainability in products and the key components of sustainable materials from the perspective of construction practitioners. Furthermore, a score on sustainability factors is determined to assess how the relevant dimensions may significantly score on sustainability. In addition, the instrument reveals the importance of examining specific visual features as direct predictors of sustainability appraisals.

This study develops the instrument of product sustainability as a tool to capture the subjective factors that may influence materials selection. This research does not create a decision support system model, in which information is inputted in a model and the model offers a best choice selection. Rather, this study attempts to demonstrate that decision making may be enhanced by considering subjective as well as objective factors in the decision making process. In order to incorporate additional information that should be considered in the decision making process, this study proposes the sustainability instrument to assess subjective characteristics in order to improve the current decision-making process. Ultimately, this study takes into consideration the perceptions of decision makers and the identification of which variables affect sustainability evaluations to enhance the value of sustainable products since sustainability terms are crucial for communication in the process of moving towards a sustainable development.

1.4 Dissertation outline

This study is divided into 6 chapters. Chapter 1 introduces the problem, provides objectives and presents a brief scope of the study. Chapter 2 offers a literature review of the various methodologies used to establish sustainability goals and selection models for materials. It presents and describes an optimization model that considers objective factors such as design, budget, and LEED requirements. Furthermore, it shows how subjective factors may be added to the optimization model for selection of materials. Chapter 3 presents a literature review of how perceptions affect decision making, their role in decision maker's attitudes and the importance of conceptualizing subjectivity to enhance the decision making process. Chapter 4 describes and presents the instrument to assess perceptions and capture the subjective factors. Chapter 5 presents a methodology for this study, discusses the sustainability instrument, and provides descriptive statistics of the data. Additionally, it describes the overall usage of the proposed model and reports findings. Finally Chapter 6 presents the instrument, expected benefits, limitations, recommendations for future research, and conclusions.

1.5 Conclusions, benefits and expected contributions

This study moves toward a clearer focus of the numerous definitions of sustainable materials and the lack of agreement upon a designation of the term. By developing an instrument to capture and assess subjective factors, this study will help the construction industry consider additional information that may improve decision making. This study will aid decision makers during the programming phase of a project when attempting to determine the materials that optimize sustainability. Determining the optimal extent of use of materials is often a challenging task due to the multiple factors that should be considered. This research contributes to new knowledge in the materials selection process by embracing the multifactorial nature of the problem. This research assists decision makers in choosing among materials to build sustainable buildings and adds new knowledge to discussions among the construction industry on which factors define and determine sustainability.

CHAPTER 2

MATERIALS SELECTION

2.1 Sustainable Buildings Rating Systems

Many methodologies have been developed to establish the degree of accomplishment of sustainability goals, guiding the planning and design processes. In these earlier stages of the construction process, planners can make decisions to improve building performance at very little or no cost, following the recommendations of the decision-making tool. The first of such tools was the Building Research Establishment Environmental Assessment Method (BREEAM). After that, other methodologies, such as Green Star from Australia (GBCA 2008), the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan (CASBEE 2008), the Building and Environmental Performance Assessment Criteria (BEPAC) from Canada (Cole et al. 2008), and the Leadership in Energy and Environmental Design (LEED) from the United States (USGBC 2010) were developed and are currently widely applied. Very comprehensive inventories of available tools for environmental assessment methods can be found in Ding (Ding 2008), the Whole Building Design Guide (WBDG 2010), and the World Green Building Council (WGBC 2010).

Although the existing methods and tools have an extended use, LEED has established strong credibility among the experts (Ding 2008) increasing its affiliates. According to Bowyer (Bowyer 2007), in April of 2007, the LEED system was comprised of 7,500 company and organization members, validating its importance as the standard environmental performance measure of a building (Ross et al. 2006, Yudelson 2008) and becoming a reference system for the design, construction, and operation of green buildings beyond the U.S. (Pulselli et al. 2007, Muse and Plaut 2006, Sherwin 2006, France 2007). Adaptations of the LEED system have been applied or are in the process of implementation in Brazil and Mexico (Lockwood 2006), two of the largest developing economies in the Western hemisphere.

Like many of the available rating systems, the LEED rating system is based on credits and points (USGBC 2010). Through each credit, the system evaluates the performance of the candidate building and awards points if the requirements are reached in a variety of areas such as sustainable sites, indoor environmental quality, and materials and resources. Although these categories should not be treated separately, but rather as a whole, it has been stated that materials are the most-significant topic in a building study (San-Jose et al. 2007) reducing the environmental footprint through the correct choice and substitution of materials (Thormack 2006). According to the LEED rating system (USGBC 2010), the selection of environmentally responsible materials considers material accessibility by encouraging the use of materials extracted, processed, and manufactured regionally, and, at the same time, promoting the development of regional economies. The LEED system also encourages the use of high recycled content, rapid renewable cycle, and low-emitting contaminant materials which aim to reduce their impact on the environment and indoor air quality of the building. As a result, the design of a green building requires a comprehensive process for material selection that considers not only the previously described standards but also design and budget requirements that are key factors for the success of the building.

2.2 Selection models

The material selection problem has been treated extensively in the literature through many approaches such as multiobjective optimization (Sirisalee et al. 2004, Ashby 2000, Zhou et al. 2009), 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 building construction literature lacks of a method that could help the builder to select the more appropriate materials, while looking at the accomplishment of environmental goals via a standard and recognized method, and meeting design and budgetary requirements at the same time.

This study reviews a research methodology applicable to materials selection (Florez 2008; Castro-Lacouture et al. 2009). The model is a mixed integer linear program (MILP) that improves green construction decision making by considering both design and budget constraints to address realistic scenarios experienced by the decision maker. In addition, the model includes soft constraints that describe the LEED requirements pertaining to the selection of materials, which may or may not be satisfied. The number of satisfied constraints constitutes the objective function to maximize. In other words, the model attempts to maximize the number of satisfied LEED constraints while satisfying design and budget constraints.

2.3 LEED-based Rating System for Material Selection

Credits in the proposed LEED-based rating system are based on those credits in the existing LEED 2009 version 3.0 for new construction and major renovations rating system that are related to material selection (USGBC 2010). Through each credit, the proposed rating system evaluates the performance of the candidate building in terms of the characteristics of the materials, such as the contribution to the heat island effect, proportion of recycled content, distance from the supplier or producer to the project site, and emissions of indoor pollutants (see Table 2.1). For each criterion, the rating system awards points if the requirements are reached, accounting a number of 11 available points.

The requirements of the proposed LEED-based rating system are adapted for the specific situation of the market. For instance, in the US market, because specifications on available materials state only the total recycled content, the credit related to recycled content do not differentiate between pre-consumer or post-consumer recycled content. Thus, credit 4 in the area of materials and resources (see Table 2.1) states that, in order to award points, the total recycled content should constitute a minimum portion of the total cost of the materials for the project, requiring a minimum 10% for 1 point and 20% for 2 points. The credit regarding regional materials (credits 5 in the area of materials and resources) takes into account the distance from the place where materials are extracted, harvested, recovered, or manufactured to the project site. However, it is not possible to track the origin of the components for most available materials, manufacturing requirements do not consider the proportion of the final product manufactured in the region, but only that at least one process has been conducted in the same region of the project. As LEED states, the aim of these credits is not only to reduce the environmental effects caused by transportation, but also to support regional economies. Credits promoting the use of rapidly renewable materials (credit 6 in the area of materials and resources), certified wood (credit 7 in the area of materials and resources), and low-emitting materials (credits 4.1, 4.2, 4.3, and 4.4 in the area of indoor environmental quality) are considered as stated in the LEED system for new construction and major renovations version 3.0 (USGBC 2010) Credit 7.2 in the area of sustainable sites considers the solar reflectance index as the only criteria for roofing materials.

Table 2.1. LEED-based Credits Considered in the Materials Selection Problem

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 Points: 1-2	Materials and Resources	Recycled Content - 10% - 20%	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 (to earn 1 point). Use materials with recycled content such that content constitutes an additional 10% (total of 20%, based on cost) of the total value of the materials in the project (to earn 2 points). 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.
5 Points: 1		Regional Materials, 10%-20% 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 (to earn 1 point). Use building materials for an additional 10% beyond (total of 20%, based on cost) of the total materials value (to earn 2 points).Only include materials permanently installed in the project, except mechanical, electrical, plumbing components and specialty items such as elevators.
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.

2.4 Mixed Integer Optimization Model for Material Selection

This section presents the mixed integer model for material selection under a modified version of the LEED rating system (Florez 2008, Castro-Lacouture et. al 2009). Let S be the set of building systems (e.g., wood finishes, floors, walls, roofs, masonry), T the set of types of materials, and Ψ_j the subset of materials that are used in system $j \in S$. Let $\Phi = M_A \cup M_P \cup M_C \cup M_W \cup M_{\overline{W}} \cup M_R \cup M_B$ be a partition based on the types of materials, where M_A represents the set of adhesives and sealants, M_P the set of paints and coatings, M_C the set of carpet systems, M_W the set of composite wood and agrifiber products (permanently installed in the building), $M_{\overline{W}}$ the set of composite wood and agrifiber products (temporally installed in the building during the construction process), M_R the set of roofing materials, and M_B the set of bricks. Note that $\Phi = \bigcup_{t \in T} M_t$, where $M_{t_1} \cap M_{t_2} = \varnothing$ for $t_1 \neq t_2; t_1, t_2 \in T$. Let Q_n^j be a category of materials such that one or more of these materials can be selected to complete a fraction or the whole system j. Consequently, $\Psi_j = \bigcup_{n=1}^{N(j)} Q_n^j$, where $N(j)$ is the maximum number of categories in the system j. Finally, the set of credits under the proposed LEED-based system, according to Table 0.1, is expressed by L.

The available budget for materials in the building systems in S is denoted by the parameter b. The dimension (unit, length, area, or volume units) of system j is expressed by d_j and the cost per unit of material is denoted by c_i. The number of points earned if credit $k \in L$ is accomplished is p_k. The recycled content of material i as a percentage of the total weight is expressed by r_i. Let v_i be the content of volatile organic compounds (VOC) of the material $i \in M_A \cup M_P$ measured in [g/L] for adhesives, sealants, and paints. Let $\dot{v}_i$ be the emission factor of volatile organic compounds (VOC) of the material $i \in M_C$ measured in [μg/m^2 h] for carpets. The maximum allowed content of VOC (in [g/L]) of a material $i \in M_A \cup M_P$ is denoted by v_i^u. The maximum allowed emission factor of VOC (in [μg/m^2 h]) of a material $i \in M_C$ is denoted by $\dot{v}_i^u$. The minimum and maximum fraction of the system $j \in S$ that can be built using one of the materials from category Q_n^j, are denoted by l_{nj} and u_{nj} ($0 \le l_{nj} \le u_{nj} \le 1$), allowing the designer to impose his/her requirements. The maximum number of materials from category Q_n^j that can be selected to build system j is K_{nj}. The constant G takes a value much greater than zero ($G >> 0$) and it is used in some of the constraints as a penalty term.

Binary parameters are also defined to describe some properties of materials: e_i takes the value of 1 if the material was extracted, recovered, manufactured, or processed in the same region that the project, it takes the value of 0, otherwise; h_i takes the value of 1 if the material $i \in M_W \cup M_{\overline{W}}$ is made by rapidly renewable materials (see Table 1), it takes the value of 0, otherwise; f_i takes the value of 1 if the material $i \in M_W$ has a certification of responsible forest management (e.g., Forest Stewardship Council's –FSC), it takes the value of 0, otherwise; m_i takes the value of 1 if the material $i \in M_W \cup M_A$ does not contain urea-formaldehyde resins, it takes the value of 0, otherwise; and s_i takes the value of 1 if material $i \in M_R$ accomplishes the required minimum solar reflectance index according to the desired slope (see Table 2.1), it takes the value of 0, otherwise.

The proposed model identifies the materials and their required amount as a fraction of the system. Let x_{ij} (≥ 0) be the fraction of system $j \in S$ that is built using material i. The binary variable y_i takes the value of 1 if the material is used (in any building system); it takes the value of 0, otherwise. Let z_k be a binary variable that takes the value of 1 if credit $k \in L$ is accomplished, as is stated in Table 2.1; it takes the value of 0, otherwise. The proposed mixed integer program follows:

$$\max \sum_{k \in L} p_k z_k \tag{1}$$

subject to,

$$l_{nj} \leq \sum_{i \in Q_n^j} x_{ij} \leq u_{nj} \qquad ; j \in S, n = 1,2,\ldots, N(j) \tag{2}$$

$$\sum_{i \in Q_n^j} y_i \leq K_{nj} \qquad ; j \in S, n = 1,2,\ldots, N(j) \tag{3}$$

$$x_{ij} \leq y_i \qquad ; j \in S, i \in \Psi_j \tag{4}$$

$$y_i \leq G x_{ij} \qquad ; j \in S, i \in \Psi_j \tag{5}$$

$$\sum_{i \in \Psi_j} x_{ij} = 1 \qquad ; j \in S \tag{6}$$

$$\sum_{j \in S} \sum_{i \in \Psi_j} c_i d_j x_{ij} \leq b \tag{7}$$

$$\sum_{i \in \Psi_j \cap M_R} s_i x_{ij} \geq 0.75 z_1 \qquad ; j \in S \tag{8}$$

$$0.10 \left(\sum_{j \in S} \sum_{i \in \Psi_j} c_i d_j x_{ij} \right) \leq \left(\sum_{j \in S} \sum_{i \in \Psi_j \setminus M_{\overline{W}}} r_i c_i d_j x_{ij} \right) + G(1 - z_2) \tag{9}$$

$$0.20 \left(\sum_{j \in S} \sum_{i \in \Psi_j} c_i d_j x_{ij} \right) \leq \left(\sum_{j \in S} \sum_{i \in \Psi \setminus M_{\overline{W}}} r_i c_i d_j x_{ij} \right) + G(1 - z_3) \tag{10}$$

$$0.10\left(\sum_{j\in S}\sum_{i\in\Psi_j} c_i d_j x_{ij}\right) \le \left(\sum_{j\in S}\sum_{i\in\Psi_j} e_i c_i d_j x_{ij}\right) + G(1-z_4) \qquad (11)$$

$$0.20\left(\sum_{j\in S}\sum_{i\in\Psi_j} c_i d_j x_{ij}\right) \le \left(\sum_{j\in S}\sum_{i\in\Psi_j} e_i c_i d_j x_{ij}\right) + G(1-z_5) \qquad (12)$$

$$0.025\left(\sum_{j\in S}\sum_{i\in\Psi_j} c_i d_j x_{ij}\right) \le \left(\sum_{j\in S}\sum_{i\in\Psi_j} h_i c_i d_i x_{ij}\right) + G(1-z_6) \qquad (13)$$

$$0.5\left(\sum_{j\in S}\sum_{i\in\Psi_j\cap M_W} c_i d_j x_{ij}\right) \le \left(\sum_{j\in S}\sum_{i\in\Psi_j\cap M_W} f_i c_i d_i x_{ij}\right) + G(1-z_7) \qquad (14)$$

$$v_i y_i \le v_i^u + (1-z_8)G \qquad ; i \in M_A \qquad (15)$$

$$v_i y_i \le v_i^u + (1-z_9)G \qquad ; i \in M_P \qquad (16)$$

$$v_i y_i \le v_i^u + (1-z_{10})G \qquad ; i \in M_C \qquad (17)$$

$$y_i(1-m_i) \le (1-z_{11})G \qquad ; i \in M_W \qquad (18)$$

$$x_{ij} \ge 0 \qquad ; j \in S, i \in \Psi_j \qquad (19)$$

$$y_i \in \{0,1\} \qquad ; i \in \Phi \qquad (20)$$

$$z_k \in \{0,1\} \qquad ; k \in L \qquad (21)$$

As is shown in (1), the model seeks to maximize the number of points awarded by the accomplishment of LEED-based credits. The set of constraints (2) allow the decision makers to impose lower and upper limits on the fraction of each system built using materials from a specific category while constraints (3) allow them to impose a maximum number of materials than can be selected to build each system. If the decision maker would like to determine the fraction of system j that must be built using materials from category Q_n^j, then he/she could set $l_{nj} = 0$ and $u_{nj} = 1$. On the other hand, if the decision maker sets $l_{nj} = u_{nj}$, then the fraction of system j built using materials from category Q_n^j is fixed. Constraints (4) and (5) articulate the variables representing the fraction of the materials used, with the corresponding binary variables that specify that a given material is used. The set of constraints in (6) states that the entire system (100%) must be completed. The budget constraint shown in (7) limits the amount of money available to purchase materials for the systems in S.

Constraints (8) through (18) consider the LEED-based requirements stated in Table 2.1. The constraints shown in (8) represent credit 7.2 from the area of sustainable sites, which states that 75% of the roof area must be built using materials complying with the required solar reflectance index. Credit 4, from the area of materials and resources, is considered in (9) and (10). Constraint (9) requires that at least 10% of the total cost of materials in the project should be allocated to materials with recycled content to award 1 point. Constraint (10) represents credit 4 from the area of materials and resources, and reflects an additional 10% of the cost invested in materials with recycled content. Notice that if constraint (10) is satisfied, then constraint (9) is also satisfied. Credit 5, promoting the purchase of regional materials, is considered in constraints (11) and (12), respectively. Likewise, if constraint (12) is satisfied, then constraint (11) is also satisfied. Constraint (13) shows the requirements stated in credit 6 from the area of materials and resources, motivating the use of rapidly renewable materials. Credit 7, from the area of materials and resources, is considered in (14) and encourages the use of certified wood. Constraints (15) and (16), show the recommended maximum VOC content for adhesives and sealants, paints, and coatings, respectively, while constraint (17) shows the maximum VOC emission factor for carpet systems. Constraint (18) contains the requirements in credit 4.4 from the area of indoor environmental quality. It discourages the use of materials containing urea-formaldehyde resins. Finally, constraints (19) enforce non-negativity conditions on the fractions, while constraints (20) and (21) state the binary nature of the decisions regarding material use and the accomplishment of the LEED credits.

2.5 Mixed Integer Optimization Model for Material Selection - Considering subjective requirements

Although the presented model for material selection considers objective factors such as budget, design and LEED constraints that may influence the decision-making process, subjective factors need to be considered as well (Glavic and Lukman 2007, Ljungberg 2007). Subjective factors may be added in the mixed integer model presented by considering additional information such as perceptions of sustainability that arise in the selection process. To include sustainability perceptions, the model presented in equations (1) through (21) can be slightly modified as follows.

Let δ be the minimum desired sustainability score; then the new constraint guarantees that the materials selected are perceived as sustainable materials by design and construction students and practitioners. The loading of material i on the sustainability item m is denoted by the parameter t_{im}. The loading of sustainability item m on factor n is denoted by a_{mn}. The binary variable y_i takes the value of 1 if the material is used (in any building system); it takes the value of 0, otherwise as in constraint (20).

Thus, the sustainability score constraint follows:

$$\sum_{n \in N} \sum_{m \in M} \sum_{i \in I} y_i t_{im} a_{mn} \geq \delta \tag{22}$$

In summary, the resulting model is comprised of the objective function (1) subject to constraints (2) thru (22). This modified model determines the materials required to comply with the minimum sustainability score and achieve the maximum number of LEED points. Therefore, an instrument is needed to assess subjective characteristics to account for the sustainability score of materials.

CHAPTER 3
SUBJECTIVE REQUIREMENTS

3.1 Literature Search

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 products. Sustainable materials are materials with high recycled content (Mora 2007, Zhou 2009), low-emitting contaminants (Mora 2007, Glavic and Lukman 2007), rapid renewable periods (Glavic and Lukman 2007), high reused content (Mora 2007, Zhou 2009) and harmful contaminants' free (Zhou 2009). In addition, sustainable materials are characterized as low consuming (Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009), low reparable and highly prolonged (Ljungberg 2007, Mora 2007), easy to build with (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), do more with less (Glavic and Lukman 2007), socially and creatively awarding (Glavic and Lukman 2007), and as trend braking (Ljungberg 2007) among others.

Although the availability of various information sources on sustainability terms is increasing and a number of studies on sustainable materials' definition have been carried out, researchers have not agreed upon a clear designation often leading to imprecise definition of the term and its usage (Glavic and Lukman 2007). In addition, the many details and aspects in the term increase the complexity of finding a common definition among construction practitioners (Heijungs et al. 2010). As a result, this study attempts to understand sustainability by concentrating on how this term is reflected in construction materials and perceived by construction professionals. Furthermore, it attempts to measure how design and construction students and practitioners comprehend sustainability. By reducing the number of variables that define sustainability, the most relevant variables can be extracted and later be used to improve the understanding of sustainable products.

3.2 Sustainable products

Products are thought to have specific perceived characteristics that contribute to their success or failure. Product characteristics include good value (financial), quality, meet decision maker's needs, unique features or solve problems other products do not, visible benefits, safe, efficient, satisfying to use, durable and serviceable (Cagan and Vogel 2002). These characteristics are thought to provide value to the product. The six components that contribute to value include emotion (senuality, power, and sense of adventure), aesthetic (visual, tactile, and auditory), product identity (personality, sense of impact, and social), ergonomics (ease of use, safety, and comfort), core technology (enabling and reliable), and quality (durability) (Cagan and Vogel 2002). Since a sustainable product must give as much satisfaction as possible to the user to be successful in the market (Ljungberg 2007), a sustainable product should incorporate all these values in its production.

There are numerous studies that have attempted to define a sustainable product. One of the studies defines a sustainable product as "a product which will give as little impact on the environment as possible during its life cycle" (Ljungberg 2007). Another study defines it as "a product that it's easy to build with and consumes less resources in production, transport and erection" (Dammann and Elle 2006). One more study defines a sustainable product as "a product that can be maintained in a specific state for an indefinite (or very long) time" (Heijungs et al. 2010). Furthermore, a sustainable product is defined as "a product made using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for consumers and which are socially and creatively rewarding for all stakeholders for the short and long term future” (Glavic and Lukman 2007).

Despite the numerous studies and as can be understand from above, there is no simple way of how to define nor develop sustainable products (Ljungberg 2007). Design and construction practitioners do not know a commonly accepted definition of what a sustainable material is (Ljungberg 2007) or a consensus regarding the meaning of sustainability assessment (Heijungs et al. 2010). Consequently, there are many different terms used to define sustainable products which will be studied and analyzed. In fact, these terms will be used to understand how sustainable products are assessed and to examine to what extent they have encountered decision maker’s perceptions of sustainability. Therefore, for the purpose of this study, sustainable materials will be broadly defined as “materials made using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for consumers and which are socially and creatively rewarding for all stakeholders for the short and long term future” (Glavic and Lukman 2007).

3.3 Measuring sustainability in products

Many methodologies have been developed to measure sustainability in products, becoming useful tools for guiding the production and design phase and informing decision makers as to what basis a particular material is sustainable or not. One of the most common tools to inform users whether a particular material is sustainable or not is using environmental marking systems such as the EU sign, Energy Star (Emidast), TCO sign, Svanen, WWF, and Environmental choice among others (Ljungberg 2007). These markings are voluntary for the companies and are used when their products comply with the environmental requirements of each specific organization. Although the markings are widely used, the demands to produce environmental products are not clear and easy to understand making it difficult to determine which product is the best choice in terms of sustainability indicators when two similar ones are compared (Ljungberg 2007).

One more approach to measure sustainability is the one based on life-cycle assessment (LCA) as a tool to quantify the environmental impact (Giudice et al. 2005, Ljungberg 2007, Abeysundara et al. 2009, Heijungs et al. 2010). The LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle. As a result, a material's impact constitutes the whole impact evaluated step by step from acquisition, manufacture, use, and disposal (Ljungberg 2007, Heijungs et al. 2010). Another approach to measure sustainability in products is using the concept of triple bottom line (TBL). The TBL is used as a framework for measuring a company's performance against economic, social and environmental parameters. It involves the triad of ecology, equity and economy. As a result, when developing a product companies move between the three corners to obtain a balance so that each category is fulfilled. One more approach, which is based on TBL, but more product oriented is Sustainable Product and Service Development (SPSD). The SPSD gives guidelines for designing products which includes questioning the functionality, determining the life-cycle stages and suppliers and optimizing the sustainability impacts. The criteria for optimizing sustainability in products include functionality, environmental impacts, social impacts, economic impacts, market demand, quality, customer requirements, technical feasibility, compliance with legislation and different specifications among others (Ljungberg 2007). However, there is no methodology that is sufficiently science-based, but that also contains an amount of subjective and well known aspects (Heijungs et al 2010). Therefore, it would be helpful to create a tool to help suppliers measure the assessment of features from the perspective of decision-makers and how visual features and the metaphysical aspects of products may influence appraisals and affect decision making in sustainable materials selection (Ljungberg 2007).

This study uses the criteria for optimizing sustainability previously described, as a basis to construct a sustainability measurement instrument. The instrument attempts to capture decision maker's perceptions since these perceived factors may constitute requirements that play a crucial role in several stages of building construction. Requirements include information such as decision maker's experience (previous relationship with the product), expectations (what the decision maker wants from the product) and environment (the decision maker context) (Horn 2005). By incorporating decision maker's perspectives, acceptance in product development is encouraged and associated value is added to the design (Horn and Salvendy 2006). In fact, close contacts with users may be an essential factor not only for releasing products in the market, but also for releasing products to be of major interest and need to the users (Ljungberg 2007) enhancing the decision-making process.

3.4 Perceptions and their role in decision-making

The decision making process usually deals with multiple factors and functions that need to be taken into account for successful outcomes and optimal decisions (Pfister and Bohm 2008, Kandil et al. 2010). Factors such as cost, quality, environmental performance, and safety are often included in the process (Zhou 2009). However, evidence is accumulating suggesting that without emotional involvement decision making might be far from optimal. Emotions account for different functions that arise in the decision making process (Pfister and Bohm 2008) and are involved in every major problem faced, influencing decisions (Schwarz 2000, Russell 2003, Pfister and Bohm

2008). Therefore, specific mechanisms that account for emotional phenomena need to be implemented in order to consider subjective factors in the decision making process.

Affect or the experienced feeling about a stimulus plays four roles in decision making (Pfister and Bohm 2008). The first role of affect is as information since it acts as good-bad basis to guide choices. The second role is as a spotlight since it focuses the decision-maker's attention on new information, making some information more accessible for further processing. The third role is as motivator, influencing approach and avoidance tendencies as well as efforts to process information. The fourth role is as common currency in judgments and decisions, providing a common currency for experiences (just as money does for goods). Therefore, the four roles of affect allow decision makers to compare different events and complex terms on a common dimension (Pfister and Bohm 2008) influencing the outcome of the decision making process.

The hierarchies of affect in the decision-making process explain the formation order of decision maker's beliefs, attitudes, and behaviors. For instance, the high involvement hierarchy (beliefs, attitude, behavior), low-involvement (beliefs, behavior, affect), experiential (affect, behavior, beliefs), and behavioral influence (behavior, beliefs, affect) (Ray 1973). As seen, the hierarchies show that decision maker interactions with products depend on the type of involvement with products and may influence the order of how decision makers form beliefs, attitudes, and behaviors towards products. In addition, the context of consumption also influences the decision-making process which includes physical aspects of the environment, influence from other decision makers, time, reason for consumption and physiological state of consumer. Therefore, decision maker behaviors and decisions are highly influenced by the situations in which products are consumed (Horn 2005).

The decision making process usually starts when decision makers perceive product characteristics by being exposed to the product. The decision maker captures information about the product from visual, auditory, haptic and other senses. Next, this perceived information goes to a handling stage, which is controlled by the decision maker's allocation of attention, memory and level of involvement with the product. With the entire product's information, then the decision maker forms a meaning of the product and processes the perceptions to make decisions or choices about the product (Horn 2005).

Consumer behavior (how decision makers perceive and interact with products) and how to conceptualize emotions and perceptions concerning their role in decision making has been fully studied (Mower and Minor 2001, Rogers 2003, Crosby et al. 2003, Chueh and Kao 2004, Barnes and Lillford 2007, Pfister and Bohm 2008). One aspect studied in the literature in consumer behavior has been how to consider perceptions of quality. The major dimensions of product quality include factors such as performance, features, reliability, conformance, durability, serviceability, aesthetics, tangibles, assurance, empathy, value, involvement and responsiveness among others (Chueh and Kao 2004, Crosby et al. 2003). These studies support that consumer perception is a contributing factor to consumer behaviors such as purchasing or word of mouth, as well as decision maker attitudes such as satisfaction, loyalty and trust (Horn 2005).

Another aspect considered is how to assess innovation. Innovation is based on a continuum (Horn 2005). Continuous innovation causes a minor change in user behavior whether dynamically continuous innovation either causes minor changes in very important behavior or major changes in unimportant behavior. Innovation is also assessed in terms of impact to the user (Rogers 2003). The major dimensions of innovation include factors such as relative advantage, compatibility with decision maker's needs, values and behaviors, ability to try without risk, observability in society, and complexity. These dimensions affect the diffusion and adoption of innovation across time in factors such as value, cost, marketing strategies, competitive activities, and uncertainty among others. Based on these factors, there are metrics of innovation for the inputs, process, and outputs of the product development process (Horn 2005). The metrics include innovation revenue per employee, competencies developed, and value of new opportunity domains relative to existing business revenue (Muller et. al 2005, Horn 2005).

One more aspect considered is how to assess perceptions of creativity (Amabile 1982, Horn and Salvendy 2006). The user-based approach of creativity considers that individuals have varying experience with products and expectations, which can influence their assessment of product creativity. This approach coincides with visual assessment, which proposes that judgments of creativity in products are subjective since a creative product can only be distinguished when seen (Amabile 1982). Consequently, the major dimensions of creativity include factors such as novelty, elaboration and synthesis, resolution, centrality, applicability, pleasure, and arousal (Horn 2005). As described above, affect plays an important role in decision making and is a contributing factor that leads to decision maker attitudes.

3.5 Decision-maker attitudes

Two models have attempted to predict decision-makers attitudes. One of such models is the attitude-toward-the-object which states that overall attitude is the summation of the strength of the conviction that an object has a specific attribute multiplied by the level of goodness or badness of that attribute (Fishbein and Ajzen 1975). This model explains that attitudes are formed from outstanding attributes from products, and these product’s attributes may be good or bad. This model does not include a measure of importance since assumes the evaluations become high as importance towards the product increases.

The other model is the behavioral intentions model which states that behavior results from intentions to behave (Horn 2005). The model assesses decision maker's attitude towards purchasability and not on the product itself. Therefore, the consumer is focused on the results of purchasing the product and not directly on the attributes of the product. With knowledge of the consequences of purchase, the factors affecting the decision may be more easily understood. The formation of the satisfaction or dissatisfaction is a result of the use, expectancy and emotion. Satisfaction in users is usually measured using Likert scales and includes both satisfaction and dissatisfaction statements to eliminate bias (Mower and Minor 2001). As a result, the assessment of satisfaction towards a product depends on the attributes of the product and also on the impact and involvement that the product has on the user (or the judge of the product). Therefore, specific mechanisms to assess affect or emotional phenomena have to be implemented.

3.6 Conceptualizing perceptions

A number of studies support the idea that all emotions are naturally classified in as either positive or negative (Besemer and O'Quin 1999, White et al. 2002, Pfister and Bohm 2008). In fact, it may be assumed that all emotional states can be mapped on a one-dimensional scale of valence, characterized by contrasting labels such as positive versus negative, and pleasurable versus harmful (Schwarz 2000, Russell 2003, Besemer and O'Quin 1999, Pfister and Bohm 2008). Research on hedonic feelings postulates a general pleasant versus unpleasant feelings on which all experiences may be evaluated (Cabanac 1992) since all decisions involve predictions of future feelings (Schwarz 2000). Following these ideas, a rating scale to score the different dimensions of the nature of products to measure subjective factors can be developed. These rating scales are usually anchored with semantic pairs or level-based (i.e. low-high) for each construct (Besemer and O'Quin 1999).

The creative product semantic scale (CPSS) developed by Besemer and O'Quin (1999) measures product creativity based on three main dimensions of the creative product analysis matrix: novelty, resolution, and elaboration and synthesis (Besemer and O'Quin 1999). Each of the three dimensions is measured with several semantic pairs. For instance, originality is measured with ten semantic pairs such as astonishing-commonplace, astounding-common, shocking-ordinary, startling-stale, surprising-customary, unexpected-expected among others. Table 3.1. provides a list of previous studies which used the CPSS and indicate construct validity through literature support. As seen in Table 3.1, the CPSS was tested in several domains with small (1 to 4) sets of products and input ratings for each semantic pair for a set of products came from non-expert judges. The score for each subscale is calculated by averaging the scores from the semantic pair within each subscale. The CPSS has shown adequate internal reliability, with measures ranging from .69 to .91. The CPSS was developed based on a measurement tool called the Creativity Product Inventory (Taylor and Sandler 1972). The Creativity Product Inventory was used to measure the creativity of scientific products and contains seven dimensions: generation, reformulation, originality, relevancy, hedonics, complexity, and condensation. Each dimension is scored by judges based on a 7-point Likert scale.

Table 3.1. Studies using CPSS as a measurement tool

Reference	Domain	Number of	Number	Internal
Besemer	T-shirts	133 students	2	.69 to .91
Besemer	Openers, art	35, 18, 19	3,1,3	.71 to .82
Besemer	Novel chairs	128 students	3	.77 to .87
Besemer	Novel chairs	185 students	3	.78 to .85
Horn 2005	Novel chairs	203 students	4	.70 to .90

In addition to rating scales, other studies have tested the Consensual Assessment Technique (CAT) for capturing product's subjective factors such as creativity. The CAT developed by Amabile (1982), is based on the consensual definition of creativity, which claims that a product is creative to the degree in which appropriate observers agree that it is creative. In the CAT, expert judges rate products (produced for the evaluation) relative to one another with independently selected dimensions. The judges are asked to report creativity scores on a 5 point Likert scale for each dimension selected, as well as other items such as technical goodness. The analysis on correlations between creativity dimensions and other items allows the judge to make conclusions about the relationships between product creativity and other factors. Studies of the CAT have shown adequate inter-rater reliability, with measures ranging from .72 to .98.

Both of the methods mentioned above measure creativity in products. The CAT method connects creativity with social conditions since creativity is a subjective judgment. On the contrary, the CPSS is not related to the person or process involved since it addresses more objective judgments. Regarding assumptions, the CAT specifies that appropriate judges are needed to correctly assess creativity. In addition, creativity can be recognized but not characterizable, people can agree on perception of creativity and various levels of creativity exist. The CPSS assumes that creativity is partially objective. However, both tools have also weaknesses (Horn 2005). The CAT is time consuming, is not appropriate for individual differences, and factors can be highly correlated. The CPSS is an instrument that doesn't define creativity, lacks of criteria to assess creativity and in defining the constructs to measure creativity is more subjective than objective and may cause bias (Horn 2005). As a result, the CPSS and the CAT are methods that are limited in its application and utility to measure creativity. Therefore, for the purpose of this study, the creativity measurement instrument developed by Horn 2005 will be used as a basis to develop an instrument to measure sustainability in products.

The concepts of sustainability in products and creativity in products share some common features. Sustainability is still a concept without an accepted definition; there is no simple way of how to neither define nor develop sustainable products. Furthermore, sustainability in products can be subjective even if products have markings since there is no methodology that is sufficiently science-based, but that also contains an amount of subjective aspects. In order to understand information on sustainable products and reveal a more valid and predictive measure of sustainability, this study will test and develop an instrument to measure sustainability. Through images and decision-maker's information and knowledge, the instrument attempts not only to capture general perceptions of sustainability but also attempts to include measurement dimensions to capture decision-maker's assessment of sustainability. The potential impact of product sustainability in decision making will be seen and evaluated through the sustainability measurement instrument as it will be demonstrated how decision maker's perspectives need to be incorporated in the decision-making process to enhance the value of the decision making process. Additionally, the most representative variables that define sustainability are determined as well as their overall importance in sustainability perceptions.

CHAPTER 4
CONCEPTUAL MODEL

4.1 Framework

Based on previous research by Horn (2005), three major assumptions are taken for this study. First, product sustainability is a subjective assessment that a person asserts towards an object. Secondly, a universal set of criteria for the judgment of product sustainability exists and the assessment of each criterion determines the overall level of product sustainability. The judgment that a product is not sustainable occurs if the product does not exhibit one or more of the criterion. A sustainable product exhibits high levels on each criterion. Therefore, to maximize product sustainability would be to maximize the assessment of all criterion levels. Judgment of the criterion levels is dependent on the judge's experience, understanding and past involvement with the product, the context in which the product is judged and the context in which the product may be used. Finally, the set of criterion used to assess product sustainability is not assumed to be a required part of the overall product evaluation. Product sustainability may or may not be a criterion for product selection, but when sustainability is considered to be a criterion, the assessment has a neutral to positive influence on the overall product evaluation.

This study specifically addresses the visual inspection of consumer products in relation to the evaluation of product sustainability, from two-dimensional images as compared to evaluating three-dimensional products through physical interaction with the product. As a result, the comprehension of product sustainability is limited to the decision-maker's experience with the product functions and understanding of the functionality from visual perception of the product. The evaluation of sustainability is also limited by the decision-maker's understanding of the product form from visual perception. Therefore, the evaluation of product sustainability in this study is constrained to the visual comprehension of product form and function.

4.2 Model description

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 (2005). 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. For the purpose of this study, a sustainable product is defined as a product made using processes and systems that are non-polluting, that conserve energy and natural resources, in economically viable, safe and healthy ways for consumers and which are 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 and one additional dimension to measure purchase intentions (see Table 4.1).

The quality dimension measures the product's capability to satisfy decision maker's requirements through a prolonged life. The functionality dimension measures the usefulness of sustainable materials. The user appeal dimension measures the arousal impact of the product sustainability. The resourcefulness dimension measures the product characteristics associated with sustainability. Finally, the purchasability dimension measures the purchase intentions (see Table 4.2).

Table 4.1. Definition of Sustainability Dimensions

Dimension	Definition
Quality	The product’s capability to satisfy requirements through a prolonged
Functionality	The product’s usefulness
User appeal	The response that sustainable products elicit
Resourcefulness	The preference for sustainable characteristics
Purchasability	The product’s capability to impact purchase intentions

The first dimension considers sustainability in terms of the capability of the product to last for a prolonged period of time. Additionally, it considers a product that has a good process performance and to require throughout its life cycle a low reparability (time between repairs is high). This dimension may be explained by definitions found in the literature associated with the quality of the product. Thus, the quality dimension is associated with a product that is easy to build with and its low reparable and has a highly prolonged life (Ljungberg 2007, Mora 2007, Dammann and Elle 2006). The second dimension considers sustainability in terms of the product’s usefulness. This dimension may be explained by definitions found in the literature associated with the functionality of the product. Thus, the functionality dimension is associated with a product that the public needs and that it’s safe to use (Zhou 2009, Mora 2007, Ljungberg 2007). The third dimension considers the response that sustainable products elicit due to interaction. This dimension may be explained by definitions found in the literature associated with the appeal of the product. Thus, the user appeal dimension is associated with a product that is socially and creatively awarding, that it’s available in a continuing renewing manner and that it’s highly satisfying to the user (Glavic and Lukman 2007, Ljungberg 2007). The fourth dimension considers to what extent a decision maker will prefer a sustainable product over a common product.

Table 4.2. Sustainability Dimensions

Dimension	Key content definition	Reference
Quality	Easy to build with	Dammann and Elle 2006
	Low reparable and highly prolonged life	Ljungberg 2007, Mora 2007 2007
	Good process performance	Zhou 2009
Functionality	Something the public needs	Glavic and Lukman 2007
	Safe to use	Zhou 2009, Mora 2007, Ljungberg 2007
User appeal	Socially and creatively awarding	Glavic and Lukman 2007
	Available in a continuing renewing manner	Glavic and Lukman 2007
	Highly satisfying to the user	Ljungberg 2007
Resourcefulness	Low consuming	Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009
	Do more with less	Glavic and Lukman 2007, Zhou 2009
	Trend braking	Ljungberg 2007
	Low environmental pollution	Zhou 2009
Purchasability	Gives much satisfaction as possible to the user to be successful in the market	Ljungberg 2007

This dimension may be explained by definitions found in the literature associated with properties of the product such as processes that make it environmentally friendly. Thus, the resourcefulness dimension is associated with a product that is low consuming, that can do more with less, gives low environmental pollution and that its trend breaking (Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009, Ljungberg 2007).

Finally, the purchasability dimension considers to what extent a decision maker will actually consider purchasing a sustainable product and will be willing to pay for it when facing the product comparison process. Thus, the purchasability dimension is associated with the product's success in the market (Ljungber 2007).

As a result, the construct of product sustainability will be broken down into five dimensions: quality, functionality, user appeal, resourcefulness, and purchasability. The influence of these dimensions in the evaluation of product sustainability will be explained by understanding the perception of the dimensions and then the expectations of the dimensions. In addition, this study will also tempt to evaluate the impact on decision maker's attitudes and the role in information processing of product sustainability evaluation.

4.3 Information processing of sustainability assessment

The process of assessment of sustainability can be explained by reviewing the model of information processing. This model provides a structure to develop the structure of the information processing of sustainability in products. The proposed model to show how decision makers evaluate sustainability is presented in Figure 4.1 (Horn 2005). The model shows the process of how decision makers comprehend information about a sustainable product and then compare the information given to previous criterion on sustainability they possess from experience and contact with the product. After comparing the information to the previous criteria, decision makers are then able to determine the level of sustainability of a product. Furthermore, decision makers are also able to use the information given to make an evaluation of sustainability.

The process of assessing sustainability follows a number of steps. The first step is the interaction between the decision maker, the product and the context. After the interaction, the process breaks down into the sensation, perception and cognition, and response stages. The first stage constitutes the sensation between the decision maker, the product and the context. The decision maker senses the interaction with both external sensors such as eyes, ears, nose, mouth and skin and internal sensors that measure the state of the blood (Horn 2005).

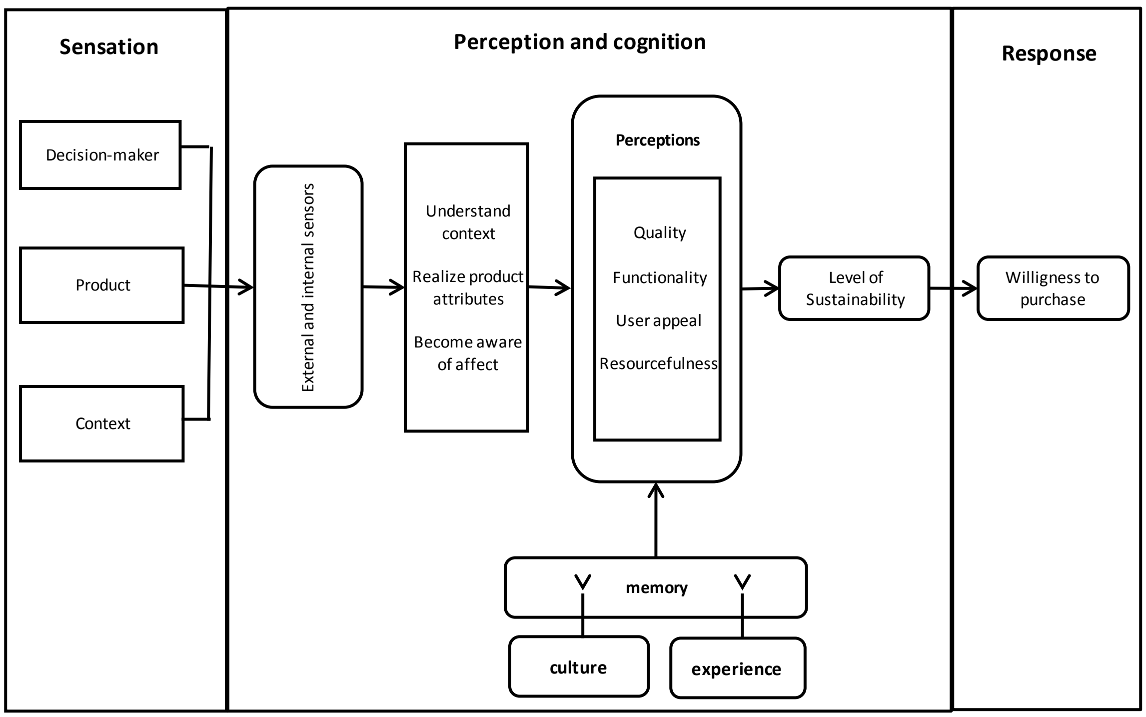

Figure 4.1. Information Processing Model of Product Sustainability Assessment

The second stage is the cognition and perception stage. In this stage, the decision maker understands and compares the information from the first stage. The sensations from the interactions between the decision maker, the product and the context help the decision maker understand and perceive the status of the product, the context and him. After recognizing the system components, the decision maker starts to understand the components. Thus, realizing the status of the context, the product and him leads the decision maker to become aware of the context, the product attributes and awareness of emotional impact. The understanding of these three components become general assessments from the interaction and not specific to any type of evaluation.

The assessment of product sustainability involves making a comparison of the general assessment from the interaction against a series of criteria (Horn 2005). The criteria are the dimensions of sustainability and constitute a series of guidelines that each decision maker possesses. These guidelines are influenced by the decision maker's experience and culture. The assessment process is the perception of the level of sustainability through each of the dimensions by comparing the general understanding of the context, product attributes, and the affect from interaction with each of the criterion.

The final stage of the process is the response to the product sustainability. The sustainable characteristics of a product might influence the decision maker's attitudes but other factors such as purchase intentions might also affect the attitudes. As a result, the process constitutes a series of steps in which the decision maker compares general product assessment with a specific set of sustainability criterion to assess and evaluate sustainability.

CHAPTER 5
METHODOLOGY

5.1 Instrument Structure

Numerous methods for gathering user data have been developed such as interviews, feedback, databases, scenarios, protocol analysis and questionnaires (Horn and Salvendy 2006). Selection of the method depends on the type of information and the perspective of the decision maker. According to the purpose of this study, protocol analysis and questionnaire are two methods that can be used to capture the information needed (Horn 2005). Protocol analysis can capture all the dimensions of the phenomenon investigated, but its very time consuming for the researcher and the subject. Therefore, a questionnaire was used to capture the information. Once the decision maker's perspectives have been captured, the analysis of the information produces knowledge for understanding concepts.

In order to test the five-dimensional instrument and to better understand the factors that could influence product sustainability perceptions, a web-based survey was conducted. The use of the survey questionnaire was an approach to capture all the dimensions of product sustainability (Horn and Salvendy 2006). The results were intended to reveal whether the sustainability perception of design and construction students and practitioners was dependent on the selected variables.

Previous to these evaluations, the first draft of the survey was reviewed and a pilot survey was performed by fourteen graduate students in the Building Construction program. Based on the results and findings of the pilot study, the adjective pairs were revised, the specific material for the survey was selected and the survey was finalized for data collection. One type of construction product was selected for evaluation: bricks.

This product was chosen based on the commonality and high usability in the construction industry.

The survey presented a brief definition of sustainable products and a two-dimensional image of a specific construction product. An e-mail was sent to each prospective subject requesting their participation. When the subject opened the Web-based survey (Survey Monkey 2009) by clicking on the link in the e-mail, a brief written introduction and instructions that asked for completion of the measurement instrument was given. The Web-based survey was available for three weeks between September and October of 2009. The survey instrument was composed of two sub-categories. The first sub-category presented the adjective pairs to measure sustainability perceptions, and the second asked about interviewee experience, contact with sustainable materials and interviewee's demographic information.

In the first sub-category, 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 described the specific product shown on the screen. 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 5.1.

For instance, the three item pairs for resourcefulness dimension are resourceful-wasteful, efficient-inefficient and innovative-common. One question asked respondents if the product of the image is inefficient or efficient on the 7-point Likert scale (1=extremely inefficient, 2=inefficient, 3=slightly inefficient, 4= neither inefficient nor efficient, 5=slightly efficient, 6=efficient, 7=extremely efficient). The other dimensions are tested in a similar manner (see Table 5.1 and Figure 5.1). Approximately half of the measurement items were reversed to reduce response bias and two questions were repeated to measure data reliability.

Table 5.1. Sustainability Measurement Instrument

Sustainability dimension	Item	Product sustainability measurement item
Quality	*P1*	ordinary-extraordinary
	P2	unreliable-reliable
	P3	temporary-durable
Functionality	*P4*	unusable-functional
	P5	impractical-useful
	P6	worthless-helpful
User appeal	*P7*	unattractive-attractive
	P8	detrimental-beneficial
	P9	disappointed-satisfied
Resourcefulness	*P10*	wasteful-resourceful
	P11	inefficient-efficient
	P12	common-innovative
Purchasability	*P13*	not willing to pay for it-willing to pay for it
	P14	not want to purchase it-want to purchase it

In the second sub-category, the subjects were asked if they had ever used a sustainable material, if they had been looking for a sustainable material, and how much more were they were willing to pay for a sustainable material. Additionally, the subject was asked about educational level, experience in the construction industry, type of work performed in construction, age, and gender. The subjects' responses to questions in the two sub-categories were automatically stored anonymously in a database when each subject clicked the "submit" button. After collecting the responses to the survey, the instrument of decision maker's perception of product sustainability can be refined and the number of dimensions of product sustainability can be determined. Once the instrument has been reduced, a product sustainability score can be given to materials to account for product sustainability perceptions and the overall weighting of importance of subjective characteristics.

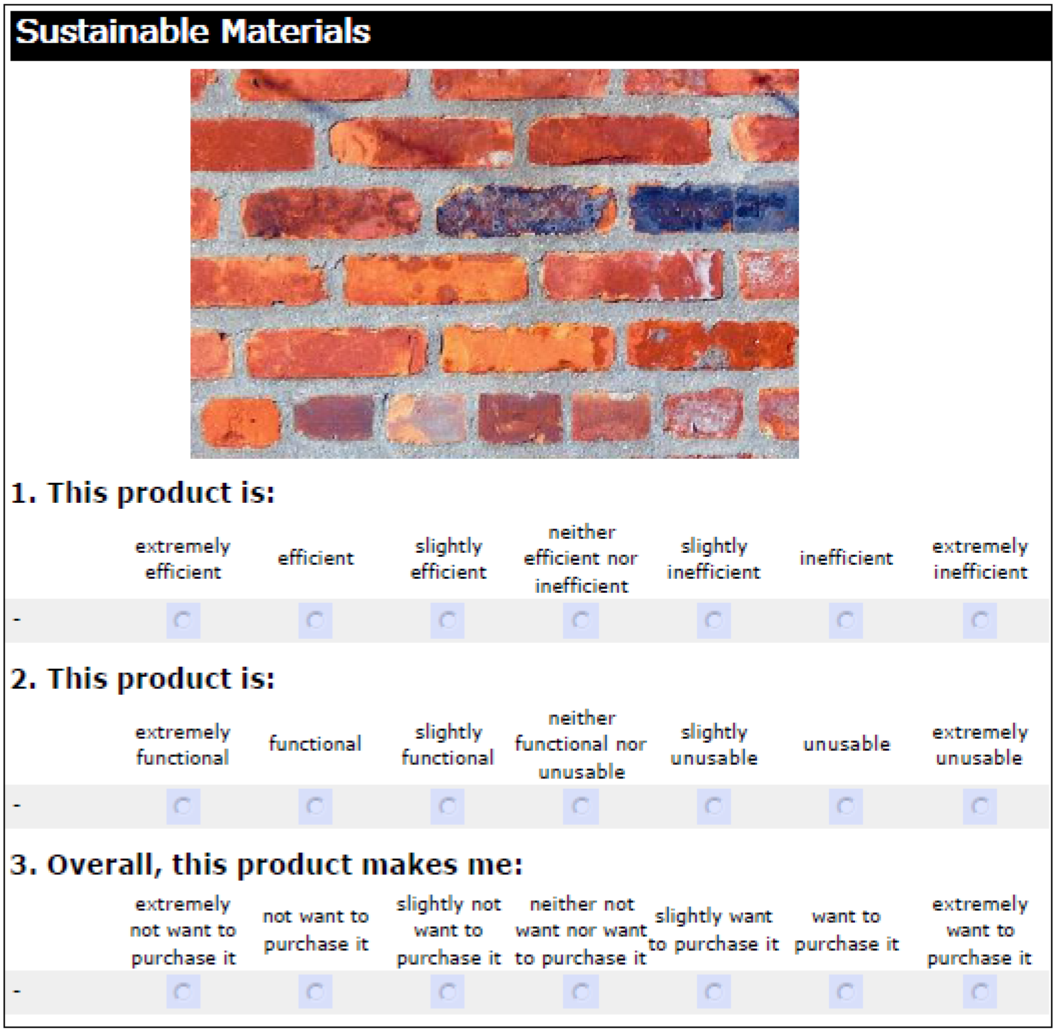

Figure 5.1. Screenshot of Survey Regarding Sustainable Items

5.2 Descriptive Statistics and Analysis

The web-based survey was sent to design and construction students and practitioners since the goal of the survey was to learn about the attitudes of construction professionals toward sustainability. The target population was selected based on their knowledge and involvement in the construction industry. The Web site presented a two-dimensional image of the specific product. The subjects were asked to evaluate the overall sustainability of the product and mark a sustainability score on the 7-point Likert scale. A total of 103 surveys were completed. The survey was sent to approximately 1190 students in Building Construction and Architecture all levels (Georgia Tech 2009).

Information on important characteristics was obtained from the survey data such as age, gender, highest level of education, experience in construction, type of work performed, usage of sustainable materials, accessibility and willingness to pay for sustainable materials. The information obtained can increase the understanding of issues affecting knowledge in product sustainability and professional awareness of sustainable materials. Learning about these issues can contribute to increase the accessibility to data sources of sustainable materials and highlight its benefits to the construction industry increasing purchase intentions of sustainable materials.

The minimum age of respondents was 18 years of age, 71% had age between 20 to 30 years, and the mean age was 26 years. Of the total number of subjects 53.9% were female and 46.1% were male. When asked about the highest level of education obtained, 71.9% responded to have at least an undergraduate degree. The experience in construction of respondents ranged from 1 to 20 years with a mean of 2.8 years. Approximately fifty-five percent (54.7%) of the respondents indicated that their work is related to architecture and design, 11.6% related to contracting business and 8.1% related to engineering. In relation to sustainability issues, the data shows that 47.2% of the respondents have used or have built a building using a sustainable material, 40.4% have been looking for sustainable materials unavailable in their region while 59.6% have looked for sustainable materials and found them in their region. Additionally, only 9% of the respondents are not willing to pay more for a sustainable material in comparison to a common material. Of the other respondents, 50% are willing to pay 20% more for a sustainable material and 42% are willing to pay 40% or more for a sustainable material.

Once all the information on important characteristics was retrieved from the survey data, descriptive statistics and statistical analysis was performed. Descriptive statistics of the data are provided in Table 5.2. The highest mean is for the independent variable *temporary-durable (=6.1)* indicating that respondents tend to assume that sustainable materials last for a long period of time by looking at the picture. This agrees with previous studies that define sustainable materials as materials that require low reparations and have a highly prolonged lifetime, reducing the impact on the environment. In addition, the variables *impractical-useful* and *unreliable-reliable* were emphasized by the respondents indicating that they also assume sustainable materials are useful and reliable. The lowest mean is for the independent variable *common-innovative (=1.5)*, indicating only a low agreement that respondents assume sustainable materials are common.

Table 5.2. Descriptive Statistics of Independent Variables

Item	Sustainability item	min	max	mean	std. dev	skewness	kurtosis
P1	*ordinary-extraordinary*	1	6	2.7	1.33	0.8	-0.2
P2	*unreliable-reliable*	2	7	6.0	0.85	-1.9	6.0
P3	*temporary-durable*	3	7	6.1	0.76	-1.0	2.3
P4	*unusable-functional*	1	7	5.8	0.99	-1.9	5.4
P5	*impractical-useful*	1	7	6.0	1.08	-2.4	7.5
P6	*worthless-helpful*	3	7	5.7	0.97	-0.9	0.8
P7	*unattractive-attractive*	1	7	5.2	1.25	-1.2	1.3
P8	*detrimental-beneficial*	3	7	5.6	0.72	-1.5	2.4
P9	*disappointed-satisfied*	3	7	5.2	1.06	-0.6	-0.9
P10	*wasteful-resourceful*	1	6	4.5	1.31	-0.6	-0.3
P11	*inefficient-efficient*	1	7	5.2	1.18	-1.7	3.3
P12	*common-innovative*	1	7	1.5	1.00	3.7	15.7
P13	*not willing to pay for it-willing to pay for it*	2	7	5.2	1.11	-0.8	0.1
P14	*not want to purchase it-want to purchase it*	2	7	5.0	1.11	-0.5	-0.9

For instance, it was found that the independent variables *disappointed-satisfied (=-0.6), wasteful-resourceful (=-0.6) and not want to purchase it-want to purchase it (=-0.5)* have the highest symmetry compared to the other variables as indicated by the skewness statistic (Gorsuch 1983). In other words, data are symmetric about the mean. The mass of the distribution is concentrated on the right for the variable *impractical-useful (=-2.4)* meaning it has relatively few low values. The variable *common-innovative (=3.7)* has relatively high values (Gorsuch 1983). Furthermore, the descriptive statistics results (kurtosis statistic) show that more of the variance for the variables *common-innovative* and *worthless-helpful* is due to infrequent extreme deviations as opposed to frequent moderately sized deviations (Gorsuch 1983). In addition, the correlation between the variables is shown in Table 5.3.

Table 5.3. Correlation Matrix of Independent Variables

	P1	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*	*P11*	*P12*	*P13*	*P14*
P1	1.00	0.02	0.24	0.03	0.13	0.22	0.28	0.14	0.28	0.18	0.17	0.27	0.34	0.28
P2	0.02	1.00	0.38	0.30	0.49	0.43	0.19	0.53	0.28	0.19	0.49	0.06	0.34	0.24
P3	0.24	0.38	1.00	0.12	0.18	0.33	0.30	0.31	0.27	0.25	0.27	0.20	0.31	0.28
P4	0.03	0.30	0.12	1.00	0.36	0.35	0.07	0.45	0.17	0.17	0.49	0.07	0.20	0.19
P5	0.13	0.49	0.18	0.36	1.00	0.44	0.02	0.44	0.26	0.18	0.48	0.02	0.28	0.25
P6	0.22	0.43	0.33	0.35	0.44	1.00	0.23	0.64	0.48	0.19	0.44	0.17	0.46	0.36
P7	0.28	0.19	0.30	0.07	0.02	0.23	1.00	0.26	0.49	0.00	0.10	0.10	0.64	0.53
P8	0.14	0.53	0.31	0.45	0.44	0.64	0.26	1.00	0.44	0.33	0.53	0.14	0.36	0.38
P9	0.28	0.28	0.27	0.17	0.26	0.48	0.49	0.44	1.00	0.13	0.28	0.16	0.73	0.59
P10	0.18	0.19	0.25	0.17	0.18	0.19	0.00	0.33	0.13	1.00	0.44	0.22	0.08	0.19
P11	0.17	0.49	0.27	0.49	0.48	0.44	0.10	0.53	0.28	0.44	1.00	0.15	0.27	0.30
P12	0.27	0.06	0.20	0.07	0.19	0.17	0.10	0.14	0.16	0.22	0.15	1.00	0.16	0.25
P13	0.34	0.34	0.31	0.20	0.28	0.46	0.64	0.36	0.73	0.08	0.27	0.16	1.00	0.67
P14	0.28	0.24	0.28	0.19	0.25	0.36	0.53	0.38	0.59	0.19	0.30	0.25	0.67	1.00

Even though the 14 independent variables in the study contain all the sustainability perceptions information and explain all the variance of the sample, some of the variables may have qualitative and quantitative distinctions. Therefore, an analysis that tests the qualitative distinctions and groups variables into factors to determine the dimensions of product sustainability is undertaken.

5.3 Sustainability Measurement Instrument Refinement

The refinement of the product sustainability instrument would be conducted across different studies (Horn and Salvendy 2009). With this initial study, the model of consumer perception of product sustainability was developed. The model includes the selection of the measurement instruments and the initial structure of the product sustainability perceptions measurement instrument. As indicated by the analysis of the collected data perceptions measures, the instrument has to be evaluated and refined. Therefore, a subsequent study will be performed to reduce the number of dimensions and refine the instrument. The first step of refinement will be to verify the appropriateness and stability of the instrument. The second step of refinement will be to purify the instrument by eliminating items in the construct of sustainability. In addition to the refinement of the product sustainability perceptions instrument, the instrument's consistency will be examined. The consistency will be tested in order to determine whether the items that load on each of the dimensions are measuring the same construct (Horn and Salvendy 2006).

With this model of product sustainability and validated instrument, both researchers and practitioners can begin to investigate how various methods, environmental factors, individual or group characteristics, and other variables may influence consumer product sustainability perceptions. Material suppliers can also use this dimensional model to incorporate design considerations, comparisons, and overall evaluations. With the understanding that consumer product sustainability is perceived in the product's level of the instrument's dimensions, suppliers can concentrate on designing these specific product qualities to enhance consumer satisfaction and purchase intentions.

To determine the dimensions of product sustainability an exploratory factor analysis was performed. All data analysis was performed using Statistical Package for the Social Sciences SPSS version 17.0 (2007). First, a reliability analysis was performed on a small sample (n=30) with the 16 variables used in the instrument. That is, the 14 adjective pairs and the 2 additional pairs that were repeated for data reliability. This analysis showed there is consistency in the measuring instrument as stated by the Cronbach alpha statistic (α=81.7). Additionally, the correlation matrix showed a high correlation between the adjective pairs that were repeated *unattractive-attractive* (0.62) and *ordinary-extraordinary* (0.80) suggesting correspondence between the variables.

After confirming the consistency of the instrument, an exploratory factor analysis was performed. This analysis was performed to determine the dimensions of material sustainability that were truly meaningful and worthy of being retained for interpretation. In other words, this analysis was intended to cluster the fourteen variables into factors and test if the initial number of sustainability dimensions was appropriate. Furthermore, the analysis determined the variables that made up each of the factors retained. Initially, the five factors (quality, functionality, user appeal, resourcefulness, and purchasability) considered in the instrument were tested. To determine the appropriate number of meaningful factors, four criteria were used (PCA 2007).

The eigen-value one criterion or Kraiser criterion states that those factors with an eigen-value greater than 1.00 should be interpreted and retained. Any factor that displays an eigen-value greater than one is accounting for a greater amount of variance than had been contributing by one variable. The five factors considered accounted for a total variance of 69%. However, two of the factors had eigenvalues smaller than one indicating an inappropriate number of factors or dimensions (Gorsuch 1983, Horn 2005). Furthermore, the factor structure examined with the Scree test shows a smooth decrease in the slope after four factors (see Figure 5.2).

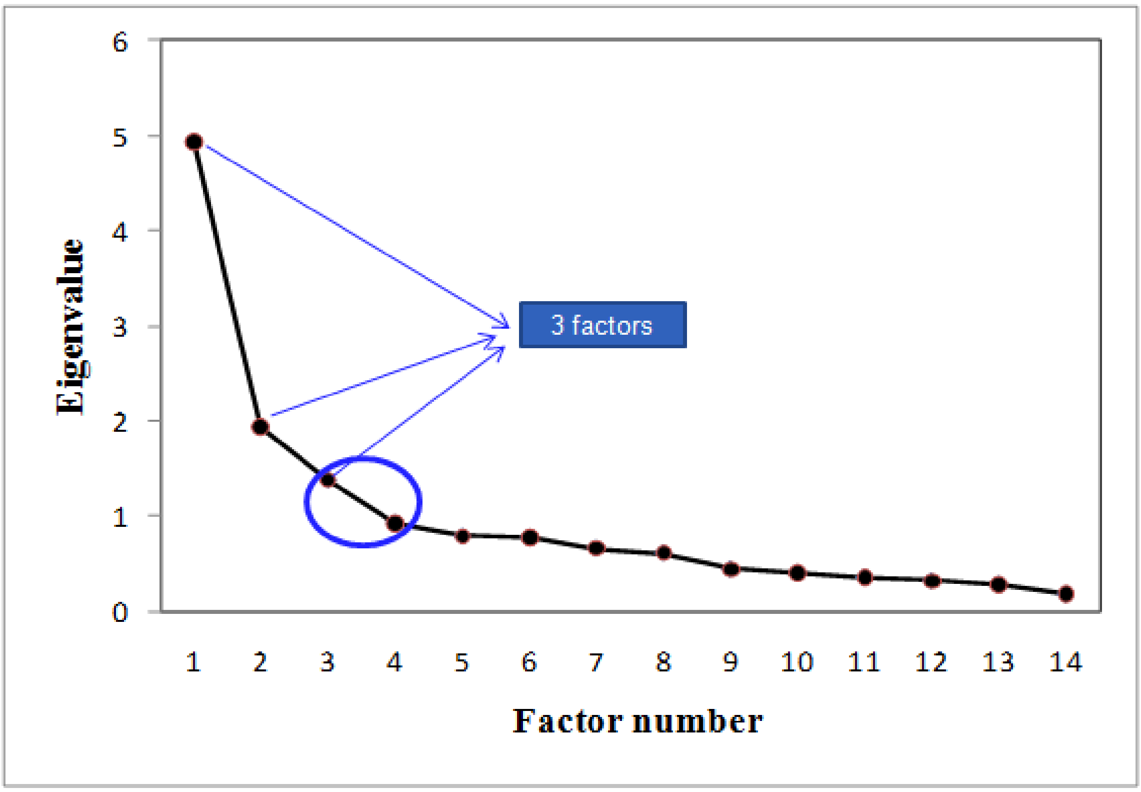

Figure 5.2. Scree Plot

Factors that appear before the slope "break" are assumed to be meaningful and are retained for rotation. Therefore, the three-factor structure is also confirmed by the Scree test criterion. The third criterion is the proportion of variance accounted for each component. The first three components account for a total proportion of variance of 56%, but the proportion of variance accounted by each of the fourth to fourteenth factors is less than 10% (see Table 5.4).

Table 5.4. Rotation Sum of Square Loadings

Factor	Total	% of variance	Cumulative %
1	3.251	23.22	23.22
2	2.872	20.51	43.73
3	1.709	12.21	55.94
4	0.940	6.72	62.66
5	0.844	6.03	68.68
6	0.782	5.59	74.27
7	0.704	5.03	79.30
8	0.618	4.42	83.72
9	0.509	3.64	87.35
10	0.478	3.41	90.76
11	0.402	2.87	93.64
12	0.382	2.73	96.36
13	0.309	2.20	98.57
14	0.200	1.43	100.00

Finally, the interpretability criteria were used. The three factors retained are measured by at least three variables and the rotated factor pattern demonstrates simple structure (PCA 2007). In other words, most of the variables have relatively high loadings on only one factor and each of the variables that load on one factor seem to be measuring a construct that is conceptually different from the construct measured by the variables loading a different factor (see Table 5.5). However, there were some variables that had insignificant factor loadings (see Table 5.6) and needed to be removed from the factor structure. Therefore, a refinement of the product sustainability instrument had to be conducted. Variables with insignificant loadings were removed and three factors which seemed to be the appropriate number according to the four criteria were tested (De Winter et al. 2009).

Table 5.5. Rotated Component Matrix

Item	Sustainability items	Factor 1	Factor 2	Factor 3
1	*ordinary-extraordinary*	0.325	-0.045	0.649
2	*unreliable-reliable*	0.374	0.598	-0.395
3	*temporary-durable*	0.419	0.252	0.046
4	*unusable-functional*	0.028	0.722	0.088
5	*impractical-useful*	0.238	0.677	-0.047
6	*worthless-helpful*	0.432	0.511	0.071
7	*unattractive-attractive*	0.817	-0.021	-0.195
8	*detrimental-beneficial*	0.349	0.640	0.094
9	*disappointed-satisfied*	0.752	0.202	0.154
10	*wasteful-resourceful*	-0.056	0.424	0.557
11	*inefficient-efficient*	0.045	0.704	0.240
12	*common-innovative*	0.030	0.065	0.756
13	*not willing to pay for it-willing to pay for it*	0.862	0.211	0.093
14	*not want to purchase it-want to purchase it*	0.695	0.182	0.311

Table 5.6. Component Score Coefficient Matrix

Item	Sustainability items	Factor 1	Factor 2	Factor 3
1	*ordinary-extraordinary*	0.108	-0.127	0.388
2	*unreliable-reliable*	0.054	0.229	-0.302
3	*temporary-durable*	0.116	0.033	-0.008
4	*unusable-functional*	-0.125	0.312	0.000
5	*impractical-useful*	-0.029	0.263	-0.088
6	*worthless-helpful*	0.072	0.145	-0.013
7	*unattractive-attractive*	0.332	-0.145	-0.153
8	*detrimental-beneficial*	0.015	0.216	-0.004
9	*disappointed-satisfied*	0.250	-0.058	0.048
10	*wasteful-resourceful*	-0.123	0.159	0.313
11	*inefficient-efficient*	-0.122	0.290	0.094
12	*common-innovative*	-0.032	-0.032	0.458
13	*not willing to pay for it-willing to pay for it*	0.295	-0.070	0.005
14	*not want to purchase it-want to purchase it*	0.225	-0.069	0.148

5.4 Refined Sustainability Measurement Instrument

Combined, the three factors accounted for 64.3% of the total variance (see Table 5.7), which although it is not considered to be high, it is comparable to other studies involving factor analysis. Lapierre and Giroux (2003) tested a six-dimensional model of creativity work environment explaining 66.9% of the total variance. Another study by Aguilar-Alonso (1996) explained 61.2% of the variance with an eight dimensional model of creative behavior. Han Ahn et al. (2008) tested a four-dimensional model of key competencies for US construction graduates explaining 64% of the total variance. Horn (2005) tested a three-dimensional model of creativity explaining a total of 64.8% of the variance. Furthermore, this analysis showed there is consistency in the measuring instrument as stated by the Cronbach alpha statistic (α=79.3).

Table 5.7. Rotation Sum of Square Loadings

Factor	Total	% of variance	Cumulative %
1	2.269	25.206	25.206
2	1.971	21.904	47.110
3	1.547	17.188	64.298
4	0.813	9.034	73.332
5	0.748	8.310	81.642
6	0.546	6.069	87.711
7	0.470	5.222	92.933
8	0.420	4.668	97.600
9	0.216	2.400	100.00

In interpreting the rotated factor pattern, an item was said to load on a given factor if the loading was approximately 0.35 or greater for that factor, and was less than 0.35 for the other factors (see Table 5.8). Using these criteria, three items were found to load the first factor (*unattractive-attractive, not willing to pay for it-willing to pay for it, and* *disappointed-satisfied*). Since two of the items were related to the user appeal dimension determined in the sustainability instrument, this factor was labeled user appeal. Three items also loaded the second factor *(impractical-useful, inefficient-efficient, unusable-functional*) which was labeled functionality given that two items were related to the functionality dimension. Finally, the third factor was also loaded by three factors (*common-innovative, wasteful-resourceful*, *ordinary-extraordinary* and was labeled resourcefulness.

Table 5.8. Component Score Coefficient Matrix

Sustainability items	Factor 1	Factor 2	Factor 3
common-innovative	-0.066	-0.088	0.548
unattractive-attractive	0.416	-0.097	-0.141
impractical-useful	0.046	0.374	-0.144
not willing to pay for it–willing to pay for it	0.336	-0.011	0.057
inefficient-efficient	-0.072	0.405	0.037
unusable-functional	-0.075	0.447	-0.109
wasteful-resourceful	-0.127	0.169	0.336
ordinary-extraordinary	0.127	-0.169	0.477
disappointed-satisfied	0.380	-0.004	0.021

As a result, a factor is defined as a linear combination of optimally-weighted observed items. The weight is optimal since no other set of weights could produce a set of components that are more successful in accounting for variance in the observed items. For instance, the subject's score on the sustainability items retained by the instrument are weighted and then summed to compute the score on a given factor. The total subject's score on the sustainability factors may then obtained by adding the scores on the three factors encountered in the analysis. Now, with the score on sustainability the application of the optimization model will proceed.

CHAPTER 6

MATERIALS SELECTION WITH SUBJECTIVE FACTORS

6.1 Optimization framework

The optimization framework shown in Figure 6.1 supports the decision maker in the complex process of material selection. The objective 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 objective 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 masonry system are brick1, brick2, and brick3. The designer knows that at least 20% of the masonry units, but no more than 40%, must be built using brick1; a half of the system must be built using brick2; and at least 20% but no more than 30% of the system must be built using either brick 3. The subjective data input module includes the decision maker's score on sustainability items. The score was determined with the instrument of decision maker's perception of product sustainability illustrated in Chapter 5. 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 the instrument can be assessed to help capture decision maker's preferences. In this case, the optimization model selects the right type of bricks while meeting the designer criteria and satisfying the minimum sustainability score.

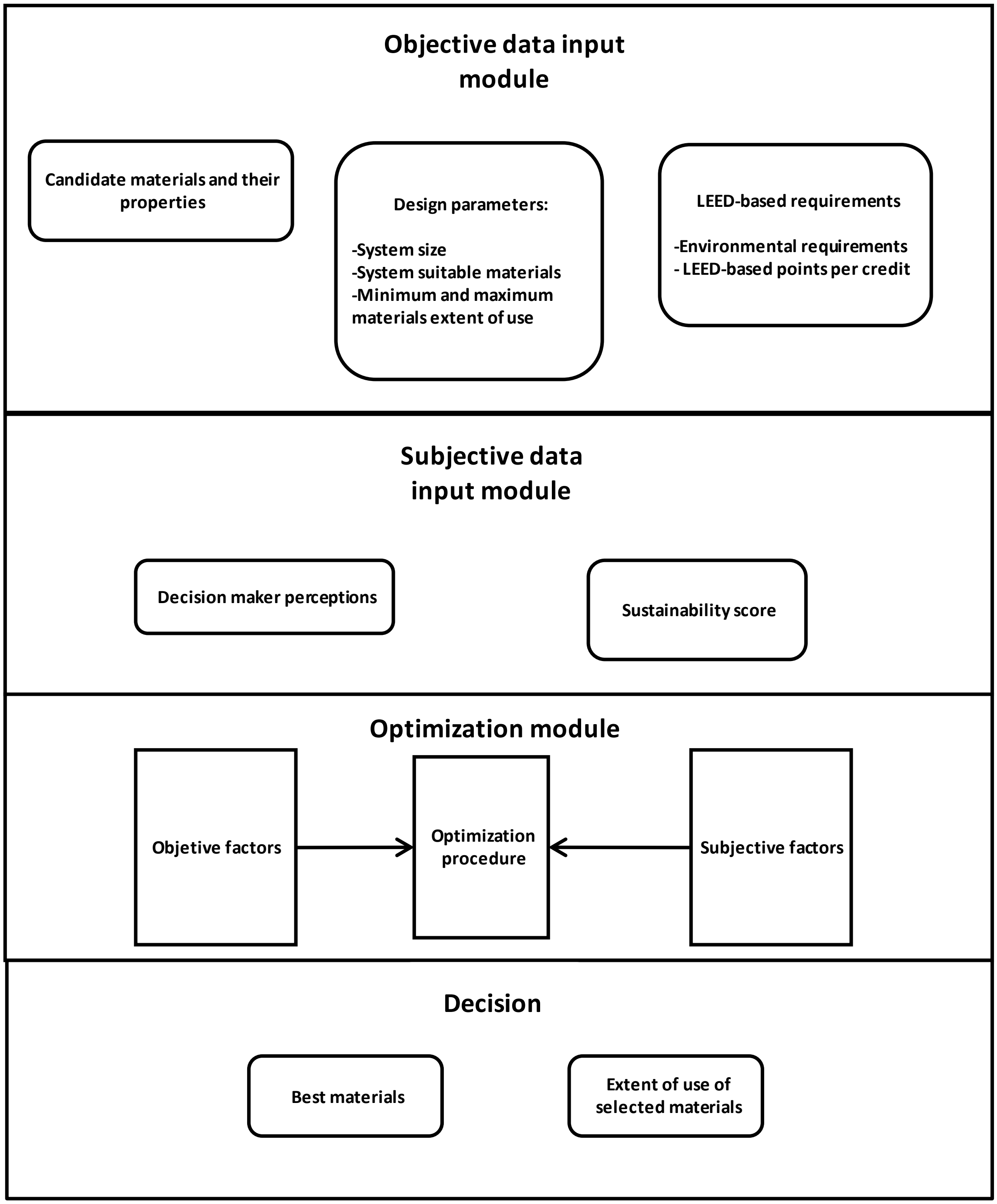

Figure 6.1. Optimization Framework

6.2 A Numerical Example Based on a Case Study

To illustrate the operation of the modified model a case study of an office building construction project is discussed. Notice that the model used to attempt to optimize sustainability is the modified version discussed in Chapter 2. The case study is based on the application of the model in an eleven-story office building with an area of 6,000 m^2. The estimated total budget for masonry materials is about USD 18,000. A system is considered: 1) masonry used in the building façade and interior walls.

6.3 Data Sources

The environmental properties required by the modified LEED-based system are mainly obtained using Building for Environmental and Economic Sustainability software BEES (NIST, 2010). Although BEES is not the only source available in the literature, it provides reliable information for a wide range of construction materials. However, some of the materials available in the US market, as well as some material properties required by the LEED system (USGBC 2010), are not included in BEES. Thus, companies' databases are also used to complement the main data source.

The information regarding systems and materials is shown in Table 6.1. The recycled content for bricks is obtained from BEES software and suppliers. Information regarding regional materials comes directly from the suppliers. Finally, the cost per unit of dimension for each material is obtained from RSMeans.

Table 6.1. System and Materials Information

System (j)	d_j	Material (i)	l_{nj}	u_{nj}	c_i (USD)	r_i	e_i	v_i	v_i^u	h_i	f_i	m_i	s_i
Masonry	39,668 (units)	*Brick 1*	0%	100%	0.45	90%	0	-	-	-	-	-	-
		Brick 2			0.33	75%	1	-	-	-	-	-	-
		Brick 3			0.50	90%	0	-	-	-	-	-	-

6.4 Optimal selection of materials

Table 6.2 shows the results of the model, where the column labeled x_{ij} indicates the fraction of the systems to be built from the selected materials. For instance, to build the masonry system, the model suggests the use of 27% of brick 2, and 73% of brick 3. Although these results show the fraction of the system that should be built using a specific material, they can also be used to quantify the required amount of each material. For instance, the model suggests purchasing 10,710 units of brick 2 and 28.958 units of brick 3. Furthermore, the results provided by the model can also be used to obtain a detailed purchase plan. As shown, Table 6.2, once the costs of all the materials are estimated, the total cost is USD 17,981.

Table 6.2. Materials Required in the Optimal Solution

System	Material	x_{ij}	Quantity	Cost
Masonry (units)	*brick 2*	27%	10,710	3,534
	brick 3	73%	28,958	14,447
			Total cost	17,981

Although the solution shown in Table 6.2 satisfies budget, design constraints, and 4 out of the 11 LEED-based constraints it does not include sustainability perceptions that might change the optimal selection of materials. In other words, the solution awards 4 out of the 11 points available, but does not account for subjective factors that arise in the decision making process. This number of awarded points may be a first step to obtain a green certification, but may fail to account for practitioner's perceptions. Therefore a further analysis to determine an optimal solution that awards the same number of LEED points and includes subjective factors will add value to the decision-making process.

As stated in the literature, subjective factors may modify the optimal selection of materials to achieve sustainability goals (Ljungberg 2007). Failure to include subjective factors may not allow the model to select more convenient materials to satisfy LEED-based constraints and decision maker's perceptions. To demonstrate that decision making might change when objective as well as subjective factors are included, the model presented in Chapter 2 Section 2.5 is used. The minimum desired sustainability score denoted by δ was computed by adding the scores on the three factors encountered. The scores for the items were supposed 4, which is the mean score for on an item to be perceived as sustainable.

Table 6.3. Materials Required in the LEED and Perceptions Model

System	Material	x_{ij}	Quantity	Cost
Masonry (units)	*brick 2*	100%	39,668	13,090
			Total cost	13,090

The amount required of each material is shown in Table 6.3. Note that this solution differs widely from that suggested in Table 6.2. The use of only brick2 to build the masonry system, awards the same number of LEED points, requires less budget, and complies with the minimum sustainability score.

It is worthwhile to note that objective as well as subjective factors play a role in the optimal selection of sustainable materials. Material constraints can restrict the capacity of the model to award points, limiting its choice of alternative. In the case in point, if none of the available bricks materials is in the region, then credit 5 from the materials and resources area will be impossible to comply with. Design constraints can also affect the number of awarded points. To illustrate this case, if the design constraints reduce the solution space such that the model is forced to select some specific materials, then the model might not be able to substitute lower quality materials with higher quality ones. Finally, sustainability perceptions can also restrict the capacity of the model to award points. In this case, the perceptions of a subject on a material might not correspond to the properties of a material preventing the model from selecting materials that help achieve a greater number of LEED points.

CHAPTER 7
GENERAL DISCUSSION

7.1 The instrument

The sustainability instrument tool derived through this study is similar to the proposed conceptual model. The tool is a three dimensional model that can be used to capture decision maker's sustainability perceptions. The factor analysis revealed there was some redundancy in the sustainability items or some items were measuring the same construct. Therefore, the items were grouped into factors. These factors account for most of the variance in the sustainability items and allow explaining almost 65% of the information retained on perceptions of sustainability.

Through the development and refinement of the sustainability instrument it is shown that the user appeal dimension is a significant dimension and explains most of the variance. The functionality and resourcefulness dimensions explain another major portion of the variance completing the set of factors that are significant in the construct of sustainability perceptions.

The first dimension is the most significant dimension of sustainability and includes the items *unattractive-attractive, not willing to pay for it-willing to pay for it,* and *disappointed-satisfied*. The importance of this dimension for the target population of this study corresponds to previous studies on characteristics of sustainable products. Previous studies have emphasized that sustainable products are products that are socially and creatively rewarding, that are available in a continuing renewing manner, are highly satisfying to the user, and are successful in the market (Glavic and Lukman 2007, Ljungberg 2007).

The second dimension includes the items *impractical-useful, inefficient-efficient, unusable-functional.* This dimension is subtended by the literature which has defined sustainable products as products that the public needs and that are safe to use (Zhou 2009, Mora 2007, Ljungberg 2007).

The third dimension includes the items *common-innovative, wasteful-resourceful*, *ordinary-extraordinary*. This dimension may be explained by definitions found in the literature associated with properties of the product and processes that make it environmentally friendly. Therefore, sustainable products are defined as products that are low consuming, that can do more with less, gives low environmental pollution and that are trend breaking (Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009, Ljungberg 2007).

As a result, the construct of product sustainability has three key factors that define it: user appeal, functionality, and resourcefulness. The influence of each of these dimensions in the evaluation of product sustainability is explained by the score of the items on each of the factors encountered in the analysis. The score of sustainability is therefore a construct made up of the assumptions of design and construction students and practitioners on sustainable materials. These assumptions or perceptions reveal that sustainable materials are defined as awarding and highly satisfying to the user, are resourceful and are functional.

The results of the case study show the importance of the availability of sustainable materials. If materials with desirable properties are not available, LEED-based requirements are nearly impossible to meet. In the case of the US market, the LEED-based system is highly dependent on the use of materials with a high content of recycled constituents. As no regulations currently require manufacturers to report data, the lack of information about materials will continue to challenge LEED-based systems. In addition, the case study shows the importance of including in the decision making process subjective factors. This study proposes and instrument to assess subjective factors. The instrument developed in this study is used to capture the subjective factors that arise during the materials selection process. The results of the model show the need to include objective as well as subjective factors in the process to optimize decisions. Subjective factors affect decisions since emotions account for different functions that arise in the decision making process and are involved in every aspect faced. With the use of the instrument developed in this study, the value of sustainable products may be enhanced since a clear definition of sustainable products facilitate communication in the process of moving towards a sustainable development.

7.2 Benefits, limitations and future research

This instrument of product sustainability helps decision makers and practitioners determine the items that construct the definition of sustainable products. With the understanding that product sustainability is perceived in the product's level of user appeal, resourcefulness, and functionality the construction industry can focus on developing and enhancing these specific characteristics to aid decision makers in the selection of the most appropriate materials to build sustainable buildings. In addition, the process of materials selection may require less time and may be facilitated by including features that decision makers usually assume to define sustainable products. The results of this study may suggest that databases should primarily consider the product's appeal, resourcefulness and functionality since these dimensions play an influential role in the evaluation of sustainability.

The findings of this study are limited to a specific type of material since the model and instrument are developed using bricks. As a result, the model may need additional dimensions and factors to be effectively validated with other types of products.

Furthermore, the findings of this study are specific to the selected subjects that participated in the study. A study involving a broader range of participant's age, educational background and context would need further validation of the instrument.

This study proposes a methodology to capture subjective factors that arise in the materials selection process. This methodology performs an analysis of which sustainability dimensions affect the construct of sustainability from the perceptions of construction and design students and practitioners. The findings in this study bring multiple issues into attention, which suggest further research and opportunity to generalize the findings.

One of the recommended follow-ups to this study is to investigate perceptions across a wider range of product types such as wood components, windows, and carpets among others. By investigating perceptions with these materials, other factors that affect perceptions of sustainability are accounted for. Therefore, it can be explored if the new items affect the outcome and if the instrument can be further validated for a wider scope of sustainable materials. This study does not study whether students and practitioners may differentiate a sustainable product from a non-sustainable product. Such a study will also help develop and improve the current electronic databases of materials by providing decision makers with easy to access information, features and reviews that assist them to identify whether a material is sustainable or not.

Another study is to involve a broader range of participant's age, educational background and context. By evaluating these changes, the instrument may be further validated since a wider target population may bring significant information that was not accounted for in the context used to develop this study.

7.3 Conclusions

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 decision maker’s appraisal of sustainability. Therefore, an instrument is needed to assess subjective characteristics in order to improve the current decision-making process by considering subjective measures.

The instrument of consumer perception of product sustainability 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 decision makers perceive a product to be sustainable and all the factors that may influence product sustainability. Therefore, suppliers can include in the material’s image visual features typically associated with sustainable characteristics, reducing large data sets to simple visuals. Through visual recognition and human’s highly developed skills of 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.

A natural extension of this work could include the evaluation of sustainable buildings. By doing so, a wider scope of decisions can be supported, including ratings of the buildings’ emotional impact and global sustainability made by users. Another possible extension to the proposed model is to compare sustainability perceptions among laypersons and construction professionals. This could help determine which variables and factors influence assessments of sustainability in both groups and differences in awareness of sustainability principles. As a result, these differences may indicate suppliers to concentrate on designing specific product qualities to enhance overall consumer satisfaction and increase purchase intentions according to the target group.

As electronic environments increase, the range of construction materials expands overwhelming users with information and making the information retrieval 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 developed in this study may contribute to benefit the marketing of sustainable materials. By investigating the factors that influence decision maker's perception of material sustainability and predicting decision maker'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 contributes on how to make sustainable practices remain viable for the well-being of present and future generations.

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