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Sustainable Infrastructure Multi-Criteria Preference Assessment of Alternatives for Early Design

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ABSTRACT

The tradeoffs between the economic, social, and environmental aspects of infrastructures are not easily evident to decision makers and stakeholders in the initial design phase. This lack of insight, often leads to designs that compromise the social and environmental aspects of designs in order to reduce the initial construction costs of infrastructure assets. In addition to the lack of insight, currently available methods for analyzing alternative infrastructure configurations with respect to decision maker preferences: require analysis on a case-by-case (e.g., pairwise) basis; are not appropriate for the initial design phase (e.g., are time-consuming); and are not adaptable to a range of alternative design solutions (e.g., adding and removing alternatives might require a re-ranking from the decision maker). This paper presents a modular preference function development strategy that aims to address these issues, termed **S**ustainable **I**nfrastructure **M**ulti-Criteria **P**reference assessment of a**L**ternatives for **E**arly **D**esign (SIMPLE-Design). The proposed strategy develops utility functions (indifference curves) for assessing decision maker preferences with regard to various tradeoffs of alternative design options, and leverages available data to provide decision makers with a consistent frame of reference for assessing alternatives. An illustration presented for a decision support tool using the Simple-Design strategy assesses decision maker preferences for commercial buildings with respect to initial construction costs, building damage and business interruption costs, casualty costs (due to the occurrence of natural hazard events), and CO_2 emission costs. The designed decision support tool provides streamlined information to support preference assessment with reasonably low cognitive load. Ten out of the twelve decision support tool users stated that allowing the decision makers to define alternatives of equal utility (value) in a systematic manner, and providing information on the various cost types (decision criteria), are the most essential elements of the assessment strategy. The presented modular preference assessment framework, as well as the decision support tool itself, are generalizable and can be adapted to other infrastructure types. The contribution to the body of knowledge is a holistic preference assessment framework that allows decision makers to make more informed decisions—and designers to better incorporate the preferences of the decision makers—during the early design process.

1. Introduction

Early infrastructure design decisions are highly complex due to the open-ended nature of the alternatives that complicate the assessment of economic, social, and environmental (i.e., triple bottom line or TBL) tradeoffs of the alternative design options. To achieve TBL-based designs, the economic, social, and environmental impacts of alternative design options should be communicated to the decision makers in the initial design phase. Additionally, the concept of resilient, robust and recoverable systems has been studied since the 1980s by civil engineers, electrical engineers and computer scientists [1–5]. However, in the last decade this concept has started to evolve more quickly for building and maintaining a robust and recoverable community. Achieving a resilient design does not mean mitigating all risks and predicting all future events. Rather it emphasizes a risk-based approach to absorption/mitigation, recovery, and adaption to potential hazard events [6–15]. Structural resilience is a well-known term in seismic design and failure mode analysis, which has four different characteristics known as robustness, redundancy, resourcefulness, and rapidity [16]. Achieving resilient and performance-based TBL designs, requires a holistic decision support system.

However, lack of data in the initial design phase leads to considerable difficulty in implementing quantitative decision support systems. Challenges include: the broad set of alternatives available in early design and limited knowledge of the potential solution space in terms of TBL measures; the lack of accurate data in the initial design phase (as

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the design has not been performed), particularly for less common design configurations; and the need for a relatively simple method for assessing preferences that makes tractable the complex nature of infrastructure design decisions given the limited available time to make decisions. A modular preference assessment methodology that can communicate the TBL impacts (tradeoffs) of a broad range of alternatives in the early design phase has the potential to greatly improve the design of infrastructure.

An alternate framing of the problem is the effect of the cognitive limitations of the human mind on achieving holistic, sustainable infrastructure designs [17]. One obstacle to the design of successful infrastructure solutions is the interaction of cognitive limitations and the compressed timeframe for decision-making. This phenomenon is known as bounded rationality [18,19]. In infrastructure design, decision makers in this mindset will seek designs that are satisfactory rather than optimal. Therefore, design professionals who focus on sustainability can use life-cycle assessment and sensitivity analysis to illustrate the value of green design to owners, who may otherwise solely focus on cost-effectiveness (i.e., who will have a bounded viewpoint) [20]. Additionally, the presentation of a scenario and the framing of a problem affect the decision made (i.e., decision makers are not completely rational) [21,22]. For example, it would be expected that providing decision makers with actual death and injury rates from earthquake events will impact the decision makers, who might otherwise favor low-cost and low-performing designs. Presenting a range of alternative designs to the decision makers in the early design phase will provide them with a holistic framing of the problem and enable them to consider a number of trade-off strategies and the consequences of various design solutions.

Elegant infrastructures are defined as solutions that break through the design complexity of infrastructures while being non-redundant and optimal [23]. Although there is a clear need for elegant infrastructure solutions, most decision frameworks fall short in analyzing the tradeoffs between the economic, social, and environmental impacts of alternative design solutions. Many decision frameworks analyze design and decision alternatives with regard to multiple criteria (e.g., construction time and construction cost), which target a single objective (e.g., minimize construction cost) such as efficient budget allocations [24] or the optimization of construction activities that aims to minimize construction time [25]. Even multi-objective approaches do not necessarily lead to elegant infrastructure outcomes due to the lack of a systematic consideration of all TBL criteria. For example, construction time-cost optimization does not consider level of service (i.e., social impacts), and water distribution network design may not consider natural hazard resilience measures [26–30]. Furthermore, decisions made during the planning, design, and construction of commercial buildings do not maximize utility for the designers, occupants, or the society [31]. This lack of consideration of all stakeholders is particularly clear in the occurrence of natural hazards.

For the design of elegant infrastructure solutions, there is a need for a preference assessment methodology that 1) provides the performance of the alternative design options to the decision maker(s) at an early design stage and assesses decision maker preferences, 2) can be utilized as constraints and boundaries to find favorable building alternatives using multi-criteria and multi-objective decision analysis (optimization) models, 3) is adaptable to a range of alternative design solutions, and 4) is easily implementable. A modular preference function development strategy that covers the performance range of alternative design configurations can meet the identified needs.

This paper proposes such a modular preference assessment framework consisting of four phases: 1) identifying the TBL-based decision criteria, 2) identifying alternative solutions of a given infrastructure (applicable subsystems and systems) that meet the requirements, 3) analyzing two or more alternative design configurations that cover the range between high- and low-performing through a detailed TBL assessment in the presence of natural hazards (and/or other risk events applicable to the built environment), 4) assessing the preference function of the decision maker(s) through a formal decision analysis methodology. The resulting preference function can then be combined with multi-objective optimization algorithms to identify the optimal system configuration(s). Through careful selection of approaches in each step, a modular decision support system can be developed that is both generally applicable and consistent with the needs of early design.

The following section of this paper reviews the role of TBL objectives in the design phase, as well as the current state of the art, with an emphasis on building infrastructure. Section 3 describes the proposed SIMPLE-Design framework, which is used in a pilot implementation for a nine-story office building described in Section 4. Finally, the implementation tool's success is evaluated and suggestions are made for future work.

2. Background

2.1. Current state of building design models under triple bottom line objectives

The current state of building design models with respect to TBL objectives can be categorized as models that 1) measure TBL impacts, 2) rate building performance, 3) assess decision maker values, and/or 4) find the optimum design option(s), as arrayed in Fig. 1. The following sections review the literature based on the primary focus of each approach (noting that some approaches span multiple categories).

2.1.1. Measure triple bottom line impacts

Input-output models, life cycle cost analysis methods, and performance-based assessment techniques (performance-based seismic design and assessment approaches) are the primary types of TBL impact analysis methods. Such models solely measure the economic, social and environmental aspects of building design options [32–37]. Although TBL impact analysis models are informative, the results of the impact analysis require multi-objective/multi-criteria optimization, and/or a preference assessment framework to analyze multiple alternatives and identify high-performing building configurations.

2.1.2. Rate performance

Environmental assessment tools are the most common method for sustainability assessments of buildings, construction sites, and other aspects of built infrastructure [38–40]. Among the green building environmental assessment tools, LEED [41], BREEAM [42], and CASBEE [43] are the most-studied worldwide. Each uses a credit-weighting scale to assess buildings, with primary focus on environmental rather than economic or social aspects of designs [40,44–48]. The revised Green Building Challenge (GBC) model includes economic issues in the assessment framework [47], and the adoption economic and social measures would significantly benefit other building performance assessment methods (such as LEED) from a TBL perspective. The main limitations of LEED, BREEAM, and CASBEE are lack of integration of their credit-weighting scale with decision maker utilities.

2.1.3. Assess decision maker values

The current state-of-the-art methods that assess decision maker values with respect to TBL measures are multi-criteria decision making methods, discrete choice experiment methods, utility functions, methods that facilitate stakeholder dialogues, and further stakeholder perception assessment techniques. A number of multi-criteria decision making methods exist for: comparing sustainability measures to stakeholder preferences in urban and regional mobility measures; incorporating economic and political concerns in the life-cycle assessment of commercial buildings; and incorporating stakeholder preferences in the sustainability evaluation [49–51]. Additional studies have been conducted to analyze the perceptions of sustainability in commercial buildings, conceptualize stakeholder engagement in the context of