Structural Safety 74 (2018) 1–13

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Performance-based engineering and multi-criteria decision analysis for sustainable and resilient building design

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ARTICLE INFO

Keywords:
Building holistic design
Decision making
Energy-efficiency
First-order reliability method
Multi-criteria decision analysis
Performance-based engineering

ABSTRACT

In this paper, an integrated approach for a holistic (involving notions of resiliency and sustainability) building design is presented to select the optimal design alternative based on multiple conflicting criteria using the multi-attribute utility theory (MAUT). A probabilistic formulation of MAUT is proposed, where the distributions of the uncertain parameters are determined by a performance-based engineering (PBE) approach. Here PBE is used to evaluate the building energy efficiency and sustainability in addition to structural safety. In the proposed framework, different design alternatives of a building are ranked based on the generalized expected utility, which is able to include the most adopted probabilistic decision models, like the expected utility and the cumulative prospect theory. The distributions of the utilities are obtained from the first-order reliability method to provide (*i*) good tradeoff between accuracy and efficiency, and (*ii*) rational decision making by evaluating the most critical realizations of the consequences of each alternative through the design point. The application of the proposed approach to a building shows that design for resilience may imply design for sustainability and that green buildings (alone) may be not resilient in the face of extreme events.

1. Introduction

Sustainable development of the urban communities is strictly related to the "disaster risk management" whose aim is the reduction of the "disaster risk." Following [1], it is noted that "natural disaster" do not exist, only natural hazards. Thus, the disaster risk reduction may be achieved by improving the practices of design and construction of the buildings or through wise environmental management. The resilience is defined as the "ability to prepare for anticipated hazards, to adapt to changing conditions, to withstand and recover fast from disruptive events induced by hazards" [2,3]. The sustainability is the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4]. Sustainable development requires a holistic view involving jointly the main pillars of sustainability and resilience (e.g. economy, ecology, society, technical and organizational) and being able to provide the real-time management of the infrastructural systems, incorporating human systems, energy systems, environmental systems, and urban systems. This can be obtained through an integrated design process, involving the different lifecycle phases: design, operation and maintenance, up to demolition or renovation. The task is challenging because there are several sources of uncertainty, the number of stakeholders is high, and the lifecycle of a building is long. Thus, it is crucial to develop an integrated methodical framework as a decision support tool for the optimal decision amongst alternatives subjected to uncertainty and incomplete information.

In a decision-making process, the first step is the choice of suitable performances $G_1,G_2,\ldots,G_n$ expressed in terms of the direct interest of various stakeholders to define the global performance of the system. Together with the performances, the decision maker explores several design alternatives and/or actions through the building lifecycle. Subsequently, making use of the decision making system, the optimal alternative may be determined with general consensus from the stakeholders. The optimal choice takes into account multiple conflicting criteria by making use of the multi-attribute utility theory (MAUT) [5]. An important challenge of MAUT for sustainable design stems from the different sources of uncertainty, giving rise to a problem of decision under uncertainty or under risk. Thus, the objective of this paper is to

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https://doi.org/10.1016/j.strusafe.2018.03.005
Received 8 September 2016; Received in revised form 22 March 2018; Accepted 23 March 2018
0167-4730/

develop a full probabilistic formulation of MAUT. The main task is modeling the probability distribution of the chosen performances in real-world engineering systems. We adopt the performance-based engineering (PBE) methodology, which is extensively used for evaluating system performance measures meaningful to various stakeholders, e.g. monetary losses, downtime, and casualties [6]. PBE approach links, in a natural way, the building design to the desired performances. For this reason, from PBE emerges principles of resilient design and sustainable design as well. Thus, PBE represents a simple and effective tool for holistic building design.

The second step in a decision-making process is the determination of the optimal probability distribution of the performances for different design options. The most popular approach in civil engineering is the equivalent cost analysis where all the performances are converted into a monetary measure through suitable conversion factors; in such case, the alternatives are compared in terms of the minimum expected cost [7]. However, research suggests that the risk cannot be entirely monetized [8]. In the utility theory, it is recognized that subjective factors should be taken into account in the risk evaluation, and this is accomplished through the utility function, which measures the desirability of the consequences. In such case the optimal alternative gives the maximum expected utility [9]. It is well recognized that the expected utility is not able to provide an accurate description of the observed behavior of the decision makers [10,11]. Some improvements have been proposed, like the cumulative prospect theory [12–14], which integrates the risk perception inside the formulation of the utility function, and it recognizes the subjective evaluation of the probability of occurrence of rare events. The main difficulty is the definition of a suitable probability weighting function measuring perception of the likelihood of the events. Recently, some researchers have proposed to rank the alternatives through the adoption of risk measures (e.g. expected values, quantiles, or superquantiles) applied to the performances [15,16].

In this paper, it is proposed to rank the alternatives through a variant of the expected utility, called generalized expected utility (GEU), able to incorporate most existing decision models (e.g. expected utility, cumulative prospect theory, risk measures) as particular cases. It is also proposed to model the risk aversion in the GEU by applying the superquantile to the utilities U.

A rational decision making can be obtained through a good understanding of the consequences [17]. This is accomplished by determining the distributions of the utilitiese through the first-order reliability method (FORM), which gives a good tradeoff between accuracy and efficiency. Moreover, the knowledge of the design point provides significant realizations of the consequences corresponding to chosen alternatives/actions. The FORM results can effectively guide the decision maker to make a rational choice of the optimal design.

The decision-making process is dynamic in the sense that the optimal decision changes when new information is available. Such dynamic behavior is effectively represented through Bayesian analysis, here modeled through the adoption of Bayesian Networks [18]. The formulation can be used for updating the uncertain input variables, but also the subjective utilities expressing the degree of preference of the decision maker and of the different stakeholders involved in the design process [19,20]. In cases where the scarcity of data makes the probabilistic analysis problematic, the optimal decision may be explored through sensitivity analysis of the decision outcomes to the various input parameters.

The proposed framework represents a powerful tool for an extended multi-objective system of management and design under uncertainty. After describing the main features of the framework, it is applied to a hypothetical office building located in California. The example shows the main strengths of the proposed approach and its capabilities for pursuing sustainable and resilient building design.

2. Multi-criteria decision making under uncertainty

Multi-criteria decision-making problems involve optimal design in the presence of multiple design criteria, typically conflicting each other. In this paper, we adopt the widely used multi-attribute utility theory (MAUT) [5] whose aim is the selection of the “best” design alternative from a pool of m preselected alternatives $a^{(1)},a^{(2)},\cdots,a^{(m)}$, explicitly known in the beginning of the solution process. The evaluation of the optimal solution is based upon the preferences of the decision maker with respect to a set of performances, or decision criteria. From a mathematical point of view, the performance of a system can be described through a set of functions $G_r = g_r[\boldsymbol{x},\boldsymbol{v}(\boldsymbol{x})]$, $r = 1,2,\cdots$ where $\boldsymbol{x} = \{x_1 \quad x_2 \quad \cdots \quad x_q\}$ collects all the “design variables” containing the control variable values representing the set of preselected alternatives, i.e. $\boldsymbol{x}^{(k)} \equiv a^{(k)}$. The vector $\boldsymbol{v}(\boldsymbol{x}) = \{\boldsymbol{v_B} \quad \boldsymbol{v_D}(\boldsymbol{x})\}$ collects all the uncertain parameters appearing in the decision-making problem where $\boldsymbol{v_B}$ collects the *basic random variables*, which are the parameters that cannot be controlled by the decision maker, e.g. hazards or environmental conditions and $\boldsymbol{v_D}(\boldsymbol{x})$ collects the *derived parameters* that are affected by the design variables, e.g. uncertain responses of the system.

2.1. Selection and definition of criteria and design alternatives

In a decision-making model, the Requirements are the most general standpoints, e.g. Functional, Social, Environmental, and Economical [21,22], which may be unfolded in several Criteria or Attributes (e.g. lifecycle cost), where each criterion may involve several Performance Indicators, e.g. energy expenditure and economic losses, see Table 1. Typically, there are several criteria to consider and generally some of them may be inevitably conflicting. The first step in the decision-making problem is to identify from the criteria a set of n performances $G_1,G_2,...,G_n$ collected in the vector $\boldsymbol{G}$. The next step is to define a finite set of m design alternatives, i.e. $\boldsymbol{a} = \{a^{(1)} \quad a^{(2)} \quad ...a^{(m)}\}$. The performance of the system depends on all indicators $G_1,G_2,...,G_n$ and it is defined through the multi-attribute function $G_s[\boldsymbol{G}(\boldsymbol{x})]$, while the performance of the i-th alternative $a^{(i)}$ reads as $G_s^{(i)} = G_s[\boldsymbol{G}(\boldsymbol{x}^{(i)})] \equiv G_s[\boldsymbol{G}^{(i)}]$.

Table 1
Requirements, criteria and indicators for a building.

Requirement	Criteria	No.	Performance Indicator
Functional	Quality perception	1	User
		2	Visitor
	Adaptability to changes	3	Modularity
Economic	Construction cost	4	Direct Cost
		5	Deviation
	Lifecycle cost	6	Utilization
		7	Maintenance
		8	Losses
Social	Integration of science	9	New patents
	Work for local companies	10	Turnover
	Annoyance of construction	11	Dust
		12	Noise
		13	Street occupation
	Safety of construction	14	Risk of casualties
Environmental	Construction	15	Water consumption
		16	CO_2 emission
		17	Energy consumption
		18	Raw materials
		19	Solid waste
	Integration in environment	20	Visual
	Utilization	21	Noise, dust, smell
		22	Energy consumption
		23	CO_2 emission
	Reintegration	24	Solid waste