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# A multi-objective feedback approach for evaluating sequential conceptual building design decisions

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A B S T R A C T

Conceptual design decision-making plays a critical role in determining life-cycle environmental impact and cost performance of buildings. Stakeholders often make these decisions without a quantitative understanding of how a particular decision will impact future choices or a project's ultimate performance. The proposed sequential decision support methodology provides stakeholders with quantitative information on the relative influence conceptual design stage decisions have on a project's life-cycle environmental impact and life-cycle cost. A case study is presented showing how the proposed methodology may be used by designers considering these performance criteria. Sensitivity analysis is performed on thousands of computationally generated building alternatives. Results are presented in the form of probabilistic distributions showing the degree to which each decision helps in achieving a given performance criterion. The method provides environmental impact and cost feedback throughout the sequential building design process, thereby guiding designers in creating low-carbon, low-cost buildings at the conceptual design phase.



## 1. Introduction

Multidisciplinary design optimization (MDO) methods exist that allow designers to explore very large design spaces, quickly evaluate many design alternatives, and find optimal or near optimal solutions for various performance criteria. The benefits of MDO methods are well documented in such industries as aerospace, automotive, and electronics. Within the architecture, engineering, and construction industry, application of MDO methods has been shown to yield significant reductions in building life-cycle environmental impact and cost compared to conventional design methods [1,2].

Although MDO has potential to improve design process efficiency and the quality of the resulting product, MDO methods are not widely used within the building design industry, particularly during conceptual design. The conceptual design stage has been recognized as a critical determinant of project environmental impact and cost [3,4]. At the conceptual design stage, many choices exist for building decisions, such as shape, orientation, massing, and materials for each building component. These decisions are typically made by architects in sequential fashion. For example, the architect may determine the orientation of a building before placing shading devices to minimize building cooling loads and life-cycle costs. Designers may also wish to understand a project's environmental impact and cost once the wall assembly system has been chosen but before deciding upon the cladding system. Such a multi-objective sequential feedback approach is typical in the Architecture, Engineering, and Construction (AEC) industry in that project stakeholders often need to evaluate design decision trade-offs for competing objectives. For example, a designer wishing to minimize both environmental impact and cost may find that a certain window-to-wall ratio lowers carbon footprint at the expense of greatly increased life-cycle cost.

Existing MDO methods do not accommodate sequential decision-making processes. MDO requires all design decisions to be made in parallel, instead of allowing designers to define variable values sequentially and thereby understand the impacts for each successive decision. Consequently designers utilizing MDO must decide on all building decisions before receiving feedback on any single design choice. Existing MDO methods therefore do not integrate well with the AEC industry, which relies on flexible and often-changing decision-making processes, especially at the early stages.

A new method is proposed that integrates aspects of MDO methods with conceptual building design. By providing feedback to designers after every single design decision and allowing for easy modification of decisions, the method integrates well with dynamic decision-making processes common to the AEC industry. The method can accommodate a range of building objectives, such as construction schedule performance, indoor comfort, and life-cycle energy use. The research here presents life-cycle cost and life-cycle environmental impact as the performance objectives of interest, since these objectives are recognized as important drivers in building design decision-making processes [5,6]. Researchers have identified several impact categories that are useful in measuring the environmental impact of buildings,

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including global warming potential, human toxicity, and acidification, among others [7]. Although the authors recognize the importance of all of these categories in assessing the life-cycle environmental impact of buildings, the proposed method is demonstrated for global warming potential. The metric used for this indicator is carbon dioxide equivalents ($CO_2e$), which measures the total amount of greenhouse gas emissions of the building. Life-cycle cost is measured in terms of US dollars, assuming a building service life of 30 years and a discount rate of 7%.

As with MDO methods, the proposed method leverages algorithms to systematically evaluate design alternatives and locate high-performing solutions. Building information modeling software is integrated with life-cycle assessment and energy simulation software, a sampling algorithm analyzes thousands of building design alternatives across the design space, and life-cycle environmental impact and cost feedback is computed for each alternative.

The proposed method differs from existing MDO methods by using probability distribution functions to support sequential decision-making processes. These functions are represented as bar charts and are generated by subdividing the range of output values for a given performance objective at regular intervals and calculating the probability of each output falling within each prescribed range, considering the full range of possible values. As decisions are made, the range and population of output values are reduced, and new distributions are generated from the remaining values. The process continues until all decisions have been made and only one output value remains. In this way, probability mass functions provide a dynamic sequential decision-making feedback tool that can aid in the understanding of buildings' life-cycle environmental impact and cost. Designers are provided with visual quantitative feedback on many alternatives and can determine the degree to which each decision helps or hurts in achieving each of their objectives. The distributions viewed by designers are dependent on the order in which the decisions are made. In other words, the order of these decisions may influence which decisions are made and, therefore, the outcome of a design problem.

Fig. 1 illustrates how the method can be applied to three different sequential decision-making strategies often used by designers. Environmental impact is displayed here as the feedback type, although distributions can be simultaneously provided for cost feedback as well. In the first row, probabilistic distributions show the range of impacts possible for all design alternatives before any decisions have been made. New probabilistic distributions are then generated after two separate decisions, such as selecting stone for the cladding material and adding shading devices to the building facade. The new results show the range of impacts possible for the remaining design decisions. Designers are able to understand the full range of control of life-cycle environmental impact and cost performance as well as the relative influence of design decisions on both of these objectives throughout the sequential decision-making process.

In Fig. 1(a)–(c), a designer would like to minimize a building design's life-cycle environmental impact. This strategy relies on single-objective optimization, which studies have shown can be an effective strategy for helping designers minimize the environmental impact of buildings [8–10]. As each sequential decision is made, the designer understands whether a decision improves upon the previous decision in terms of either reducing or increasing the building's remaining life-cycle environmental impacts. The designer also understands with each new decision whether chances improve, worsen, or have been eliminated of achieving the design with the lowest possible carbon footprint. In this case, the figures show that the average of the values comprising the distribution of impacts steadily decreases after each of the two decisions, and a designer interested in minimizing environmental impact may continue on with a third decision. Throughout the

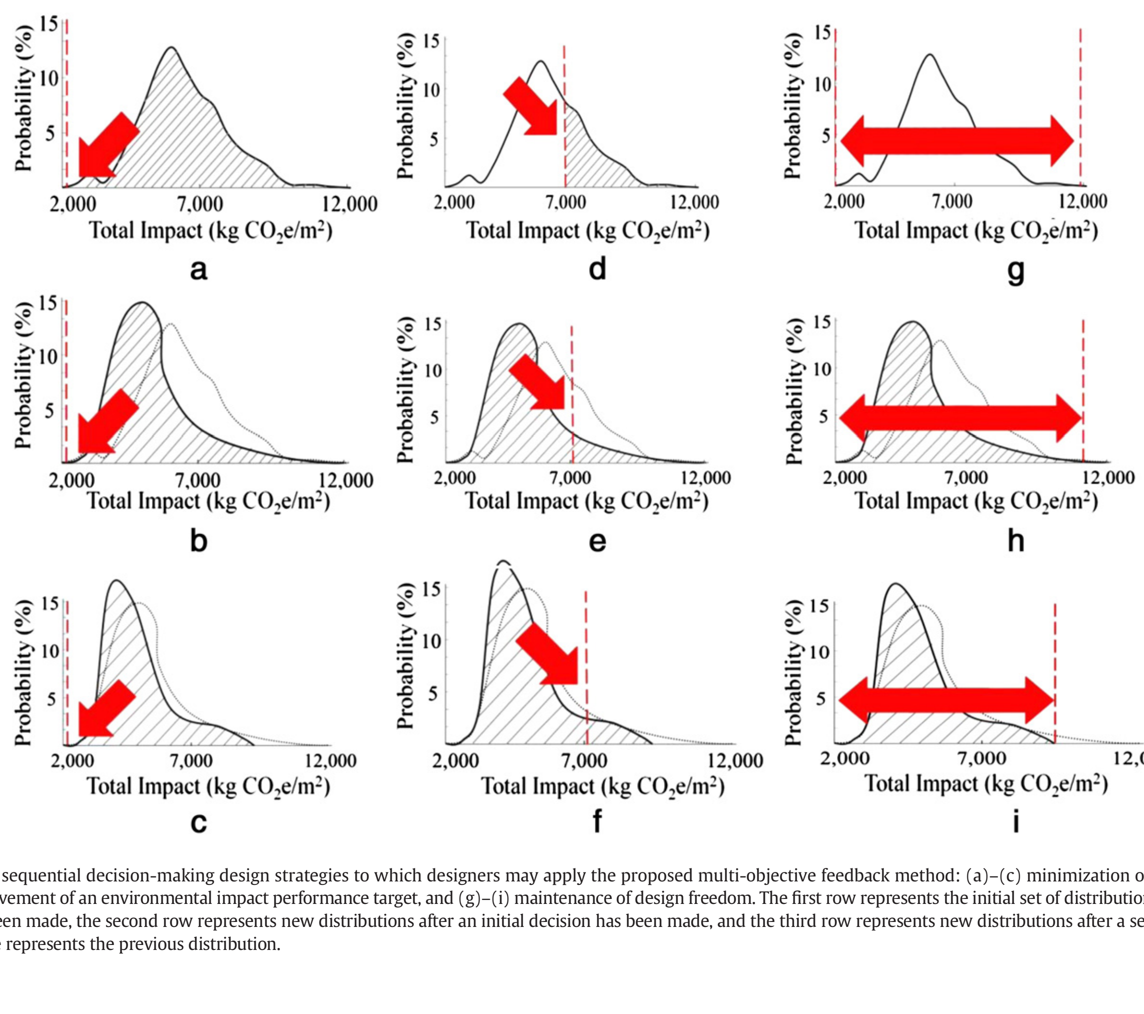


**Fig. 1.** Three sequential decision-making design strategies to which designers may apply the proposed multi-objective feedback method: (a)–(c) minimization of carbon footprint, (d)–(f) achievement of an environmental impact performance target, and (g)–(i) maintenance of design freedom. The first row represents the initial set of distributions before any decisions have been made, the second row represents new distributions after an initial decision has been made, and the third row represents new distributions after a second decision. The dashed curve represents the previous distribution.