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Building design-space exploration through quasi-optimization of life cycle impacts and costs

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ABSTRACT

To aid the design of buildings with lower environmental impacts, it is important to be able to rapidly compare the predicted impacts and costs of design alternatives at early stages of the design process when many influential decisions are made. At the same time, it is also important to preserve design flexibility in order to better accommodate diverse project constraints and goals. This paper presents the first use of an early-design, probabilistic life cycle assessment (LCA) method to identify and summarize the characteristics of buildings with near-optimum or "quasi-optimum" life cycle impacts and costs. Two design guidance methods are explored: sequential specification – in which influential attributes are iteratively identified and specified – and genetic optimization. The efficiency of these methods are compared using information entropy to quantify the flexibility of the probabilistic design as it is refined. Genetic optimization is found to be more efficient than sequential specification because it leads to more optimal solutions with greater flexibility. Quasi-optimum designs are identified and analyzed to determine which attributes must be specified in a particular way and which attributes have more flexible ranges to achieve a given percentage of the optimum reduction in impacts and costs. It is found that quasi-optimum designs representing 75% of these optimum reductions can be associated with a 40% increase in design flexibility over optimized designs. Twelve cases are presented that explore the influence of climate, analysis period, energy-related impact factor variability, and optimization weighting of impacts and costs on quasi-optimum designs.

1. Introduction

Demand for low-impact or "green" buildings is rising [1]. Life cycle assessment (LCA) is a method that can be used to quantify the environmental impacts associated with different building options. However, the detail and time required for an LCA typically restricts its use to later stages of the design process when it can only be used to evaluate a small number of alternatives. To use LCA as a more explorative tool, the method must be adapted so that it can be applied at earlier stages of the design process when fewer details are available but more options are still under consideration. Furthermore, most effectively guide early-design decisions, LCAs should be coupled with methods that can identify preferable or optimized design options. However, while several prior studies have described the optimization of various aspects of building performance, the process of optimization in many ways runs counter to the objective of the early design process; the goal of the former is to identify a single "best" option, whereas the goal of the latter is to explore and assess many different options with a variety of design criteria, some of which (such as aesthetic preferences) may be difficult or impossible to incorporate explicitly into an optimization problem. What is needed is a tool that can accommodate high levels of early-design uncertainty but still efficiently identify low-impact and low-cost designs while maintaining maximal creative flexibility for the designer.

To address this gap, this work couples an early-design, probabilistic LCA tool called the Building Attribute to Impact Algorithm [2] with a derivative-free optimization method to identify ranges of near optimum (*quasi-optimum*) designs and their characteristics. The information theory concept of information entropy is used as a metric of flexibility for a probabilistic building design, approximately representing the volume of the design space that is still considered at each step of a guided design process as details are added. Quasi-optimum designs with the majority of the optimum improvement in impacts and costs are found to provide substantial increases in entropy over the completely optimized solution. In addition, design parameters are analyzed to identify which attributes are critical (i.e., must be specified in a particular way to

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Abbreviations

AAM	Attribute-to-Activity Model
AC	Air conditioner
BAIA	|Building Attribute to Impact Algorithm
BEopt	Building Energy Optimization, NREL software
CV	Coefficient of variation
GWP	Global warming potential
HVAC	Heating, ventilation, and air conditioning
JMP	Statistical software from SAS
LCA	Life cycle assessment
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
MC	Monte Carlo
MSHP	Mini-split heat pump
NREL	National Renewable Energy Laboratory
NSGA	Non-dominating Sorting Genetic Algorithm
SI	Supporting information
WWR	Window-to-wall ratio

achieve near-optimum costs and impacts), and which are flexible. In a set of case studies, most geometrical and occupant-related attributes were found to be flexible in all cases, while the flexibility of most systems-related attributes varied across the cases. By exercising their creativity within a quasi-optimum region of the design space, designers can facilitate the creation of buildings with lower impacts and costs.

1.1. LCA-based building design optimization

This first section of literature review discusses building design optimization, with special attention to life-cycle approaches. In recent years, numerous studies have addressed optimizing various aspects of building performance. A review of 74 papers using optimization methods to improve the sustainability of a building can be found in [3], and a review of approximately 100 papers using evolutionary algorithms, derivative-free search methods, and hybrid algorithms applied to the optimization of building design can be found in [4]. Several papers from these two reviews are included in the discussion here. Across this literature, much attention has been given to the minimization of a building's operational energy or energy-related environmental impacts, including over 30 papers mentioned in these review papers (for some more recent examples, see [5–10]). Fewer studies have focused on minimizing the life cycle impacts and costs of a whole building, including the costs and impacts associated with both materials and operational energy use. Some have optimized the design of an office building ([11,12]) residential building ([13–15]), school building ([16]), or a specific component of the building such as the envelope ([17–19]). However, these studies do not treat material uncertainty as robustly as the approach presented here, generally do not address the efficiency of the design guidance or optimization methods, and do not explore near-optimum solutions. In general, most optimization studies with multiple objectives focus on Pareto-optimal solutions to assess the trade-offs between conflicting design goals. In fact, many studies use a specific variant of genetic algorithm called the Non-dominating Sorting Genetic Algorithm II (NSGA-II) [20], which is used to identify solutions along the Pareto frontier in [5,16,18,21–24]. While this approach undoubtedly yields valuable insights and can provide the designer with alternatives for consideration, the Pareto frontier does not by itself address which aspects of the design are more critical and which have more flexibility for achieving near-optimum performance, nor have Pareto-optimal designs been used to answer these questions in the majority of studies that employ NSGA-II or related methods.

1.2. Information entropy applied to design

This second section of literature review discusses how information entropy has been used in previous design-related studies. To ensure the maximization of design flexibility, that flexibility must be measured. Here, information entropy is proposed as the metric for flexibility of an uncertain or probabilistic design. When applied to design, information entropy can be utilized as a measure of the number of available states in a design space, allowing a mathematical description of the relationship between uncertainty and design information and their evolution over a design process [25]. It can also be used as a measure of how precisely a design is defined [26]. Krus applied information entropy to optimizing the design of a structural beam [25], exploring the conceptual design of an unmanned aircraft [27], measuring the quality of the design space of an aircraft wing [26], and improving the design parameterization of the same aircraft wing [28]. Menhorn and Slomka use maximum information entropy (in which all states have an equal probability, as in the example above) to quantify the complexity of digital circuit designs from early stages of the design process, allowing comparisons between designs used for different technologies and using different levels of abstraction [29]. Ferent and Doboli used information entropy as one of four separation scores to cluster a set of 50 analog circuits and determine their main similarities and differences [30]. In the building sector, information entropy has been applied to the selection of criteria weights in multi-criteria decision making for facade alternatives [31].

1.3. Literature gaps and research contributions

Two gaps have been identified in previous approaches to LCA-based design optimization. The first is a lack of consideration of near-optimum solutions, and the second is a lack of metric to quantify the flexibility of an uncertain or probabilistic design. Concerning the first gap, the lack of consideration of near-optimum solutions limits the scenarios in which the optimization results can or will be applied. The only analysis of near-optimal solutions that the authors are aware of is found in a study by Rapone and Saro [32], in which three near-optimum alternatives are presented that are within 2% of the best solution to minimize the operational emissions associated with the façade design of an office building. These alternatives are briefly highlighted as examples of additional strategies that can yield very good results while allowing more design options, but no statistical analysis is done to summarize the characteristics of all the near-optimum solutions discovered. In contrast, this paper considers all solutions explored over the course of the genetic optimization and establishes quasi-optimum "levels" based on the percentage of improvement from the initial to the optimized designs. The attribute ranges for designs in a given quasi-optimum region are then analyzed to summarize the viable design alternatives within a certain proximity of the fully optimized impacts and costs.

Finally, with regards to the second gap, though information entropy has been used to measure the complexity, diversity, or precision of a design in other applications as discussed above [25–29], very few papers have used information entropy in any analysis of the building design process. To the best of the authors' knowledge, this is the first example of information entropy being used to quantify the flexibility of an uncertain or probabilistic building design as it is being iteratively refined or optimized. In addition, though other studies have compared the efficiency of optimization methods in terms of computation time [33] or number of optimization iterations [34], one of the contributions of this paper is the comparison of design guidance efficiencies based on the amount of information that needs to be added to an uncertain design in order to optimize or nearly optimize a given design metric.