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Impact of progressive sustainable target value assessment on building design decisions

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ABSTRACT

The built environment creates significant environmental, economic, and social impacts. In the building construction industry, building designers, contractors, and owners have developed methods to consider costs, but currently have few methods to effectively assess and control a building's life cycle energy and environmental impacts during the design phase. Managing and reducing these environmental impacts during the course of design development requires iterative assessment and rapid information turn-around and decision-making. When left unconsidered, poor environmental design decisions leave potential design revisions and their value unrealized. This research combines life cycle assessment (LCA) and target value design (TVD) to rapidly produce more sustainable building designs in a methodology called sustainable target value (STV) design. The STV design process involves environmental design targets and an STV tool to quantify environmental design performance in an iterative design process. By establishing site-specific sustainability targets and iteratively using the STV tool to assess the impacts of design changes, this research demonstrates that building designs can be improved at the design stage to perform at higher environmental standards than if they are only assessed once design is complete.

1. Introduction

Buildings are the largest consumer of energy and greatest contributor to climate change in the United States—consuming approximately 49% of primary energy and contributing 47% of greenhouse gases emitted annually [1]. The built environment also contributes to acidification, ozone depletion, water consumption, and eutrophication, among others. These impacts stem from all stages of the building life cycle which includes raw material extraction, manufacturing, transport to site, construction, operation, and end-of-life and can be quantified using the life cycle assessment (LCA) methodology. Further, these life cycle impacts are largely decided at the design phase [2–4].

The majority of decisions that influence the life cycle environmental impacts of a building are determined early in the design process. Studies have shown that the earlier an environmental or energy assessment is conducted, the greater is the potential to effectively influence the life cycle performance of the building [5]. However, evaluation of building environmental performance is typically not performed until the design development stage or later [6]. This delay is due to the fact that several barriers exist with respect to assessing building sustainability in building design [2]. These include data availability, lack of building designer expertise, and lack of quantified environmental targets and inability to measure performance against these targets [7].

Because buildings are so environmentally impactful, hundreds of tools and strategies for 'green' design have been developed. A useful method of categorizing these tools was proposed by Gowri; the subsets are (1) knowledge-based methods, (2) rating schema, and (3) performance-based tools [8]. Knowledge-based tools are usually manuals, guidelines, or other reference materials such as EnergyStar or Green Building Advisor. Building rating schema are design checklists, frameworks, and calculators used to quantify a building's sustainability profile. These include popular tools like Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and National Australian Building Environmental Rating System (NABERS). Performance-based tools include life cycle assessment methods and energy simulation tools for calculating building energy consumption and environmental emissions such as SimaPro and GaBi.

All of these subsets of green building design methods provide a method of intervention in traditional design to implement sustainable strategies. Limitations exist for implementation of each

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subset of sustainable building design method. Knowledge-based methods do not include quantified definitions of sustainability, but instead base sustainability on the criteria included. For instance, the method may call for construction run-off control or inclusion of renewable energy such as solar photovoltaic panels [9]. Similarly, rating schema provide checklists which assume that if all of the boxes are checked or points earned, the building will be sustainable. Sustainability is defined by the criteria included in the rating schema. When using knowledge-based methods or rating schema, many sustainability-related design decisions are based solely on designer experience and qualitative assessment [7,10]. Further, these building sustainability methods often fail to accurately predict environmental performance [11,12]. As a result of the qualitative nature of assessment using knowledge-based tools and rating schema, these subsets of green building methods are not useful for iterative and progressive building sustainability assessment. The final subset of green design methods, performance-based tools, have the potential to achieve comprehensive quantitative sustainability metrics for measurement and comparison of designs [13]. Performance-based building sustainability tools which incorporate LCA have been developed to provide quantified assessment of environmental performance in terms of environmental indicators such as carbon dioxide equivalence (CO_2e) and overcome the criterion-based definition of sustainability. Limitations of these methods include availability of data, boundary definition, and uniqueness of designs [14–16]. However, due to the quantification of performance and potential to compare performance of various design decisions, performance-based sustainability tools that incorporate LCA are useful for sustainable building design assessment.

One potential solution is the sustainable target value (STV) framework which has been recently proposed by Russell-Smith et al. [17] to enable setting site specific targets and quantified environmental assessment at the design stage. The STV design methodology enables building designers to explore the sustainability of multiple design alternatives during design. It includes targets for environmental metrics such as global warming potential and primary energy consumption for the life cycle of a building based on earth's carrying capacity as well as a Microsoft Excel-based tool to predict design performance relative to these site-specific targets. The STV methodology is based on the integration of life cycle assessment, target value design (TVD), and life cycle costing (LCC). TVD has been used iteratively throughout design progression to inform the design process [18]. Iterative TVD has been shown to improve building designs with respect to cost and to increase the exploration of design alternatives [18]. This work shows that progressive use of the STV framework during design does the same with respect to environmental impacts such as global warming potential (GWP).

2. Life cycle assessment of building performance

LCA is an internationally standardized method of accounting for all inputs, outputs, and flows within a process, product, or system boundary to accurately quantify a comprehensive set of environmental, social, and economic indicators [19]. It is used to quantify the energy and material flows associated with each life cycle stage from raw material extraction through material processing, manufacture, distribution, use, and end-of-life for a given product or service [20]. LCA forms the analytic basis for many performance-based sustainability design approaches used today [21].

The LCA methodology has been applied to quantify the environmental sustainability impacts of constructed facilities. The preponderance of LCA studies show that the majority of life cycle environmental impacts accrue during building operation. Keoleian et al. [22] found a wide distribution of impacts accruing from all stages of the life cycle of a residential building, with most coming from the use phase. Junnila et al. [23,24] determined that for commercial structures over 90% of life cycle energy consumption and 80% of carbon dioxide emissions are a result of the operation of a building. Scheuer et al. [15] found that, for a new university building, greater than 95% of life cycle energy consumption is attributable to the use phase. In a comprehensive review of 16 other studies, Sartori and Hestnes [25] found strong correlation between total life cycle energy consumption and operating energy consumption. Gustavsson et al. [26] also found that use phase impacts dominate life cycle impacts, and that choice of heating system can affect these impacts.

Limited LCA studies have been conducted that focus on buildings with low use phase consumption due to on-site generation and highly efficient systems. These studies demonstrate that the distribution of impacts amongst life cycle phases may change when the use phase energy consumption is reduced [27,28]. Blanchard and Reppe [29] conducted an early study to this effect and found that, for structures using highly energy efficient materials and operation technologies, embodied impacts constitute a larger percentage of life cycle impacts. Recently, Karimpour et al. [30] found that embodied impacts can represent 25–35% of total impacts. However, as Faludi et al. [31] noted, even buildings designed to be energy efficient, with higher than historic embodied impacts, attribute on the order of 60% of life cycle impacts to energy consumption. Faludi and Lepech [32] found that the priority for sustainable building design is reducing use phase energy consumption. Due to the high percentage of impacts that result from energy consumption, it is important to design energy efficient buildings in order to reduce these impacts.

To date, LCA has predominantly been used to retroactively calculate the impacts of buildings once they are already built [33]. When implemented in design, LCA has been typically implemented once design was largely complete [2], at which point it is too late to change environmentally impactful decisions such as building orientation, window-to-wall ratio, and HVAC system [5]. However, LCA has proven valuable for quantified product-oriented environmental management [34] – the LCA methodology can be used to determine, at the design phase, a building's impacts over its entire life cycle and to quantify which components are most impactful. New building design offers an opportunity to reduce impact on the natural environment, and as a result, to reduce operational costs and energy scarcity concerns. If used iteratively, LCA can facilitate exploration of design alternatives and inform design decisions. Building designers have been using similar techniques from a cost perspective; target value design (TVD) has been used to reduce building design and construction costs and inform design decisions.

3. Target value design and life cycle costing

The concept of target costing was first implemented by Japanese automotive manufacturers in the 1960s [35]. In this process, the target cost is determined and the product designed and redesigned iteratively to meet it. TVD is the term used for target costing in the building construction industry [36]. This management technique is implemented in building design and construction projects with the goal of driving designs that deliver customer values without exceeding project monetary constraints. This is in contrast to the historical norm for building design and costing. Historically, buildings have been designed based on customer-architect conversations and once designs were complete, the costs were estimated; cost has been an outcome of design, not a driver of design.

TVD has made cost a driver, similar to time and location, in order to deliver value [36]. In TVD, target costs are set at the project goal