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Sustainable target value design: integrating life cycle assessment and target value design to improve building energy and environmental performance

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ABSTRACT

Buildings are the largest consumer of energy and greatest contributor to climate change in the United States—consuming approximately half of energy produced and contributing close to half of greenhouse gas emissions. Building designers, contractors, and owners currently have few methods to effectively control a building's life cycle energy and environmental impacts during the design phase. Managing and reducing these impacts during design requires rapid information turnaround and decision-making. When left unconsidered, poor environmental design decisions leave potential design value uncaptured. This research combines life cycle assessment (LCA) and target value design (TVD) to rapidly produce more sustainable building designs. By establishing site-specific sustainability targets and using dynamically-updating life cycle assessments, this research demonstrates that buildings can be designed to perform at higher environmental standards than those designed without a target in place. The research also offers unique opportunities to analyze the tradeoffs between design and operational decisions.

1. Introduction

The built environment creates significant environmental, economic, and social impacts. Buildings are the largest consumers of energy and greatest contributors to climate change in the United States; the building sector consumes approximately 49% of energy produced in the U.S. and contributes close to 47% of greenhouse gas emissions (EIA, 2011). The energy consumption and airborne and waterborne emissions associated with constructed facilities influence U.S. national energy policy, contribute to global climate change and ozone depletion, and impact human health. Protecting the natural environment is important for social and economic prosperity—required for food, energy, medicines, and industrial resources.

Current building practices significantly impact the environment and ecosystems and the resources they provide. Yet, the Energy Information Association (EIA) projects that building energy consumption, and the resulting CO_2-equivalent emissions, will grow by over 7 exajoules in the next two decades with over two thirds of this energy supplied by fossil fuels (EIA, 2008). To address this growth, more systematic approaches for environmentally-focused building design, construction, and operation are needed. Analogous to conventional building design cycles, such systematic approaches begin with quantitative environmental assessment of building designs followed by iterative design and engineered improvement of building materials and systems to reduce impact and improve overall sustainability.

2. Life cycle assessment

Given the complexity of interactions between the built and the natural environments, life cycle assessment (LCA) represents a comprehensive approach to examining the environmental impacts of an entire building. 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 (Finnveden et al., 2009). Its purpose is to quantify the energy and material flows associated with each life cycle stage from raw material extraction through material processing, manufacture, distribution, use and maintenance, and end-of-life for a given product or service (Hunt and Franklin, 1996). Today, life cycle assessment

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forms the analytic basis for many performance-based sustainability design approaches (McAloone and Bey, 2009).

Numerous life cycle assessment studies have investigated the environmental sustainability impacts of constructed facilities. The consensus to date has been that the majority of life cycle energy and carbon impacts are accrued during the use phase. Junnila and Horvath (2003; Junnila et al., 2006) found that for commercial structures over 90% of life cycle energy consumption and 80% of carbon dioxide emissions stem from the use phase of the building. Scheuer et al. (2003) found that over 95% of life cycle energy impacts are a result of use phase consumption in a case study of a new university building. In an economic input–output LCA of residences, Ochoa et al. (2002) determined that greater than 90% of energy consumption and carbon dioxide emissions are attributable to the use phase. In a comprehensive review of 16 other studies, Sartori and Hestnes (2007) found significant impacts throughout the life cycle of constructed facilities, with strong correlation between total life cycle energy consumption and operating energy consumption. Gustavsson et al. (2010) also found that use phase impacts dominate life cycle impacts, but that choice of heating system for a residential structure can affect these impacts. Keoleian et al. (2001) 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.

Several studies have specifically analyzed energy efficient buildings or buildings that incorporate on-site electricity generation to determine how these factors affect the distribution of life cycle environmental impacts. Blanchard and Reppe (1998) examined residential structures that use highly energy efficient materials and operation technologies and found that such technologies push impacts from the use phase onto the material production and construction phases, increasing the embodied impacts of built environments. Further, Faludi and Lepech (2012) found that the priority for sustainable building design is reducing use phase energy consumption. Faludi et al. (2012) noted that even buildings designed to be energy efficient, using advanced prefabrication manufacturing and including onsite solar photovoltaic generation, attribute 60% of life cycle impacts to 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.

New building design and construction offers an opportunity to reduce impact on the natural environment, and as a result, to reduce operational costs and energy scarcity concerns. The potential exists to create built environments that meet the needs of economy, utility, durability, and comfort and are environmentally responsible and resource-efficient throughout their life cycle (US EPA, 2010). To date, LCA has predominantly been used to retroactively calculate the impacts of buildings (Peuportier et al., 2013); however, LCA can be a useful tool during building design (Basbagill et al., 2013). LCA can be leveraged to inform building design decisions from an environmental perspective (Khasreen et al., 2009).

LCA has been explored as a tool for design of products and has been found to be valuable for quantified product-oriented environmental management (Guinee et al., 1993a). The LCA methodology can be used to determine, at the design phase, a product's impacts over its entire life cycle and to quantify which components are most impactful (Keoleian, 1993) – however, LCA has often been avoided due to the detailed data required and lack of simplicity of available tools (Guinee et al., 1993b; Ellram et al., 2008). This paper introduces a method and software assessment tool to inform decisions that impact the entire life cycle of a building during the design phase. The goal is to provide a user friendly tool to inform and drive design decisions from an environmental perspective. From a cost perspective, target value design (TVD) has been used to reduce building design and construction costs and inform design decisions. This paper presents a parallel method, based on the integration of LCA and TVD, for environmental impacts.

3. Target value design

The concept of target costing has been implemented in manufacturing for several decades and was first popularized by Japanese manufacturers (Zimina et al., 2012). In this process, the target cost is determined and the product designed and redesigned iteratively to meet it. Target value design (TVD) is target costing applied to building construction projects (Ballard, 2008). It is a management technique used in building design and construction in order to drive designs that deliver customer values and are within project constraints. Historically, buildings were 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 (like time and location) in order to deliver value (Ballard, 2008).

Target costs are set early on, when the project goals are being defined. They are set below allowable cost and often assume better than "best practice" performance. TVD has been effective in the development of fast, dynamic, and complex projects (Ballard and Reiser, 2004; Ballard and Rybkowski, 2009). Studies have shown that TVD provides an 'integrated' method to facilitate a collaborative life cycle costing (LCC) assessment process by increasing the level of shared understanding and communication among stakeholders (Woo Lee, 2012). Ballard demonstrated TVD as an effective method to reduce project cost, finding a range of 6–21% cost savings and an average savings of 14% across six projects that incorporated TVD methodology (Ballard, 2008).

Initially used for design and construction, Ballard has since explored broader application of TVD to whole-life cost concerns (Ballard, 2008). Whole-life TVD is a broad application of TVD involving facility operation and user costs beyond first costs (e.g. design and construction costs). This integrated approach combines life cycle costing and TVD, and enables comparison of life cycle cost impacts of design alternatives at the design phase (Pishdad-Bozorgi and Karasulu, 2013). This approach also provides building stakeholders monetary information on the tradeoffs between design and operational decisions so they can make design decisions that improve life cycle costs (Woo Lee, 2012). In parallel, the methodology of setting targets for the facility life cycle from the design phase can be implemented for environmental metrics. The methodology of setting and analyzing environmental target values is developed and demonstrated in this paper. This method, called sustainable target value (STV) design has been developed by leveraging LCA and whole life TVD in building design in an effort to produce significantly more environmentally sustainable buildings.

4. Sustainable target value (STV) design – target-setting rationale

The goal of STV design is to reduce the environmental impacts of buildings throughout their life cycle by setting targets for environmental indicators at the design phase. The indicators chosen were primary energy and water consumption as major resources used during building operation and global warming potential (GWP) and ozone depletion potential (ODP) as global pollutants. The hypothesis was that setting STVs would produce life cycle environmental impact reductions parallel to the cost reductions resulting from traditional TVD.

A major challenge arose in determining how to set the targets. While building cost data is prevalent and standardized, making "better than standard" targets easier to determine, environmental