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Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices

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ABSTRACT

Construction of residential buildings using off-site methods, in particular modular construction, is receiving considerable attention. However, the sustainability performance of modular buildings has rarely been investigated through a life cycle perspective. In this paper, a life cycle sustainability performance assessment framework is developed for modular buildings and its application is examined. In the first part of the paper, suitable life cycle sustainability performance criteria (SPCs) for modular buildings were developed and ranked. In this regard, potential SPCs were identified through a comprehensive literature review and expert interviews. These SPCs were then evaluated by construction experts through two questionnaire surveys against three evaluation criteria: applicability, data availability, and data accuracy. The evaluation criteria's weights were determined through a group decision making process using the Analytic Hierarchy Process (AHP) multi-criteria decision analysis (MCDA) method. Consequently, the experts' feedback was analyzed with the help of the Elimination and Choice Translating Reality (ELECTRE) outranking MCDA method and all the SPCs were ranked within their associated sustainability categories (i.e., environmental, economic, and social). In the second part of the paper, application of the proposed framework has been discussed and validated through a case study of a modular building in British Columbia, Canada. Sustainability performance of modular buildings in the proposed framework were assessed by developing aggregated sustainability indices for the selected SPCs and comparing them with corresponding benchmarks. In this regard, appropriate sustainability performance indicators (SPIs) under each selected SPC have been developed and calculated. Consequently, through an aggregation process, sustainability indices are developed using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) MCDA method. In this paper, the environmental life cycle performance of the case study building has been benchmarked and recommendations have been made for performance improvements. This research is deemed useful for the construction practitioners since it provides a methodical framework for life cycle sustainability performance assessment of modular buildings and assists with the selection of sustainable methods of construction.

1. Introduction

1.1. Background

Similar to 'conventional' 'stick-built' (on-site) buildings, buildings constructed using modular construction method are permanent structures. These two types of buildings differ in their respective life cycle phases. The main difference is the design and construction phase. In the case of modular construction, the building is designed based on a number of modules, in which they are built in a modular construction facility for majority of the construction work and then transported to the building site and placed on a permanent foundation [1,2].

According to the published literature, modular construction as one of the principal methods of off-site construction offers various advantages. Speed of construction, safety, productivity, product quality, and less environmental impacts, are among the advantages of using modular construction [3–10]. Conversely, transportation restraints, increased coordination and communication, and public's negative perception are among the disadvantages of this method of construction [11–14].

Despite many reported advantages of modular construction, its application is still limited when compared to the conventional construction approach [15–18]. This is mainly because the various advantages of using modular construction are not well understood by different stakeholders [19–21].

Many studies claimed that certain buildings are 'sustainable' only

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because they perform well in some aspects, such as energy consumption. In other words, sustainability has often been considered and evaluated exclusively according to the environmental dimension and thus 'sustainable building', 'environmentally sustainable building', and 'green building' are known terms that are interchangeably used. However, this approach is not appropriate for determining a sustainable building [22–25]. The concept of sustainability has been categorized in the environmental, social and economic dimensions (namely triple bottom line or TBL) [26]. The environmental dimension indicates minimizing the environmental impacts over the life cycle of a building [27]. The economic dimension implies the affordability to support the direct and indirect costs of a building, without neglecting other essential needs [28]. However, this requisite depends on the context and people and also recalls the time uncertainty of economic sustainability. In fact, a change in what is an economically sustainable choice in buildings is possible according to economic cycles and markets developments. A sustainable building should deliver economic value over time, taking into account future life-cycle costs of operation, maintenance, refurbishment and disposal [27]. The social dimension of a sustainable building is the most ignored one as it was rarely investigated. However, some studies mentioned the characteristics of a building that encourages social sustainability [29–31]. It is not expected from a building to simultaneously show the best environmental, economic, and social performance, since in some cases they are contradictory. For example, construction of an energy efficient building requires more costs. Therefore, balancing the impacts of a building on these three dimensions (not individually maximizing/minimizing) over the entire life cycle is a key factor towards sustainable buildings.

Sustainability assessments are intended to gather and provide information to ease decision-making processes [32]. Several methodologies and systems have been developed and published to assess the level of sustainability in buildings. One of the widely used sustainability assessment methods includes the rating systems (also called green building rating systems). Several rating tools that are used to assess environmental sustainability of buildings include, LEED (International), Green Globes (US and Canada), LBC (International), BREEAM (International), CASBEE (Japan), among others. Rating systems deal with mainly environmental sustainability performance of buildings by providing a set of performance criteria and scoring each building project based on those criteria. These systems examine the current performance or the expected performance of a "whole building" and allow comparison of different buildings [33]. Despite many advantages, a number of shortcomings were reported with the use of some of the rating systems, such as the complexity and diversity of criteria (e.g., energy modelling), the bureaucratic process of assessment, and cost factors (e.g., assessment collation and certification fees), and so forth [34]. Another important category for conducting (environmental) sustainability assessment of buildings consists of the life cycle assessment systems or LCA-based tools, such as ATHENA (US and Canada), BEES (US), Eco-Quantum (Netherlands), EcoEffect (Sweden), ENVEST (UK), among others. LCA-based tools were mainly developed to evaluate the life cycle environmental impacts of a building as a whole. They usually follow a bottom-up approach, meaning that the impacts of the building's materials and components are combined to determine the environmental impacts of the whole building [35].

1.2. Sustainability of modular buildings

A literature review of modular construction revealed that there were only a very few studies that had been conducted on the environmental life cycle assessment of modular buildings [36]. This work also showed that there was no sustainability performance assessment research that addressed all triple bottom line (TBL) sustainability dimensions of modular buildings over their life cycle. Therefore, it is necessary to comparatively evaluate the life cycle sustainability of buildings built by modular construction method and its counterparts (conventional construction) to gain a deeper understanding of the sustainability performance of modular buildings.

The main objective of this research is to propose a methodical framework that can be used to benchmark the life cycle sustainability performance of residential modular buildings. To attain the main objective, the following specific sub-objectives have been accomplished in this paper:

- Identification and selection of appropriate sustainability criteria for modular buildings;
- Determination of suitable sustainability indicators under each sustainability criterion as well as their weights, measurement methods, and benchmarks;
- Development of sustainability indices for benchmarking the performance of modular buildings; and
- Validation of the proposed framework with a case study modular building.

The framework presented in this paper is intended to assist with making informed decisions on selection of the best method of construction (modular vs. conventional). Furthermore, it can be used to explore and improve the low sustainability performing areas over the life cycle of a new modular building design, even if the decision on the construction method has already been made. The methodology outlined in this paper can also be adopted for sustainability assessment benchmarking in other construction practices or by researchers in other fields to evaluate a process or product's performance metrics with respect to their benchmarks.

This paper is structured as follows: Section 2 outlines the methodology of the proposed framework and explains how the detailed analyses are conducted. Results of the conducted surveys and analyses followed by discussions are presented in Section 3. Within the same section, for the proof-of-concept, the proposed framework has been validated with a case study of a modular building in the Okanagan, British Columbia, Canada. The last section (Section 4) briefly summarizes the main conclusions and recommendations for future study.

2. Methodology

The conceptual framework proposed in this research for sustainability assessment of modular buildings is presented in Fig. 1. The framework consists of two main parts that have been separated by a dashed line in the figure. In the first part, primary potential sustainability performance criteria (SPCs) were compiled and grouped into three main sustainability categories through screening the existing criteria available in the literature. Three SPC evaluation criteria were defined and their importance weights were assigned with the help of the Analytic Hierarchy Process (AHP) multi-criteria decision analysis (MCDA) method. Then, two questionnaire surveys were designed and conducted to evaluate the SPC categories against the evaluation criteria. The construction experts' feedback collected through the surveys was analyzed using the Elimination and Choice Translating Reality (ELECTRE) MCDA method to rank the SPCs within the sustainability categories. In the second part of the framework, the application of the developed SPC categories in the sustainability performance assessment of modular buildings was shown. First, by considering the rank orders, maximum possible number of SPCs within the intended sustainability category is selected depending on circumstances of the building project. To develop sustainability indices for the selected SPCs, suitable sustainability performance indicators (SPIs) associated with each SPC along with their measurement methods and relative importance weights have been determined using the literature and expert opinions. The concept of performance level (PL) was introduced for normalization of the calculated SPIs with respect to their benchmark values. Then, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) MCDA method has been used to develop the