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SUSTAINABILITY PERFORMANCE ASSESSMENT: A LIFE CYCLE BASED FRAMEWORK FOR MODULAR BUILDINGS

Mohammad Kamali[1, 2] and Kasun Hewage[1]
[1] School of Engineering, University of British Columbia, BC, Canada
[2] mohammad.kamali@ubc.ca

ABSTRACT

Appropriate methods of construction can significantly contribute to achieving the goals of sustainability. In this regard, sustainability performance assessment of a building in its full life cycle is needed to select most sustainable construction methods. In this paper, a life cycle based performance assessment framework is proposed for modular buildings. The proposed framework follows a step-by-step approach to identify and select appropriate sustainability indicators (and sub-indicators) for modular buildings, quantify the selected indicators, and develop the least/most desirable performance values. Subsequently, the proposed framework provides a methodology to calculate the overall sustainability performance index of a given building as well as individual sustainability performance indices for each of the sustainability categories, i.e., environmental, economic, and social. In addition, under each sustainability category, different sustainability performance sub-indices associated with the building's life cycle phases are derived separately. The calculated sustainability indices will help decision makers to make informed decisions on the most appropriate construction methods (i.e., modular vs. conventional) on a given project. The outcomes can also be used to address the low sustainability performing areas over the life cycle of a building, even if the decision on the construction method has already been made.

Keywords: Life cycle sustainability assessment, performance assessment, sustainability indicators, benchmarking, modular construction, multi-criteria decision analysis

1- INTRODUCTION

Different types of buildings, i.e., residential, commercial, medical, industrial, among others, have had a vital role in people's life today. However, their method of construction and the subsequent impacts on the environment and the societies can be significantly different. Consequently, attention to the impacts of buildings and the construction industry on the environment, society, and economy has been increasing rapidly in recent years. In terms of the economic impacts, for example, the construction industry accounts for 6% and 7.5% of Canada's and Australia's GDP, respectively (Statistics Canada 2011, Zuo and Zhao 2014). The resource depletion and environmental impacts of buildings is also significant. For example, buildings are responsible for up to 40% of the total energy consumption (WBCSD 2008). In the case of the social significance of buildings, both the occupants and neighbour communities are affected. There are social impacts on occupants, such as health, well being, satisfaction, and safety, and also on surrounding neighborhoods, such as construction noise and dust, traffic congestion, and local social development.

Modular construction is one of the main off-site construction methods that is claimed to be beneficial to the environment and societies (Ahn and Kim 2014). However, similar to any new product, technology, etc., its usefulness should be evaluated and compared to its counterpart conventional construction. In addition, to consider a modular building as a sustainable one, the evaluation process should be carried out by addressing all the sustainability dimensions and all life cycle phases of the building. Even though a few studies assessed the environmental performance of modular buildings, a comprehensive literature review conducted by Kamali and Hewage (2016) did not find any sustainability assessment studies of modular buildings that addressed all sustainability dimensions and all life cycle phases. Therefore, holistic life cycle performance assessment studies of buildings built using modular construction are imperative.

This paper discusses a new methodology to assess sustainability performance of residential modular buildings. In the proposed framework, the modular buildings' sustainability is assessed through integrating the sustainability criteria from all the sustainability dimensions (environmental, economic, and social), and their desirable performance values using multi-criteria decision analyses (MCDA). The proposed framework is intended to be used by the construction practitioners, such as building designers and developers, decision makers, and so forth, in selecting the construction methods with the capability of achieving the life cycle sustainability. The methodology outlined in this paper can also be adopted for sustainability assessment benchmarking of other construction practices or products/processes in fields other than construction.

2- BACKGROUND

A brief background on sustainable buildings and modular buildings is provided in the following sections.

2.1 Sustainable buildings

Many studies claimed that certain buildings are 'sustainable' only because they perform excellent in some directions, for example, when a building is only slightly less energy-demanding than buildings constructed using conventional practices. However, this is not adequate for representing a sustainable building (Harvey 2006). This misconception originated from paying attention to only the environmental impacts of buildings, which mainly associated with the concept of green buildings, and neglecting the impacts of the other significant dimensions, i.e., economic and social. The attention to environmentally responsible buildings initiated in the middle of the last century (Kibert 2016). To date, sustainable buildings are often confused with environmentally responsible buildings, in particular energy efficient buildings, as it is shown by the interchangeable use of the terms: sustainable building, green building, and high performance building.

The above mentioned aspects, i.e., environmental, economic, and social, are known as the main dimensions of sustainability or triple bottom line (TBL). The economic dimension implies the affordability to support the direct and indirect costs of the building, without neglecting other essential needs (Son et al. 2011). 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 (Chiu 2002, Parr and Zaretsky 2010, Dempsey et al. 2011). A building should perform environmentally, economically, and socially responsible to be considered sustainable. However, 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 the building on these three dimensions (not individually maximizing/minimizing) over the life cycle is a key factor towards sustainable buildings.

The literature developed various criteria (so-called indicators) from all the three sustainability dimensions that can contribute to sustainability over the life cycle of buildings. For example, in a sustainable building, the environmental impacts can be neutralized by including its context and regeneration (e.g., use of renewable materials and energy). In addition, market and economic value as well as the demand for safe building, flexibility, occupants' well-being and satisfaction, aesthetics improvements, and so forth, are enhanced (Barari 2013).

2.2 Modular buildings

The construction industry has been exposed to the process of industrialization in recent decades. Therefore, off-site construction played an important role as an alternative to the conventional (on-site) methods of construction. Off-site construction refers to the process of manufacturing and preassembling of building elements, components or modules prior to their installation on the final jobsite (Goodier and Gibb 2007). Based on the degree of work off the construction site, off-site construction is categorized into component subassembly, non-volumetric preassembly, volumetric preassembly, and complete construction (Gibb and Pendlebury 2006). The latter category is also known as modular construction in which different materials and components are assembled in a manufacturing center and form fully finished modules. This also includes all the mechanical, plumbing, electrical, and trim work. Upon completion, the modules are transported to the final project site and installed on permanent foundations to form the final building (O'Brien et al. 2000). Majority of the work is performed off-site and only approximately 15% is done on the project site, such as foundations and utility hookups (Kawecki 2010).

This method of construction can be applied to different types of buildings, such as residential single and multi-family buildings, educational centers and student housing, hospitals, offices, and hotels. However, the use of this method is still limited in practice. For example, buildings in the developing countries are rarely constructed using off-site and modular construction methods (Mao et al. 2015). Although the use of modular construction in the building sector of the developed countries is more than that of the developing countries, it is not still extensive (Quale et al. 2012). According to the literature, the public's negative perception of off-site construction methods is one of the significant challenges to modular construction. This is because of the difficulty of ascertaining the advantages that modular construction provides over the traditional methods. For example, modular and prefabricated homes are usually believed as trailers or mobile homes or manufactured houses (Boyd et al. 2013, Haas et al. 2000). However, similar to a conventional building, a modular building is a permanent house that is built according to codes which are more restrictive than the codes for temporary and transportable trailers. For many of those involved in the construction industry, the benefits of off-site construction techniques were not well understood. Therefore, decisions on the selection of off-site construction methods are mostly made according to anecdotal evidence rather than solid analytical evidence (Na 2007, Pasquire and Gibb 2002, Blismas et al. 2006).

3- SUSTAINABILITY PERFORMANCE ASSESSMENT OF MODULAR BUILDINGS

The proposed sustainability performance assessment framework in this research is based on the least and most desirable performance values. It consists of five phases as illustrated in Figure 1.

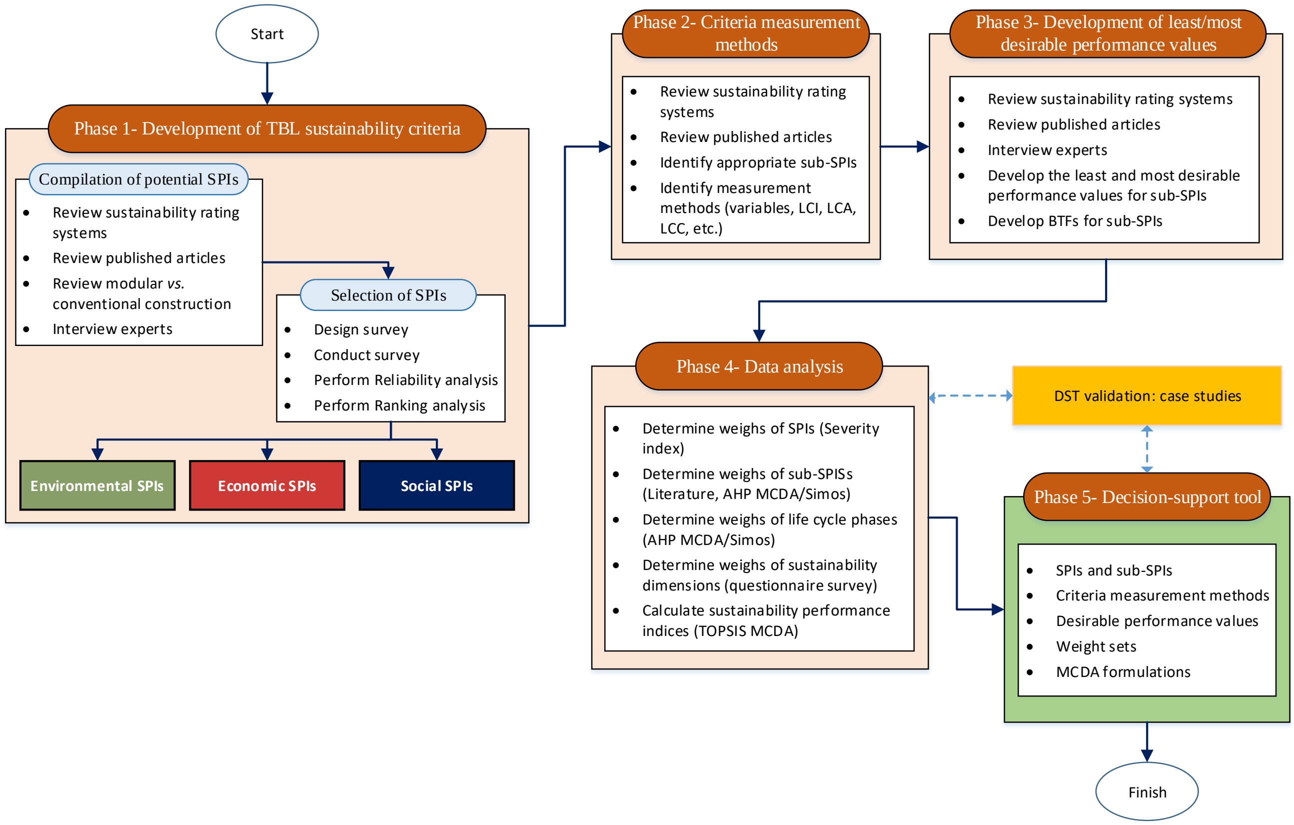

Figure 1: The conceptual sustainability assessment framework presented in this paper.

The framework follows a bottom-up approach and consists of five phases. It commences with identifying the appropriate sustainability criteria, namely sustainability performance indicators (SPIs), and the corresponding sub-criteria. It then focuses on the measurement methods of the sub-SPIs as well as the development of their least and most desirable performance values to calculate the performance level of each parent SPI. Eventually, a set of sustainability indices in different layers, i.e., life cycle phase layer, sustainability dimension layer, and finally, overall sustainability layer are derived for the building. After taking all the above steps (Phases 1-4), the results are incorporated in a decision-support tool (Phase 5). Each phase is described in the following sections. In addition, some of the results of implementation of these phases are briefly presented.

3.1 Phase 1- Development of TBL sustainability criteria

Sustainability performance indicators (SPIs), are employed to assess the sustainability of a product or process. According to Robert et al. (2005), indicators are used to measure program, status, and change towards achieving the goals of sustainability. Sustainability indicators can be used for different purposes, such as sustainability comparisons among similar buildings, performance assessment, decision making, among others. There are numerous sustainability indicators that have been reported in the literature for the built environment; however, many of them may not be suitable for a given construction project. Therefore, to efficiently appraise the sustainability performance of every construction project, first, a set of appropriate SPIs that suit the conditions of the project, should be identified and selected. In this regard, the objective of Phase 1 is to compile the most significant SPIs that are relevant to assess the sustainability of modular versus conventional buildings. This objective was achieved through conducting literature reviews, questionnaire surveys, and expert interviews as well as performing reliability analysis and ranking analysis as outlined below.

A literature review has been performed to compile the primary potential SPIs. Two categories of sources were used for the review. The first source category consisted of sustainable building rating systems that are mainly intended to be used internationally, such as Leadership in Energy and Environmental Design

(LEED) and Living Building Challenge (LBC), or in North America, such as Green Globes. The second source category comprised other published documents related to sustainable construction, such as journal and conference papers, by which relevant sustainability indicators for one or more sustainability dimensions were provided. A number of rounds of screening has been completed to compile the primary potential SPIs. First, a long list of sustainability indicators was created and depending on the nature of an indicator, it was categorized into one of the sustainability categories (environmental, economic, or social). After that, indicators with the same meaning but different terminology were merged into a one indicator. Then, those indicators that had relationships or overlaps were combined or modified. In this regard, a number of main SPIs were developed in which other indicators can be represented under them (called sub-SPIs in this paper). The final step was to narrow the SPI list down by identifying the frequency of each SPI in the reviewed literature. To ensure the comprehensiveness of the developed SPIs, a separate literature review as well as informal expert interviews were conducted. Eventually, based on the literature reviews and interviews, the final developed TBL sustainability indicators included 12 environmental SPIs, 9 economic SPIs, and 12 social. Details can be seen in Kamali and Hewage (2015, 2016).

In order to select the most appropriate SPIs, the developed TBL SPI categories were evaluated based on their applicability for sustainability assessment of residential modular buildings. A questionnaire survey was designed and conducted with experts in the construction industry and academia. Then, reliability analysis and ranking analysis (severity index method) were applied to determine the importance levels of SPIs and rank them within the associated sustainability categories. Table 1 shows the importance level of each SPI within the associated sustainability category. See Kamali and Hewage (2017) for details.

Depending on the decision makers' limitations in a building project, such as time, cost, data availability, and so forth, maximum possible number of the top SPIs under each sustainability category can be selected (according to their rank orders) and used in the sustainability performance assessment framework. In this paper, it is ideally assumed that none of the above mentioned limitations exist; thus, all the SPIs with the importance level higher than 'Low' are selected to be included in the assessment process. Consequently, 9 environmental SPIs, 9 economic SPIs (all of them), and 9 social SPIs are chosen (Table 1).

Table 1: Importance levels of the developed TBL SPIs (adapted from Kamali and Hewage 2017).

	SPI	Rank	Importance
Environmental category	Waste management	1	High
	Energy performance and efficiency strategies	2	High
	Material consumption in construction	3	High
	Greenhouse gas emissions	4	High
	Site disruption and appropriate strategies	5	Medium
	Renewable and environmentally preferable products	6	Medium
	Embodied Energy	7	Medium
	Regional (local) materials	8	Medium
	Renewable energy use	9	Medium
	Site selection	10	Low
	Water and wastewater efficiency strategies	11	Low
	Alternative transportation	12	Very Low
Economic category	Design and construction time	1	Very High
	Design and construction costs	2	Very High
	Durability of the building	3	High
	Integrated management	4	High
	Investment and related risks	5	High
	Operational costs	6	High
	Flexibility	7	Medium
	Maintenance costs	8	Medium
	End of life costs	9	Medium
Social category	Workforce health and safety	1	Very High
	Community disturbance	2	High

Safety and security	3	High
User acceptance and satisfaction	4	High
Affordability	5	High
Functionality and physical space usability	6	Medium
Influence on the local economy	7	Medium
Aesthetic options and beauty of the building	8	Medium
Health, comfort and well-being of occupants	9	Medium
Influence on local social development	10	Low
Neighborhood accessibility and amenities	11	Low
Cultural and heritage conservation	12	Very Low

3.2 Phase 2- Criteria measurement methods

As mentioned above, the developed SPIs are the main sustainability criteria in which each SPI may (or may not) also have a number of sub-SPIs. In this phase, appropriate sub-SPIs under each selected SPI in the previous phase are identified and their measurement methods are explored.

The proposed methodology aims at evaluating the performance of modular buildings with the life cycle view. Therefore, the selected SPIs within each sustainability category (e.g., environmental SPIs) are placed in the associated life cycle phase clusters, i.e., ‘design and construction’, ‘occupancy or use’, and ‘end of life’. Figure 2 shows the life cycle phase clusters and the corresponding SPIs for the environmental category. Majority of the environmental SPIs were found to be in the design and construction cluster. In cases where a SPI can belong to two or all three life cycle phases, it is split and redefined under the corresponding clusters. For example, ‘waste management’ strategies, i.e., reduce, reuse, and recycle, are significant in all the life cycle phase that can prevent from resource depletion and reduce environmental consequences of waste disposal. However, as far as the generated waste due to the construction (or demolition) activities is concerned, these strategies can be implemented during the design and construction phase and also the end of life phase. The waste generated in the use (occupancy) phase is municipal waste which is not related to the building. Therefore, this SPI was redefined as ‘construction waste management’ and ‘end of life waste management’.

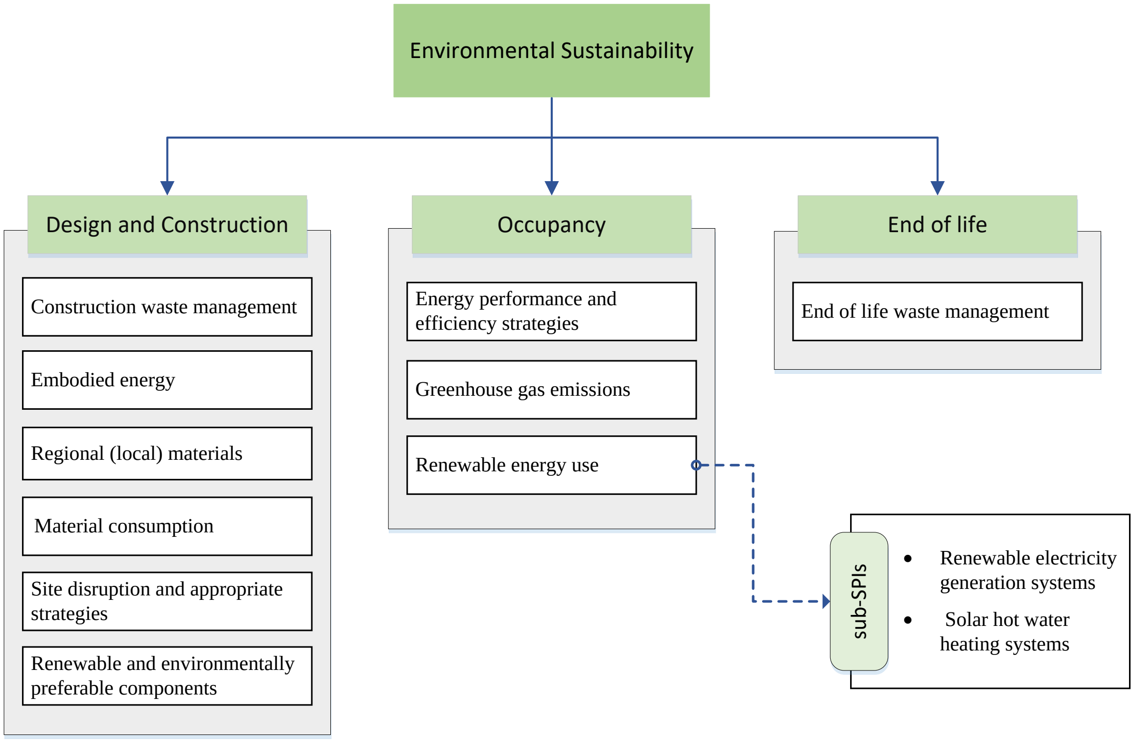

Figure 2: The selected environmental SPIs and corresponding life cycle phases

To identify the suitable sub-SPI under each selected SPI and their measurement ways, a literature review needs to be conducted. The literature regarding sustainability (green) rating systems and other published studies have been reviewed by the authors. Similar to what has been done in Phase 1, through a few screening processes, all sub-SPIs related to a SPI were recognized, listed, renamed, and refined. For example, the SPI ‘renewable energy use’ which is in the occupancy cluster came out to have two sub-SPIs namely ‘renewable electricity generation systems’ and ‘solar hot water heating systems’ as seen in Figure 2. The sub-SPIs corresponding to a number of the environmental SPI are listed in Table 2.

Table 2: The environmental SPIs, associated sub-SPIs, and their units of measurement.

SPI	sub-SPI	unit
Construction waste management	Plan for material efficient framing	Yes/No
	Construction waste reduction	%
	Reuse of recycled aggregates	%
Embodied Energy	Raw material extraction	MJ/kg, MJ/m^2
	Raw material transport	MJ/kg, MJ/m^2
	Product manufacture	MJ/kg, MJ/m^2
	Product transport	MJ/kg, MJ/m^2
	Installation	MJ/kg, MJ/m^2
Greenhouse gas emissions	Electricity	kWh
	Heating (natural gas, propane, diesel, etc.)	m^3, L
Renewable energy use	Renewable electricity generation systems	AREL (%)
	Solar hot water heating systems	DHW (%)

Once all the sub-SPIs are identified, the next step is to find the appropriate ways to measure them. By reviewing the literature, it was found out that in some cases there are different methods proposed to calculate a sub-SPI. The approach followed in this paper is to choose the simplest methods by which each sub-SPI can be measured by having the minimum amount of data. The detail descriptions of the sub-SPI measurements methods are beyond the aim and scope of this paper. Another important point noticed during the literature review process was that the sub-SPIs under a SPI do not necessarily have the same unit. For instance, while all the sub-SPIs of ‘embodied energy’ are of the same unit, this is not the case for the two sub-SPIs of ‘renewable energy use’ (see the last column of Table 2). Therefore, the concept of *performance level* (*PL*) is introduced and employed in this paper to enable different units to be represented as a single unit. This concept is described in Phase 3 below.

3.3 Phase 3- Development of the least and most desirable performance values

As stated above, the proposed framework is constructed on the life cycle sustainability performance assessment of TBL SPIs. In other words, the life cycle performance of modular buildings can be assessed by comparing the buildings’ calculated SPI values with the corresponding least/most desirable performance values. However, because many of the developed SPIs include more than one sub-SPI, establishing the least/most desirable performance value of a SPI requires establishing the least/most desirable performance values of corresponding sub-SPIs. Furthermore, in cases the sub-SPIs of a SPI are of different units, a normalizing method is needed so all the calculated sub-SPIs can be represented by the same unit, called performance level in this paper, and combined to obtain the SPIs’ performances.

In this regard, first, the least and most desirable performance values for each and every sub-SPI in residential conventional buildings should be established with the help of published literature (rating systems, public reports, etc.) and expert and stakeholder consultations. Consequently, the least desirable performance and the most desirable performance of a sub-SPI are assigned the performance levels of 1 and 10, respectively. The desirable performance values available in the literature are presented in different ways. In some cases, they are stated based on specific values. For example, Buchanan and Honey (1994) estimated the least ‘embodied energy’ requirements (i.e., most desirable performance) as 218 GJ for house construction in New Zealand, using several different designs for a typical small house (94 m^2 floor area). However, in some other cases, the performance of a building with respect to a criterion is valued by assigning points. For example, Canadian version of LEED assigns 1 point for every 3% of the annual reference electrical load (AREL%) met by the building's 'renewable electricity generation systems' (maximum 10 points) (CaGBC 2009). Therefore, the least and most desirable performance levels of this sub-SPI come out to be 1 for AREL=3% and 10 for AREL=30%. For those sub-SPIs in which there are no desirable performance values available in the literature (mostly qualitative SPIs), these values are determined based on expert opinions. For example, one of the sub-SPIs for the social SPI 'safety and security' can be related to the type of door and window locking mechanisms. The best and worst performance of this sub-SPI can be determined by expert ranking of different commonly used locks in buildings.

For a given building, the calculated values of sub-SPIs are then compared to the desirable performance levels using benchmarking transformation functions (BTFs). Consequently, an effort has been made to develop appropriate BTFs (linear, polynomial, etc.) according to the availability of benchmark values. These BTFs transform the calculated value of each sub-SPIs into a performance level ranging from 1 to 10, with 1 being poor (i.e., least desirable performance) and 10 being excellent (i.e., most desirable performance). As an example, a polynomial BTF was developed for 'renewable electricity generation systems' as:

[1] $PL = 9\text{E-}13\ (AREL\%)^2 + 30(AREL\%) + 1$

Where PL is the performance level of the sub-SPI (between 1 and 10), and AREL is the percentage of the annual reference electrical load in the building.

It is important to note that, for some sub-SPIs, an increasing trend (benefit criterion), whereas for others a decreasing trend (cost criterion) is desirable. Using the explained methodology, all the sub-SPIs can be expressed by the same unit (i.e., performance level), regardless of their original units of measurements. Upon completion of these steps, the performance levels of all sub-SPIs under a SPI can be aggregated to obtain the performance level of the SPI using a suitable MCDA method (see Phase 4 below).

3.4 Phase 4- Data analysis

As mentioned earlier, the proposed framework provides a methodology to evaluate the sustainability of modular buildings in different layers from a single sub-SPI's performance to the building's overall performance. In this regard, for each sustainability category (e.g., environmental category), an individual sustainability performance index and three sub-indices are derived and used to state the sustainability performance of modular buildings. The sustainability performance sub-indices are defined according to the three life cycle phase clusters described previously. Therefore, the three overall sustainability performance indices and nine sustainability performance sub-indices (= 3 sustainability dimensions × 3 life cycle phases) are named as follows:

- Environmental sustainability index (En-SI)
    - Environmental construction phase sustainability index (En-CSI)
    - Environmental use phase sustainability index (En-USI)
    - Environmental end of life phase sustainability index (En-ESI)
- Economic sustainability index (Ec-SI)
    - Economic construction phase sustainability index (Ec-CSI)
    - Economic use phase sustainability index (Ec-USI)
    - Economic end of life phase sustainability index (Ec-ESI)
- Social sustainability index (So-SI)
    - Social construction phase sustainability index (So-CSI)
    - Social use phase sustainability index (So-USI)
    - Social end of life phase sustainability index (So-ESI)

Furthermore, by combining the above indices, an overall TBL sustainability index, namely TBL-SI, can be calculated which states the overall life cycle sustainability performance of the building under study.

In order to evaluate a building's sustainability performance based on the relative closeness of the calculated performance score of individual SPIs to the most desirable performance and also the remoteness from least desirable performance, there is a need of an aggregation approach based on the synthesizing criterion (Figueira et al. 2005). Therefore, the Technique for Order reference by Similarity to Ideal Solution (TOPSIS) method of MCDA is used to aggregate the performance levels of the SPIs to develop the above mentioned sustainability indices in different layers. The indices developed by TOPSIS are based on the concept of similarity (i.e., relative closeness) to the positive-ideal solution (PIS) and the remoteness from the negative-ideal solution (NIS) (Hwang and Yoon 1981). The method assumes that the performance level of each indicator is either a monotonically increasing or decreasing function, which means the higher value of index corresponds to higher performance (Haider 2015).

TOPSIS MCDA method can be employed only when the relative importance weights of the items in a layer (i.e., sub-SPIs, SPI, life cycle phases, or sustainability dimensions) are available. Therefore, the next imperative task is to determine the following weight sets:

- sub-SPIs under each SPI
- SPIs under each life cycle phase cluster
- life cycle phase clusters
- sustainability dimensions

This can be performed through AHP method (Saaty 1980), Simos' weighting method (Figueira and Roy 2002), or any other appropriate methods. For example, the relative importance weights of the selected SPIs under life cycle phase clusters, can be derived from the results of ranking analyses (severity index values) previously conducted by the authors (Kamali and Hewage 2017).

3.5 Phase 5- Decision-support tool

The results of implementation of Phases 1-4 including the developed SPIs, the identified sub-SPIs and their measurement methods, the sub-SPIs' desirable performance levels and associated BTFs, and the weight sets, will be incorporated in a decision-support tool. In addition, the applicability of the proposed decision-support tool will be demonstrated by performing a number of case study analyses for modular buildings. The building with the highest sustainability performance index associated with each life cycle phase (or any other layer depending on the aim and scope of the assessment) can be considered as the benchmark building for that layer. Thus, any other case study building's performances can be compared with this building to find the performance gaps and ways for improving their performance within that layer.

The user of the developed decision-support tool needs to provide the data of the subject modular building. This data is required to calculate the sub-SPIs using the developed measurement methods. Then, the performance levels of the sub-SPIs, and subsequently SPIs can be calculated. Finally, the sustainability indices are derived which can help the user to identify the sustainability performance of the building with respect to the benchmark building in the intended layer. This can lead to choose or reject the current modular practices that are going to be employed to construct the building. In addition, it can assist the user to adopt appropriate strategies to enhance the sustainability performance of the building by identifying and addressing the low performing areas over the life cycle of the building.

4- CONCLUSIONS

This paper presents a new framework in sustainability assessment of residential modular buildings. The core of the proposed methodology is life cycle performance approach by which the gap for the analytical relationships between modular and conventional buildings in terms of sustainability is covered. It is important to note that this framework is only a base model for sustainability assessment of modular buildings. Future research could focus on the interrelationships between the SPIs within a life cycle phase cluster, between SPIs of different life cycle phase clusters, and between SPIs of different sustainability categories. This helps to determine more realistic weight sets; therefore, more realistic sustainability indices are calculated through using multi-criteria analyses.

The life cycle based framework presented in this paper is intended to assist the construction practitioners, such as building designers, decision makers, and developers, to assess the life cycle sustainability performance of modular and conventional construction options to make informed decisions on selection of the best construction method. In addition, it can be used to address the low sustainability performing areas over the life cycle of a building, 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 of other construction practices or by researchers in other fields to evaluate the sustainability performance of a process or product with respect to its least and most desirable performances.

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