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Sustainability Assessment of a Residential Building using a Life Cycle Assessment Approach

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Building and construction industry is responsible for resource scarcity, global warming impacts, land use changes and the loss of bio-diversity, which have direct and indirect socio-economic implications. Sustainable building design is thus inevitable through the selection of highly durable and less energy intensive-materials that could reduce environmental degradation in an economically viable and socially acceptable manner. This paper presents the life cycle sustainability assessment (LCSA) framework to assess the environmental, social and economic objectives of residential buildings. Two buildings of different material compositions have been used to test this framework. Firstly, the service life of this building has been calculated as durability of building materials play a key role in enhancing resource conservation for the future generations. A factor method has been used to carry out the service life of each component of the building envelope. The minimum estimated service life of building systems is considered as the overall service life of building components. Secondly, a life cycle assessment framework utilising environmental life cycle assessment, life cycle costing and social life cycle assessment have been utilised to determine environmental, economic and social indicators of the studied buildings. All these triple bottom line indicators in this framework have been calculated on an annual basis in order to capture the advantage of increased service life of buildings. This framework will be applied to assess the sustainability performance of alternative buildings for comparative analysis and to find out the most sustainable building option.

1. Introduction

Construction industry has been estimated to consume 21 % of global energy consumption in 2040 and operational energy for buildings is expected to increase by 32 % by 2040 due to urbanisation in non-OECD countries. Australia is committed to reduce GHG emissions by 26 – 28 % below 2005 levels by 2030 (DOE, 2015). Approximately 3.3 x 10^6 houses are expected to build in Australia by 2030 (NHSC, 2011), contributing to GHG emissions. It is inevitable to design a sustainability assessment framework to overcome energy and environmental challenges associated with the growth of housing industries.

Sustainability is an ecologically focused development that considers carrying capacity to conserve natural resources for the future generation. Life cycle thinking (LCT) can help achieve sustainability as it considers environmental conservation, social equity, and economic prosperity associated with a product over its entire life beyond the traditional focus on production process. Life Cycle Assessment (LCA) is a commonly used method to materialise the theory of LCT, due to its consolidated way of analysing framework, evaluation of impact and characteristic of data. LCA is being used all over the world for socio-economic and environmental comparison of products, generating government policies, environmental product declaration, strategic planning and information collection and dissemination of product. Life cycle sustainability assessment (LCSA) is a comprehensive tool, to implement the LCT more effectively considering social, economic and environmental impact as a single entity to make a well-informed decision that is more sustainable throughout the product's life (UNEP, 2012). It applies ELCA (environmental life cycle assessment), LCC (life cycle components) and SLCA (Social life cycle assessment) tools to assess environmental, economic and social objectives of sustainability. The ELCA has been in use to assess the environmental impacts of building industry since 1990. ISO 14040 and ISO 14044 are the guidelines for the assessment. Along with ELCA, LCC

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became a crucial assessment in building industry with start of the 21st century. SLCA was used in buildings for the first time in 2012 to study the social impacts of construction and demolition sector. LCSA is quite an emerging approach to address the sustainability of the building sector. The life span of the product needs to be factored into the sustainability assessment process as durability is important for resource conservation. Unfortunately, in life cycle assessment research studies, scope is mostly limited to assumption of lifespan. Failing to consider the estimation of actual life span of products into sustainability assessment has resulted in the wastage of a large amount of energy in landfill. In building's sustainability assessment, Grant et al. (2014) considered the service life models to interpret the service life of buildings and find out the co-relation between the frequency of replacement and maintenance of buildings for entire life. Rauf and Crawford (2013) has featured the need of prediction of service life for ELCA of buildings and calculated the relationship between recurrent energy and building component life, showing reliance of sustainability on service life.

This study strives to incorporate service life of the building into LCSA. A LCSA framework for residential buildings has been developed to integrate the triple bottom line objectives of sustainability based on UNEP/ SETAC (UNEP, 2012), and factor method described in ISO 15686-2 is utilised for service life estimation (Hovde and Conrad, 2004). The paper assesses the sustainability performance of two residential buildings at the same location. These buildings have different material specifications but same architectural design. One building represents a typical house of Western Australian with a building envelope of timber truss with terracotta tile roofing, hollow concrete block walls with single glazed windows and conventional concrete slab footing. The second building has almost the same specification as the first building except for the fact that 30 % cement in slab footing has been replaced by fly ash. Firstly, Service life (SL) of building components have been estimated using a factor method. Secondly, the LCSA framework utilising environmental life cycle assessment, life cycle costing and social life cycle assessment have been utilised to determine environmental, economic and social indicators of two buildings. All these triple bottom line indicators in this framework have been calculated on an annual basis to capture the advantage of increased service life of buildings.

2. Materials and Methodology

2.1 Service life estimation

Building is a complex product of construction industry containing numerous components with varying service life, structural importance, exposure conditions and failure criteria, which could directly or indirectly affect the sustainability performance of the building industries. Without considering the structural importance and service life of building and building components, repair and replacement of building components cannot be assessed properly (Rauf and Crawford, 2013). Service life is the period during which building is expected to perform the intended function. However, with the change of functional, geographic and climatic conditions, the intended service life may be shortened or prolonged. The Factor method published in ISO 15686-2, is a service life estimation method that considers factors such as quality of material, execution and workmanship, maintenance level, functional use and indoor/ outdoor climatic conditions of building (Matthias et al., 2013). The estimated service life (ESL) of building component is calculated by multiplying various factors with a reference service life, as shown in Eq (1).

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G \quad (1)$$

Whereas ESL and RSL are estimated and reference Service Life of Building or Building component. Factor A, B and C are quality of materials, design and workmanship. Factor D and E are Indoor and outdoor environment effect and Factor F and G are In-use conditions and maintenance level.

The evaluation process is based on collection of data for building components from manufacturer reports, technical data sheets, existing literature resources and official reports of concerned departments and experience of industry experts. In this study, material characteristics, literature, government publications, exposure conditions, Australian codes and standards and failure mechanism of components are investigated to an extent that help to deduce reliable values for RSL and contributing factors. The most likely values of modification factors are taken to estimate the service life of components of residential building located in Perth city of Western Australia. The ESL of whole building is considered equal to the ESL of structural component with lowest value (Madrigal et al., 2015).

2.2 Life cycle sustainability assessment

Four phases of ISO 14040 framework that are (1) goal and scope definition (2) compilation of life cycle inventory, (3) Life cycle impact assessment and (4) interpretation, are used as baseline for Life cycle sustainability analysis (UNEP, 2012). All the three assessments are carried out simultaneously as shown in Figure 1 with same system boundary. The cradle to grave approach including mining to material, construction, use and end of life stages is used to carry out the sustainability assessment of buildings. A quantitative inventory of cost, material and energy is compiled for LCC and ELCA and qualitative and quantitative data is collected for SLCA from official publications of involved organisations and response of all stakeholders who are directly or indirectly involved in all stages of building life cycle. Sima-Pro 8.3 is used for ELCA and to calculate LCC, Eq(2) is used (Pelzeter, 2007).

LCC = Capital cost + Present value of (operational cost + replacement cost + end of life cost) (2)

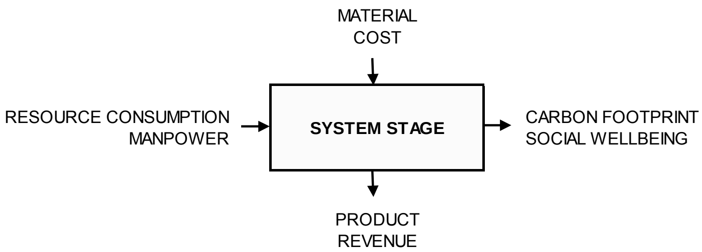

Figure 1: Life cycle assessment stage Inventory for LCSA of Buildings

To observe all aspects of sustainability assessment, multi-criteria analysis approach with indicators is selected.
The first task is to choose appropriate, Triple Bottom Line indicators for building sustainability assessment. A list of relevant social, economic and environmental indicators is developed from existing research studies and sent to research experts of Australian Universities for consensus survey to assign a score as per relevancy and importance of indicators. Following Lim and Biswas (2015), overall weight of an indicator is determined by using Eq(3).

$$w_i = \frac{\sum_{R=1}^{N} S_{ri}}{N * \sum_{i=I_1}^{I_n} S_i} \quad (3)$$

Where, N= Number of respondents
R= 1, 2,……………N respondents
i = I_1, I_2,…………..,I_n, indicators for social, economic and environmental aspects
S_{ri} = Score given by a Respondent ‘r’ for an indicator ‘i’ and S_i = value of each score
Threshold values of the selected sustainability indicators are determined by considering existing case studies, and consulting stakeholders and experts, directly or indirectly involved in the supply of materials, construction, operation and maintenance of buildings for their opinions and recommendations. These values are set as 0 to 5 on Likert scale from worst to best. If the calculated values of environmental, economic and social indicators that are obtained from the field data using ELCA, LCC and SLCA tools respectively, are equal or greater than the maximum threshold value, this indicator will receive a maximum score of 5. For a value less than maximum threshold value, following equations are used to calculate the position of the indicator on a 5-point Likert scale. If the lower indicator score leads to sustainability as for carbon footprint, Eq(4) is used and for indicators like net benefit, GDP and employment rate, where higher score is sustainable, Eq(5) is used.

$$P = \frac{\text{Threshold value}}{\text{Calculated value}} \text{ x } 5 \quad (4)$$

$$P = \frac{\text{Calculated value}}{\text{Threshold value}} \text{ x } 5 \quad (5)$$

The difference between 5 and the position value of the indicator on Likert scale is Gap, to be multiplied with corresponding weight of the indicator. The products of gap and weight of indicators were then summed up to determine the total score for sustainability. Likewise, the total score of different types of buildings with varied service life have been calculated to compare their sustainability performance. The building with the minimum total score will offer the best sustainability performance among buildings and the indicator with the highest gap is being identified as the hotspot requiring further improvement of the sustainability performance.

3. Testing the framework using calculated and hypothetical results

This newly developed sustainability framework has been applied to assess the sustainability performance of two residential buildings in Perth, Western Australia. The covered area, architectural design, and utility of the buildings are same except for the difference in concrete composition used for foundation slab. The buildings specifications are timber frame roof with terracotta tiles, hollow concrete block walls rendered outside and plastered inside and on-grade concrete slab with ceramic tile flooring. The concrete used in slab footing for Building-1 is conventional concrete using ordinary Portland cement. In Building-2, a class F fly ash is used to replace 30 % of the ordinary Portland cement in the concrete used for footing slab.

3.1 Service life assessment

The ESL of building components is estimated using factor method (Table 1). The reference service life for building components are taken from manufacturer data sheets, existing case studies and literature on service life and expert opinion. The building design quality is improved by considering measures like wall rendering to reduce block porosity, steel reinforcing in concrete slab to avoid cracking and termite treatment of roof timber frame. The climatic conditions of Perth city are considered to estimate the effect of outdoor environmental factor. The material quality is considered high after referencing manufacturer's data sheets from Western Australia. Annual compliance reports on technical building inspections by Building commission, Government of Western Australia are used to estimate the workmanship quality. However, maintenance is considered standard and in-use conditions are not weighted in the study as it varies greatly and is dependent on the occupier.

Table 1: Sample calculation for estimated service life of building components

Slab footing	RSL	Factor A	Factor B	Factor C	Factor D	Factor E	Factor F	Factor G	ESL
Building-1	50	1.3	1.4	0.9	1	0.9	1	1	74
Building-2	50	1.3	1.4	0.9	1	1.1	1	1	90

The ESL for building structural component with the least value is considered ESL of whole building (Table 2). In Building-1, the footing slab has the ESL of 74 y, whereas in Building-2 the ESL increased to 90 y. The partial replacement of cement by 30 % fly ash in Building-2, reduced permeability, chloride diffusion and drying shrinkage of concrete resulting in reduced chance of cracks thus increasing its durability (Rafieizonooz et al., 2017). The increase in service life of the concrete footing by using 30 % fly ash is taken as conservative considering the significant improvement of durability properties that a properly designed fly ash concrete can have, as shown by Nath et al. (2018). The building components i.e., ceiling, Terracotta tile roofing and ceramic tile flooring have comparatively small ESL and are to be replaced once in ESL of building to maintain the living condition of building.

Table 2: Estimated service life of building components in y

Envelope	Roofing system			Wall system	Footing system	
Building components	Timber frame	Ceiling	Terracotta tiles	Hollow block wall	Ceramic tiles	Slab footing
Building-1	84	59	67	90	50	74
Building-2	84	59	67	90	50	90

3.2 LCSA analysis

The sustainability indicators of LCSA are hypothetical, which were considered for testing the framework, as if they were selected and weighted through a consensus survey. Using the same system boundary in Figure 1, ELCA, LCC and S-LCA tools have been used to calculate indicators for environmental (i.e. Life cycle GHG emissions, Life cycle embodied energy), economic (i.e. Life cycle cost, gross benefit) and social (i.e. working condition, social wellbeing and equality) objectives of sustainability of Buildings 1 and 2. The threshold values are assigned to indicators for environmental and economic objectives after considering a number of existing Australian and international case studies and official publications of government agencies, whereas the social indicators such as workers' satisfaction at work and equal opportunity are assessed by the stakeholders in the building supply chain.

The GHG emissions analysis results are presented in Table 3. Cradle to grave carbon footprint are reduced by 1.62 % from 9.24 to 9.09 t CO_2-eq/building/y. The Life cycle GHG emissions are 683.8 t CO_2-eq for Building-1 with 74-y ESL and 776.16 t CO_2-eq for Building-2 with 84-y ESL. Although the life cycle GHG emissions of the building is increased by 10.4 % with an increase of ESL by 10 y, the building's GHG emissions per year are reduced by 1.62 %, showing the increased service life of building has reduced per year GHG emissions. Similarly, the per year embodied energy as shown in Table 4, is decreased by 1.97 % with an increase of 10-y service life of Building-2 as compared to Building-1 showing the consistency with GHG emission results.

Table 3: GHG emissions for LCA stages of buildings

LCA stages	Mining to material stage	Construction stage	Use stage	End of life stage	Total GHG emissions/y	Life cycle GHG emissions
			t CO_2-eq/ y			t CO_2-eq
Building-1	0.88	0.08	8.22	0.06	9.24	683.8
Building-2	0.75	0.07	8.22	0.05	9.09	776.16

Table 4: EE for LCA stages of buildings

LCA Stages	Mining to material stage	Construction stage	Use stage	End of life stage	Total EE/y	Life cycle EE
	GJ/building/y					GJ
Building-1	10.65	1.1	72.64	0.84	85.23	6,307.02
Building-2	9.2	0.97	72.64	0.74	83.55	7,018.2

Using the gap analysis of the sustainability framework in section-2, the environmental score has been estimated to be 2.08 for Building-1 and 2.12 for Building-2, confirming that the increased ESL has improved the environmental performance of the building. The ELCA results show that the use stage contributes to the major portion of annual GHG and embodied energy (90 % and 85 %) and is identified as the hotspot, which could be treated by replacing fossil fuel energy with renewable energy for operating end use appliances and achieving better energy efficiency techniques (Nemet et al., 2018). The results of the sustainability assessment are presented in Table 5 and score of sustainability indicators and sustainability objectives are graphically presented in Figure 2.

Table 5: Sustainability assessment results

Indicator description			Threshold value	Building-1			Building-2		
LCSA Objectives	Indicator	Weight, W	Score 5 on Likert scale	Score	Gap, G	Total Score, W x G	Score	Gap G	Total Score W x G
Environmental	Life cycle GHG emissions	0.26	4 t CO_2-eq /building/year	2.17	2.83	0.73	2.21	2.79	0.72
	Life Cycle EE	0.26	35 GJ EE /building/y	1.99	3.01	0.77	2.04	2.96	0.76
Economic	Life cycle cost	0.19	min. construction cost/m^2	2.98	2.02	0.38	2.64	2.36	0.44
	Gross benefit	0.11	20 % of revenue	3.94	1.06	0.12	3.83	1.17	0.13
Social	Working condition	0.11	100 % satisfaction	3.05	1.95	0.20	3.00	2	0.21
	Equal opportunity	0.08	100 % satisfaction	3.54	1.46	0.12	3.54	1.46	0.12

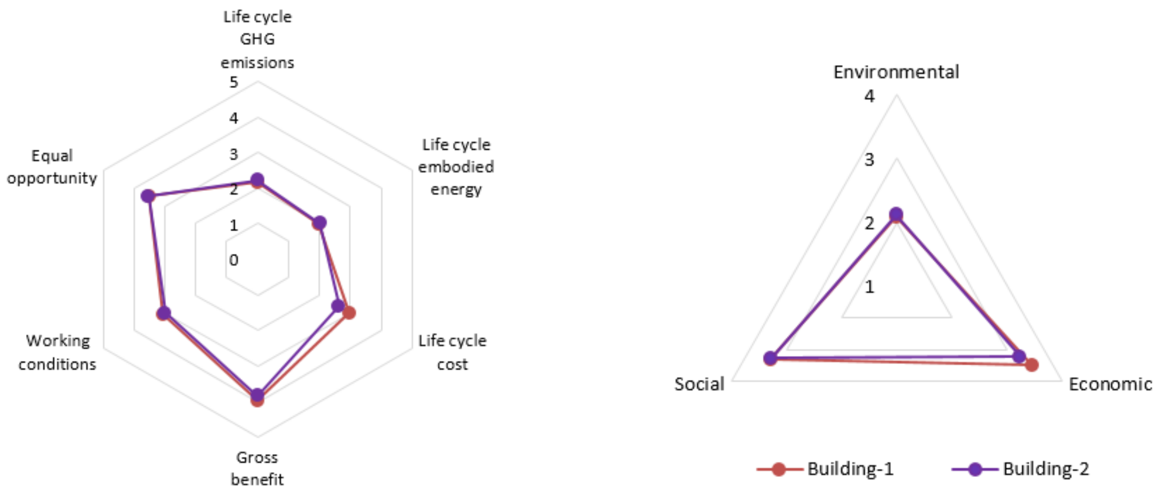

Figure 2: Score of sustainability indicators (Left), Score of sustainability objectives (Right)

The life cycle cost of Building-1 is about 2,000 USD less than Building-2 for entire building life. The LCC/building/y is 4,018 USD and 3,563 USD for Building-1 and 2. The cost comparison also shows that there is an increase in overall life cycle cost and a decrease in LCC/ year with an increased ESL. The profit margin for Building-1 is 1,235 USD higher than Building-2. The economic score for Building-1 is 3.46 and for Building-2 is 3.23. Building-1 is economically sustainable than Building-2 due to high cost of substitute material. For S-LCA, in both cases, maximum level of satisfaction has not been made as the position values of average responses for working conditions and equal opportunities for Building 1 are 3.05 and 3.54, while for Building 2, the respected values are 3.00 and 3.54.

The triple bottom line total Score is 2.32 for Building-1 and 2.38 for Building-2, showing that overall sustainability performance of Building-1 is better than Building-2 and Building-2 is eco-friendlier. The operation stage GHG emissions and EE have been identified as the sustainability hotspot, requiring more attention for improving overall sustainability performance of the building.

4. Conclusions and future work

This life cycle sustainability assessment frame work has been proposed to integrate estimated service life in life cycle assessment process. The intent is to develop a comprehensive and adaptable framework to assess the sustainability of building sectors using ESL of building and building components and to avoid resources dumping to landfill or excessive replacements. The study has also emphasised the need of cleaner production strategies to reduce the carbon footprint and operational cost of building as also performed in recent studies. The framework has been successfully tested on residential building and it is found that there is still a scope for improving the framework by using more appropriate weights of existing indicators, by including more indicators to refine the framework. The proposed framework will be utilised to assess more building options that are made of different industrial by-products and recycled materials to reduce the sustainability gap of residential buildings.

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