School of Civil and Mechanical Engineering

Sustainability Implication of Residential Building Materials Considering Service Life Variability

Shahana Janjua
0000-0002-4367-3972

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TO MY FATHER

WHO

DREAMED BIG FOR US

DECLARATION

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number # HRE2018-0307.

Shahana Yousaf JANJUA

02/06/2021

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ABSTRACT

Civilizations are recognized by the buildings and infrastructure they have. The construction and building industries significantly contribute to the economic growth of a country by boosting GDP and providing employment opportunities to its people. Nonetheless, the other side is darker enough to get terrified. Thirty-six percent of global energy consumption and 39% of subsequent GHG emissions are related to the construction and building industries. Some other sustainability impacts of these industries are solid waste generation, resource depletion, land-use changes, pollution, and localized health issues. Construction materials are the major contributor to these impacts after energy utilization in this sector. Though the building sector has already embraced the concept of life cycle thinking for sustainable, smart, and green building design, the social and economic impacts of the building sector cannot be ignored. A sustainable building design that cost-effectively strives for resource efficiency, reduced environmental degradation, safe-keeping human dignity and wellbeing, is thus inevitable.

This research identified that residential buildings are a major chunk of building and construction industries, and contribute to one-third of the sustainability consequence. The literature review of existing case studies, sustainability tools and methods highlighted that the sustainability assessment frameworks of the residential buildings are based on weak sustainability concepts allowing the trade-off between social, economic and environmental objectives to achieve the sustainability of residential buildings. The life cycle studies though addressed the entire life span of the buildings, yet lacking the integration of actual building life resulting in uncertainties in interpretations. The use stage operational energy of the buildings is the widely studied area in sustainability assessment, nonetheless, the repair and maintenance activities in use stage are entirely ignored. Similarly, the life cycle sustainability assessment (LCSA) being the comparatively new technique, is facing many challenges including integration of triple bottom line (TBL) sustainability objectives as well as TBL sustainability tools (environmental life cycle assessment–ELCA, Social life cycle assessment–SLCA, Life cycle costing–LCC), involvement of stakeholders in the development of comprehensive and region-specific key performance indicators (KPI), and the identification of hotspots for potential improvements. Most importantly, the service life of buildings and building components need to be integrated into the LCSA of buildings for realistic sustainability assessment. Hence, a holistic LCSA framework is needed to assess the TBL sustainability of residential buildings addressing the aforementioned gaps.

In this doctoral research, an LCSA framework was developed for residential buildings utilizing strong sustainability concept to address all dimensions of TBL sustainability competently. The LCSA framework used a multi-criteria analysis with a bottom-up hierarchical approach, sequentially using KPIs, impact categories, and sustainability objectives. The KPIs being the smallest unit were quantifiable and ranked as 1-5 on a 5-point Likert scale with 5 as the threshold value. The KPIs were initially selected based on the literature review and then finalized by the feedback of area experts from four stakeholder categories through consnsus survey.

The weight to each KPI was allocated using level of importance provided by survey participants. The threshold values for KPIs were ascertained by exploring existing case studies and sustainability standards. The gap between the threshold value and the position values of KPIs on a 5-point Likert scale was multiplied by the corresponding weight to find the 'performance gap' for each KPI. Likewise, overall sustainability performance gap was determined. The framework was successfully applied to the case study buildings typical to Western Australia. The initial assessment identified the hotspots in the sustainability performance of the buildings. The cleaner production strategies (CPS) were applied to treat the hotspots and then follow-up LCSA was carried out to improve the sustainability performance of the buildings. Results showed that an improvement of sustainability score of 30-49% of the case study buildings due to implementation of CPS including solar photovoltaic cells, solar water heater, replacement of single glazed windows with double glazed windows and the replacement of virgin steel to recycled steel.

The application of this LCSA framework confirmed that it was capable to identify the hotspots and achieve the sustainability improvement of a residential building due to the application of CPS. The sustainability assessment also concluded that the service life of building components and the whole building could significantly influence the overall sustainability performance of buildings. The thermal efficiency and durability of building materials play a crucial role in the TBL sustainability of the buildings.

ACRONYMS

AUD	Australian Dollar
BI	Biodiversity Integrity Index
C & D	Construction And Demolition
CB	Concrete Block
CC	Conventional Concrete
CO_2 eq	Carbon dioxide equivalent
CPS	Cleaner Production Strategies
DB	Double Brick
E	Environmental
EC	Economic
ELCA	Environmental Life Cycle Assessment
EPD	Environmental Product Declaration
ESL	Estimated Service Life
FAGC	Fly Ash Green Concrete
G	Gap
GDP	Gross domestic product
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GJ	Gigajoules
Ha-a	Annual Hectare
ISO	International Standards Organization
kl	Kilolitre
km	Kilometre
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life-Cycle Inventory

LCSA	Life Cycle Sustainability Assessment
NA	Natural Aggregates
OPC	Ordinary Portland Cement
P	Position Value
PO_4 eq	Phosphate Equivalent
RA	Recycled Aggregates
RO	Research Objectives
S	Social
SF	Steel Frame
SLCA	Social Life Cycle Assessment
SO_2 eq	Sulphur Dioxide Equivalent
STC	Sound Transmission Class
TBL	Triple Bottom Line
TF	Timber Frame
W	Weight

LIST OF PUBLICATIONS INCLUDED AS PART OF THE THESIS

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Peer-reviewed papers published in indexed journals

The publications listed below are reproduced in full in Appendices 1–5.

1. Janjua SY, Sarker PK, Biswas WK. A review of residential buildings' sustainability performance using a life cycle assessment approach. *J Sustainability Res.* 2019, 1:e190006. https://doi.org/10.20900/jsr20190006
2. Janjua SY, Sarker PK, Biswas WK. Sustainability Implication of a residential building using a lifecycle assessment approach. *Chemical Engineering Transactions*. 2019, 72:19-24. http://doi.org/10.3303/CET1972004
3. Janjua SY, Sarker PK, Biswas WK. Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings. *Journal of Environmental Management.* 2020, 264:110476. https://doi.org/10.1016/j.jenvman.2020.110476
4. Janjua SY, Sarker PK, Biswas WK. Impact of Service Life on the Environmental Performance of Buildings. *Buildings*. 2019, 9:9. http://doi.org/10.3390/buildings9010009
5. Janjua SY, Sarker PK, Biswas WK. Sustainability Implications of the service life of residential buildings- An application of life cycle sustainability assessment framework. *Environmental and sustainability indicators*. 2021. 10:100109. http://doi.org/10.1016/j.indic.2021.100109

STATEMENT OF CONTRIBUTION AND CO-AUTHORSHIP DECLARATION

I hereby declare that I have authored following publications. The level of my intellectual input to each publication is indicated in brackets as below. Signed verification statements from each of my co-authors are provided in Appendices 1-5.

Ms. Shahana Y. Janjua

Associate Professor Wahidul K Biswas (Supervisor)

Associate Professor Prabir K. Sarker (Co-Supervisor)

1. Janjua SY, Sarker PK, Biswas WK. A review of residential buildings' sustainability performance using a life cycle assessment approach. *J Sustainability Res*. 2019, 1:e190006. https://doi.org/10.20900/jsr20190006 (80% contribution by lead author/ PhD candidate)
2. Janjua SY, Sarker PK, Biswas WK. Sustainability Implication of a residential building using a lifecycle assessment approach. *Chemical Engineering Transactions*. 2019, 72:19-24. https://doi.org/10.3303/CET1972004 (80% contribution by lead author/ PhD candidate)
3. Janjua SY, Sarker PK, Biswas WK. Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings. *Journal of Environmental Management.* 2020, 264:110476. https://doi.org/10.1016/j.jenvman.2020.110476 (80% contribution by lead author/ PhD candidate)

4. Janjua SY, Sarker PK, Biswas WK. Impact of Service Life on the Environmental Performance of Buildings. *Buildings*. 2019, 9:9. http://doi.org/10.3390/buildings9010009 (80% contribution by lead author/ PhD candidate)
5. Janjua SY, Sarker PK, Biswas WK. Sustainability Implications of the service life of residential buildings- An application of life cycle sustainability assessment framework. *Environmental and sustainability indicators*. 2021, 2021. 10:100109. http://doi.org/10.1016/j.indic.2021.100109 (80% contribution by lead author/PhD candidate)

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CHAPTER 1: INTRODUCTION

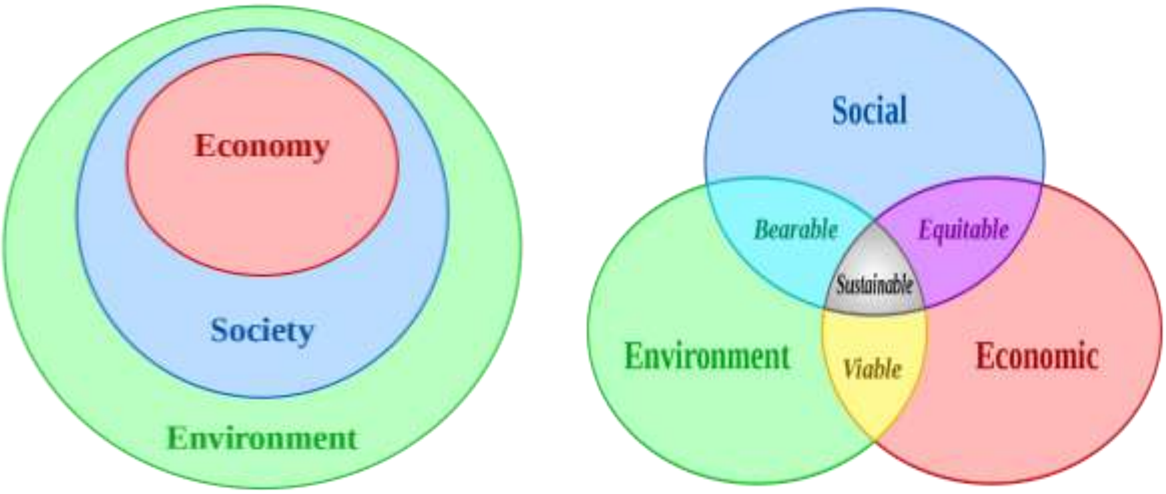
1.1 Introduction

This thesis presents the development and practical application of a life cycle sustainability assessment (LCSA) framework to assess the sustainability implications of service life of buildings and building components and to determine social, economic and environmental strategies to further improve the sustainability performance of residential buildings.

1.2 Background

While building and construction sector boosts economic growth and society's prosperity and wellbeing, it also fortifies the environmental burden. The worldwide energy consumption and subsequent GHG emissions associated with this sector are 36% and 39% respectively [1]. Globally, this sector consumes 33% of resources and 20% of fresh water and generates 40% of all solid wastes [2, 3]. On the other hand, building and construction sector provides 5-10% of employment, and 5-15% of the national economy worldwide, accounting for more than $8.8 trillion per year globally [2, 4]. The building industry in Australia consumes 21% of energy, with 23% subsequent GHG emissions and generates 30% of the nation's annual waste [5]. Nonetheless, the building industry is also creating more than a million jobs annually while contributing to 8% of Australia's GDP [6]. In Australia, building industry is growing at a high rate due to urbanization [7, 8] with residential buildings being 65% of the total buildings constructed annually [9]. Therefore, there is a significant potential for environmental improvement in residential buildings, which constitute the major portion of the construction industry, by using sustainable materials and clean energy sources [10].

Sustainability endeavours to harmonize the environmental, social and economic objectives at national, regional and global levels [11]. Though the sustainability approach caters for environmental, social and economic objectives, it is grounded on two major philosophies (i.e., strong sustainability and weak sustainability). Sustainable development is an integrated approach to create harmony between economic, social and environmental objectives (Figure 1-1a) rather than a trade-off between these three objectives of sustainability. Weak sustainability (Figure 1-1b) as presented by an interlocking diagram allows the trade of between sectors and does not take into account carrying capacity or resource limitation of the earth. Though the weak sustainability provides a more realistic picture creating a balance between three objectives, it neglects the broader concept of sustainable development. Sustainable development considers both inter and intra-generational equity with a focus on conservation of natural resources. Strong sustainability provoke the thought that natural resources are finite and a way to survive within the carrying capacity of natural system need to be tailored. The sustainable development goals of United Nations i.e., SDG11 and SDG 13 target Resilient and sustainable infrastructure/ cities and resilient infrastructure for climate change. Sustainable building development could be one of the pathways to achieve strong sustainability by addressing environmental challenges while enhancing social equity and economic development [12]. These building industries are resource intensive and we are running out of these resources due to rapid growth in population and there are environmental consequences associated with the exploitation of construction materials. The traditional building industry forms the backbone of social and economic development of a country at the cost of environment and natural resources degradations [13]. A sustainable building is a design philosophy striving for cost-effective building developed within earth's carrying capacity with reduced a level of impacts on social wellbeing and dignity [14].



[a] *[b]*

Figure 1-1: Sustainability diagram of sustainable development [15]: a) Strong sustainability, b) Weak sustainability

Each building is a unique set of several components of various construction materials, structural and architectural designs, functional requirements, exposure conditions, and subsequent damage mechanisms. Therefore, it is not a straightforward task to implement the principles and guidelines of sustainability in the building sector.

The life cycle sustainability assessment (LCSA) is an emerging tool utilising a life cycle assessment (LCA) approach to assess the sustainability performance of the buildings by integrating the three objectives of sustainability (environmental, social, and economic).

Though the environmental life cycle assessment (ELCA), life cycle costing (LCC), and social life cycle assessment (SLCA) have been considered separately rather synchronously in building sector, only a few studies have been found to address the life cycle sustainability performance of residential buildings. Onat et al. [16], proposed an integrated LCSA framework and assessed the sustainability of the US building industry, where triple bottom line (TBL) indicators were calculated using generic data. An analytic hierarchy process based sustainability framework for buildings with an assumed life span of 60 years was proposed by Hossaini et al. [17], with a minimal focus on the social impacts of buildings. Another LCSA study was carried out following a cradle to gate approach without integrating the TBL impacts into a single value or entity [18]. Balasbaneh et al. [19], carried out a life cycle sustainability performance of the buildings with an assumed service life of 50 years, where very few TBL indicators were selected based on literature review. None of these current and previous studies have considered the region-specific sustainability indicators, involving stakeholder participation for indicator selection, and the integration of the TBL sustainability objectives to avoid trades-off between TBL objectives in assessing the sustainability performance of residential buildings (Figure 1-1).

Service life has a significant bearing on buildings' sustainability performance. As per ISO 15686-1, "Service life is the period after construction, in which a building and its parts meet or exceed the acceptable minimum requirements of performance established" [20]. A building is a complex structure of various building materials each with different inherent durability characteristics in variable exposure conditions. Each building component has a defined functional requirement and is expected to perform as per its specific function in service life of that building. Existing LCA studies have considered a service life of 30-70 years with the most often used value of 50 years for residential buildings irrespective of the building materials, surrounding environment, deterioration, and maintenance [21, 22]. This discrepancy in service life either underestimate or overestimate the sustainability assessment of buildings. The service life of building and maintenance activities are linked to each other. It should also be taken into account that the longer service life requires more maintenance and replacements of non-structural components to keep the building in its functional condition or vice versa. Existing LCA studies which have not considered the maintenance and replacements activities in building design phases are estimated to increase the embodied energy of residential buildings by 37% [23].

This research addresses three gaps as identified above including the absence of a comprehensive framework for integrating as well as improving TBL objectives, utilisation of a scientific method for developing TBL indicators and the incorporation of realistic service life of a building and its components into the sustainability assessment framework.

Thus an integrative comprehensive LCSA framework needs to be developed, which is capable of integrating TBL sustainability objectives utilizing region-specific TBL indicators with possible perspectives and participation of stakeholders, while taking into account service life of building and building components, to assess the sustainability performance of the residential building over its entire life span.

1.3 Problem statement and research questions

The author has thus endeavoured to assess the sustainability performance of the residential buildings integrating TBL sustainability objectives using a life cycle thinking approach to assess the TBL impacts of residential buildings, taking the influence of the estimated service life (ESL) of buildings into account. This research has addressed the following research questions in this thesis;

1. Why is sustainability assessment important for residential buildings?
2. What are the research gaps in existing LCSA frameworks of residential buildings?
3. What could be some improvement strategies for improving the LCSA to design a sustainable building?
4. How can service life of the building and building components be estimated?
5. Does service life affect the life cycle sustainability performance of the buildings?
6. Do repair and replacement activities affect the life cycle sustainability performance of the buildings?
7. What could be a holistic LCSA framework to assess and improve the life cycle sustainability performance of the residential buildings?

1.4 Goal, objectives, and scope

The goal of this research is to develop a holistic LCSA framework to assess and improve the sustainability performance of residential buildings considering service life variation. To achieve this goal, research has focused on the following four objectives that have been achieved through the publication of five journal articles.

1.4.1 Research Objective 1 (RO1): Paper 1 (Janjua et al. [24]) – The review

'To review the contemporary methods and techniques for TBL sustainability assessment, use of construction materials and service life of residential buildings to identify the research gaps in order to develop research questions'

The literature review established a considerable part of the scope of this research. Existing case studies for sustainability performance of the residential buildings, building materials, and service life were reviewed to identify the key concern areas for achieving sustainability of building industries. The scope of this research is limited to only one storeyed residential houses not considering commercial and tall buildings. The contemporary sustainability assessment frameworks, techniques, and tools were reviewed to identify the weaknesses and strengths of these frameworks which entailed the development of an LCSA framework to assess the life cycle sustainability of residential buildings. The research gaps from this literature review identified the need for the development of a comprehensive LCSA framework to achieve sustainable residential buildings.

1.4.2 Research Objective 2: Part 1–Development of LCSA framework - (Janjua et al., [25]); Part 2 - TBL indicator development (Janjua et al., [26])

'To develop a holistic LCSA framework for assessing the sustainability performance of residential building industry taking service life variations into account'

Following the literature review and identification of the research gaps, an integrative LCSA framework was developed using a bottom-up approach for the TBL sustainability assessment of the residential buildings, using key performance indicators (KPIs), impact categories, and sustainability objectives. The development of the LCSA framework involved two stages:

- ***Development of Sustainability Assessment Framework***: The basic structure of the framework illustrates how the TBL indicators, impact categories, and sustainability objectives have been integrated to assess the overall TBL sustainability of residential buildings. This framework also explained how the service life of the building and building components was determined and integrated into the framework. The framework was tested using a hypothetical case study to provide a better conceptual understanding of the implication of service life on the building sustainability performance.
- ***Development of TBL indicators:*** In the second stage, the TBL indicators for the LCSA

were selected and weighted through a consensus survey by area experts. Following an human ethics approval, an online survey was thus conducted to area experts in sustainable buildings in Australia as the scope of this research is confined to Western Australian buildings. This is also because of the fact that policy, socio-economic situation and resource utilisation vary across countries and regions. Secondly, the threshold values of the finally selected TBL indicators were shortlisted through a rigorous review of existing case studies and standards of sustainability. Finally, the LCSA framework using scientifically developed TBL indicators was tested using hypothetical data to address any potential issues prior to they are practically implemented on the ground.

1.4.3 Research Objective 3 (RO3): Paper 4 (Janjua et al., [22]) – Impact of service life on the environmental performance of buildings

'To estimate the service life of the building components as well as overall building, and the replacement intervals of the building components in order to determine the effect of estimated service life (ESL) on the environmental performance of buildings'

Initially, a detached house typical to Western Australian living style was selected as a reference house with a commonly used service life of 50 years. By creating variations of building materials of this reference building, 12 combinations of case study buildings were made so that the impact of service life of these buildings on their environmental performance can be assessed. The service life of case study buildings and building components and replacement intervals of building components were estimated. Finally, ELCA was carried out to determine the annual environmental impacts of the buildings with the varied estimated service life to compare with the reference building.

1.4.4 Research Objective 4 (RO4): Paper 5 (Janjua et al., [27]) – The application of LCSA framework

'To practically apply the LCSA framework to case study buildings, to assess the TBL sustainability performance, and then to identify the sustainability hotspots and to select relevant cleaner production strategies (CPS) to further improve the sustainability performance of buildings.'

Firstly, 14 case study buildings typical to Western Australia were selected to assess the TBL sustainability performance. Secondly, the service life of the whole building and its components was estimated. The replacement intervals of non-structural building components during the

ESL of the respective building were estimated using ESL of these components. Thirdly, the life cycle inventories (LCIs) were compiled for each building. Once the LCIs were developed, 22 key performance indicators (KPIs) were calculated for each building following the LCSA framework. The performance gap of each KPI was calculated and then the hotspot analysis was conducted to find out the reasons for sustainability performance gaps. Fourthly, CPS was selected accordingly to further improve the sustainability performance. In order for this to be done, a follow-up LCA analysis was carried out to estimate the improved sustainability performance. The performance gap for the smallest units (KPIs) was integrated to impact categories and then to sustainability objectives. Overall, the sustainability scores of the case study buildings were determined to assess the impact of service life on TBL sustainability performance of buildings.

1.5 Research methods

A theoretical framework involving the use of life cycle sustainability approach was developed which enables the assessment of the implications of building service life on the economic, social and environmental objectives of sustainability. Firstly, the LCSA framework for sustainability assessment was developed. A methodology for estimating the service life estimation of buildings was incorporated into this framework. The hierarchy of TBL sustainability evaluation was developed in the framework (i.e. KPIs, impact categories, TBL objective and overall sustainability score). The KPIs for each TBL objectives for this framework were developed through a consensus survey. A human ethics approval (Approval no. HRE2018-0307, Appendix-6) from Curtin University was required before launching the survey. An intensive literature review was conducted to develop a list of KPIs. This list was then sent to area experts to obtain their opinions regarding the relevance and importance of these KPIs. Following the survey, some new KPIs were included as they were suggested by the experts. Based on the survey, the weight was allocated to each KPI. The threshold values of these KPIs were selected using a thorough literature review to compare the sustainability performance with the field or actual values. The LCSA framework was then tested using a hypothetical building. Western Australia's residential buildings were taken as case studies. The first step of the implementation of LCSA framework was to estimate the service life of the case study buildings. Then life cycle assessment approach was followed to calculate the triple bottom line KPIs of 14 case study buildings with different service lives. The calculated values of these KPIs were compared with the corresponding threshold values to determine the sustainability performance 'gaps'. The KPIs with the highest gaps were considered as the sustainability hotspots. Accordingly, cleaner production strategies were incorporated into the LCSA framework to determine the improved sustainability performance of the buildings. Last but not the least, this LCSA framework showed how the variation of service life affect the sustainability performance of the case study buildings.

1.6 Significance

This sustainability framework is first of its kind to overcome the existing weaknesses of LCSA frameworks [28] by integrating the three objectives (environmental, social and economic) of sustainability with the same functional unit for all TBL KPIs. Secondly, the framework involved area experts in the selection of KPIs, and allocation of their weights. Thirdly, the framework incorporated ESL of building and building components and their replacements into the sustainability performance assessment. Finally, the framework enabled the identification of hotspots to select the right strategies to design sustainable building.

This research can potentially assist the stakeholders in the building supply chain by assessing the buildings' expected sustainability outcomes with reference to the inherent properties of building materials including thermal efficiency and durability at the design phase. The framework is flexible and can be applied to a building made of any type of building materials and located in any region in the world. The framework methodology will help assess the service life of building materials and its integration into the TBL sustainability performance of the buildings.

1.7 Limitations of the research

The limitations of this research work are as follows;

1. The TBL sustainability indicators of the LCSA framework are only applicable to residential buildings in Australia. However, the methodology for development of KPIs can be adopted to develop the KPIs in any region around the globe.

2. The threshold values for KPIs used in this research are region-specific based on Australian codes and standards of sustainability, national statistics, and in agreements with international treaties, and local case studies. These threshold values change over time due to change in technology, policy, climate and socio-economic variables.

3. Technological advancement and potential policy changes can also alter both KPIs and their weights over time. Therefore, it is important to review periodically for potential changes of KPIs.

4. The AccuRate sustainability software was used to calculate the operational energy for case study buildings. The material library for this software is limited to building envelops. This research considered the structural components of case study buildings, in addition to building envelops. Therefore, the research was confined to only two types of operational energy inputs i.e., for concrete block wall and brick wall buildings. The variability of operational energy consumption for buildings considering different buildings could lead to more elaborated difference in sustainability performance.

1.8 Thesis outline

This is a PhD thesis consisting of five research articles (Appendix 1-5) and six chapters as illustrated in Figure 1-1.

Chapter 1 introduces the thesis by providing the background, goals, objectives, scope, and significance of the research. It also highlights the research method, significance and limitations of the overall research.

Chapter 2 (Research article-1 [24]: Appendix 1) provides a review of the existing literature of sustainability assessment, building materials, and service life estimation. It also analysed the contemporary LCSA frameworks of the building industry and highlighted the research gap, which formed the basis of developing a holistic LCSA framework.

Chapter 3 (Research article-2 [25]: Appendix 2, Research article-3 [26]: Appendix 3) presents the concepts and principles for developing the LCSA framework for sustainability assessment of residential buildings, and emphasized the need for estimating the service life of buildings and developing TBL sustainability indicators.

Chapter 4 (Research article-4 [22]: Appendix 4) explains the estimation of the service life of case study buildings, calculation of intervals of major repairs, and environmental assessment of case study buildings to determine the impact of maintenance activities and ESL on the environmental performance of buildings.

Chapter 5 (Research article-5 [27]: Appendix 5) is the practical application of the LCSA framework to case study buildings typical to Western Australia. The life cycle sustainability assessment of the buildings was carried out considering the estimated service life of the case study buildings, then the hotspots were identified for applying CPS to improve the sustainability performance of the buildings.

Chapter 6 summarises how the objectives of this research were achieved through published journal articles specifically written for this doctoral research.

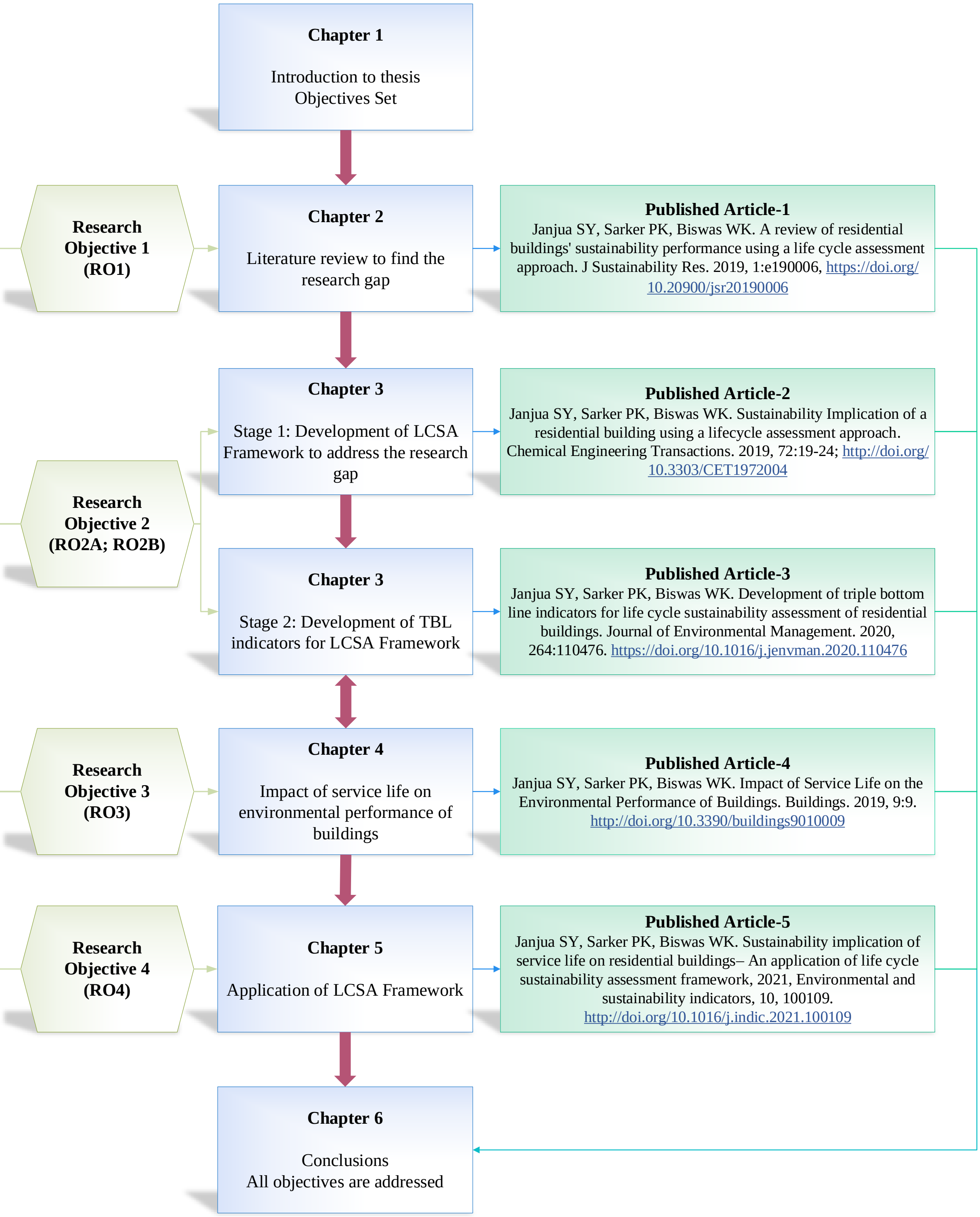


Figure 1-2: Thesis Outline

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The objective of this chapter was to review the contemporary methods and techniques for TBL sustainability assessment, use of construction materials, and service life of residential buildings to identify the research gaps, develop research questions and then to find avenues for improving LCSA framework for the building industry.

This chapter of the doctoral thesis was published in the 'Journal of Sustainability Research' as a review article entitled '***A review of residential buildings' sustainability performance using a life cycle assessment approach'*** (Appendix-1, [24]).

2.2 Review of TBL sustainability performance of residential buildings

Though building and construction industries are backbone to social and economic development of a country, it also contributes significantly to the environmental degradation. This sector is consuming more than one third of the global energy, resources and generating more than 40% of solid wastes [1-3]. Building industry is growing at an alarming rate around the world due to urbanisation and population growth. Australian residential building sector accounts for 59% of the Australian construction industries and are two third of the building sector [9]. Therefore, building sector could have a great potential to reduce the environmental impacts within a short time, using sustainable materials with increased life span and embodied energy consumption [10].

A rigorous literature review of existing studies of sustainability assessment of buildings, building materials, the service life of residential buildings and sustainability assessment tools and techniques (LCA, SCLA, LCCA, LCSA, and CPS) was carried out to identify the research gap in the sustainability performance of residential buildings in four steps. Firstly, keywords (sustainability; residential buildings; life cycle assessment; life cycle sustainability assessment; service life etc.,) and criteria (peer reviewed articles, published in English, scientific research publications by recognised bodies) were used to search articles published over last decade (2009-2019) from four databases (Scopus, Web of Science, Science direct, and Compendex) for developing research questions of this PhD work. Secondly, the collected papers were listed using excel sheets, and duplicates were removed. Thirdly, the abstracts of the articles, found through the database search, were thoroughly reviewed to determine the relevancy of the article to this research. Finally, the relevant articles were divided into two main categories; 1) Building materials and service life of buildings, 2) Sustainability assessment related research for residential buildings.

2.2.1 Building materials and service life of buildings

This section of the research article-1 [24 page 4-8] reviewed the selection of sustainable materials and the service life of buildings. Building materials being the main element of a building were found crucial to building sustainability. The selection of building materials requires a balance between environmental, social, economic, and technical aspects. Regardless of whether these are synthetic or natural, all materials come from Mother Nature. A material closer to nature is more sustainable due to the avoidance of intermediate upstream activities (i.e., processing and transportation), resulting in lower energy consumption, GHG emissions, and less hazardous chemicals. The development of building and construction industries has led to the exploitation of critical natural capital by extraction of raw materials which can potentially be reduced by using recycled C&D waste as construction materials. Industrial by-products (e.g., fly ash, steel slag, imperial smelting furnace slag, copper slag, and silica fumes) have produced better results for structural and environmental performance than natural aggregates in some instances. The research has shown that the re-use of C&D waste reduces overall environmental impacts as well as the cost of buildings. Nevertheless, the local sourcing of materials is crucial as it reduces the TBL impacts indirectly by reducing the transportation of heavy construction materials, promoting local businesses and enhancing wellbeing of the community.

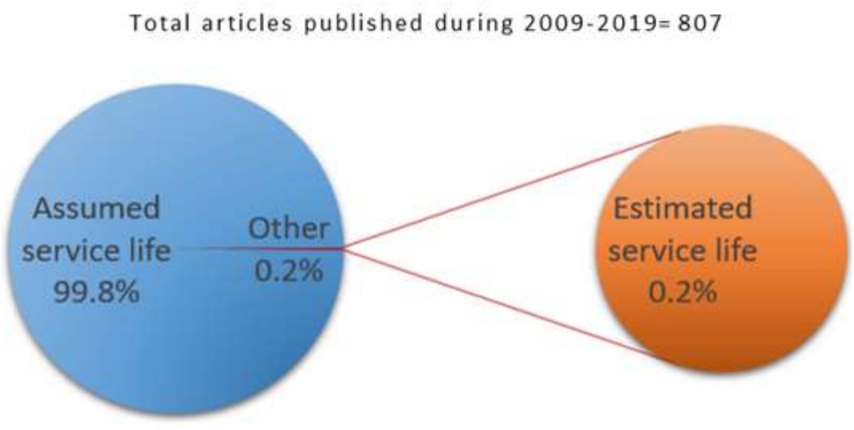


Figure 2-1: Breakdown of articles published during 2009-2019 in terms of integration of service life to TBL assessment tools

Life cycle assessment has widely been used to determine the environmental benefits of the use of alternative materials and green building design. Life cycle assessments are based on the entire life of the building. Different approaches have been applied to assess the service life of the building components and buildings. The factor method of ISO 15686 [29] is widely used to estimate the service life of building components by taking into account the location and exposure conditions. The service life of the building and building components is important to assess the TBL sustainability impacts of the buildings.

The articles, published so far, have considered the life span of 30-100 years in the LCA of buildings with the most commonly used value of 50 years [21 page 3; 24 page 6 &9]. This study identified that out of 807 studies on building sustainability, only two of the existing research articles [21, 23] have addressed the impact of service life on the life cycle assessment of buildings (Figure 2-1). The absence of calculated service life of building and building components and maintenance intervals in life cycle assessment studies results in uncertainty in LCA results due to use of assumed early end of life. The service life considered for the LCA analysis of this PhD research was estimated based on materials and the design of the building.

2.2.2 Sustainability in residential buildings

Sustainability in residential buildings is reviewed in this section of the research article-1 [24 page 8-18] by investigating existing studies on ELCA, LCC, SLCA, and LCSA. This review paper identified that out of 807 publications on the sustainability performance of residential buildings, only 0.6% (6 /807) articles addressed the TBL sustainability performance of the buildings (Figure 2-2).

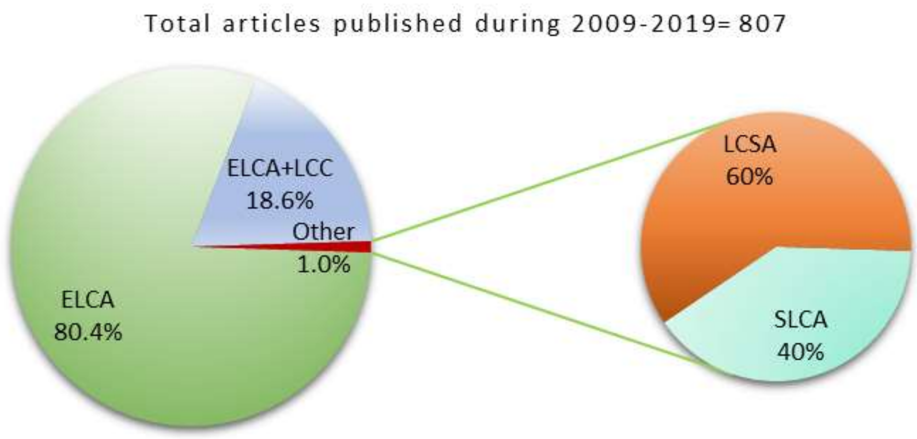


Figure 2-2: Breakdown of articles published during 2009-2019 in terms of TBL assessment tools

“Life cycle assessment (LCA) is a tool to assess the environmental objectives and potential impacts associated with the production and use of a product/system, by developing an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases" [30]. Based on the guidelines of LCA by ISO 14040-44 [30], life cycle assessments are carried out for life cycle stages (pre-use stage, use stage, post-use stage) of buildings.

This review identified that 33% of existing ELCA studies have focused on all life cycle stages while 25% on pre-use stage, 29% on use stage, and 13% on the post-use stage of residential buildings [24 page 9]. Most studies have addressed the carbon footprint, embodied energy, and operational energy as environmental indicators for the sustainability assessment of residential buildings [31]. ELCA has been applied to quantify, verify and register the product data for assisting manufacturers officially to publish a document called environmental product declaration (EPD). Similarly, environmental certification (LEED, Green Star, BREEAM, and DGNB) involves the use of an ELCA tool to assess and certify the sustainability performance of buildings [32]. The environmental impact assessments of building materials have been used to improve the thermal performance of buildings resulting in lower operational energy demand. The recycling and re-use of C&D waste have been found to recover 32-42% of embodied energy in the post-use stage [33]. The life cycle assessment studies so far published have assumed the service life of 50 years for building, disregarding the type and structural performance of the building materials used [24 page 6 &9]. The maintenance activities in the use stage of the building life have been either miscalculated or neglected in the LCA studies owing to assumed/ predetermined building life span. Not considering this input also effect the calculation of life cycle costs [34, 21 page 187-188]. Therefore, this study has considered maintenance and replacement in active service life of buildings.

Life cycle costing is used to measure the cost of ownership of a project. Klöppfer [35] defined LCC as "a logical counterpart of LCA for the economic assessment". Using the same system boundaries as ELCA, LCC has been used to assess the cost-effectiveness of the eco-friendly options of the buildings. The combination of LCC and ELCA also leads to the involvement of stakeholders with conflicting interests, making it difficult to attain environmentally friendly buildings [36].

Another aspect of sustainability i.e., social sustainability can also be assessed using the same system boundaries as ELCA and LCC by following four steps of LCA guidelines [30]. SLCA addresses the concerns of the stakeholders during the life span of the building, and identify the socially problematic/ unrest area/ process known as the social hotspots. SLCA is comparatively a new tool experiencing challenges in terms of LCI compilation, and the selection of right impact indicators and stakeholders. A few studies using SLCA (3 of 807) specifically focused on residential buildings with social wellbeing and employment as social indicators.

The integration of above mentioned three tools (ELCA, LCC, SLCA) developed a sustainability assessment tool called life cycle sustainability assessment (LCSA) that assesses the environmental, social and economic objectives of sustainability of a product serve as a single entity. ELCA, SLCA, and LCC have been covered in residential buildings individually rather than combine. Contemporary LCSA frameworks for residential buildings [16-19, 37] experienced challenges in terms of indicator development, stakeholder selection, integration of sustainability objectives, site-specific data collection, identification of hotspots, and application of improvement strategies. The LCSA framework in this PhD study addressed the aforementioned drawbacks [27 Table-1, page 3]. All these LCSA studies have also used an assumed service life for buildings and neglected the role of maintenance activities in the sustainability performance of buildings [16 page 1490; 17 page 1224; 18 page 557; 19 page 237].

2.3 Identification of research gap

This review article concluded that the existing LCSA frameworks are lacking a comprehensive approach to assessing all stages of the TBL sustainability performance of residential buildings. There exists improvement opportunities in the development of region-specific TBL indicators by involving selection of key stakeholders, gathering site-specific data, and identification of hotspots for proposing improvement strategies. Therefore, a holistic LCSA framework needs to be developed for addressing the aforementioned gaps in the TBL sustainability assessment of the residential buildings, while taking into account the service life variations of buildings made of different materials.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The objective of this chapter is to develop a holistic life cycle sustainability assessment (LCSA) framework for residential buildings to achieve TBL sustainability (environmental, social, and economic) objectives. This framework involved a bottom-up hierarchical approach for sustainability assessment, sequentially utilising KPIs, impact categories, and sustainability objectives to assess the TBL sustainability performance of the residential buildings. The development of LCSA took place in following two stages:

Stage-1: Development of a theoretical framework of LCSA for sustainability assessment of residential buildings

The novelty of this LCSA framework was to assess the implications of service life of buildings and building materials on the sustainability performance of buildings. Secondly, this framework enabled the integration of three objectives of sustainability to obtain a single score and to provide further breakdown of TBL indicators to find hotspots in order to further improve the sustainability performance of residential buildings. This part of the thesis was published in Chemical Engineering Transactions journal with a title '***Sustainability Assessment of a Residential Building Using a Life Cycle Assessment Approach'*** (Appendix- 2, [25]).

Stage-2: Development of TBL sustainability indicators for the LCSA framework of residential buildings

The implementation of LCSA framework in residential buildings required the development of TBL sustainability indicators. This primary selection of indicators was done using a literature review and then the area experts were consulted to finally select the TBL indicators. The indicator development part of the framework was published in the Journal of Environmental Management as a refereed article entitled, ***'Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings'*** (Appendix- 3, [26]).

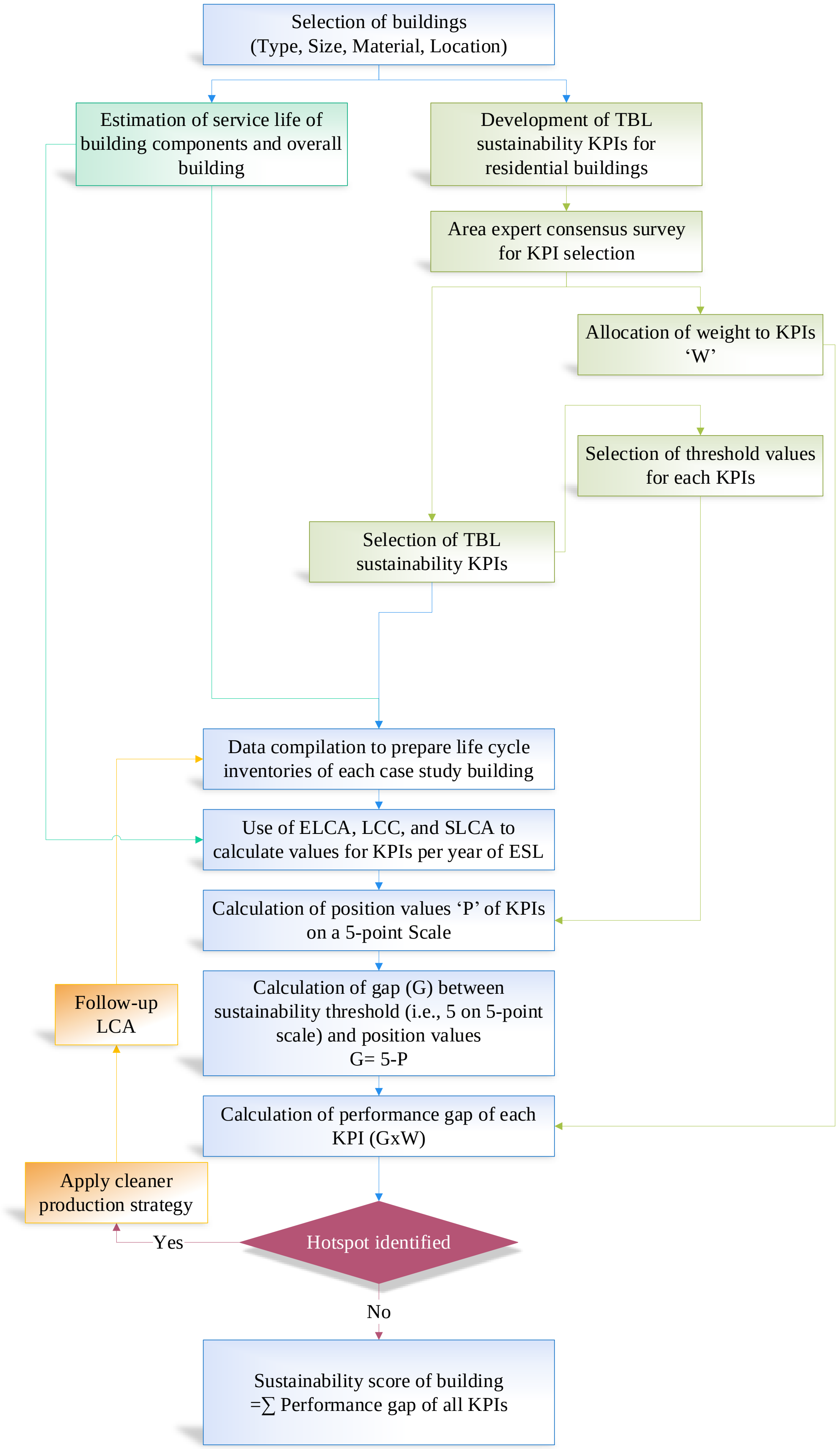


Figure 3-1: Flowchart of LCSA Framework [27]

3.2 Development of LCSA framework

The three steps of the development of the LCSA framework are as follows:

1. A meticulous review of sustainability assessment concepts, standards and tools, TBL matrices, and existing framework structures was carried out to come up with an LCSA framework for residential buildings.
2. The formulae and procedure involved in service life estimations, and sustainability assessment of residential buildings were developed.
3. A hypothetical example was used to test the applicability of the LCSA framework for calculating a single sustainability score to identify opportunities for further improvements. Figure 3-1 presents the flowchart adopted for the LCSA framework for residential buildings.

In order to develop this framework, a wide range of contemporary sustainability assessment approaches and concepts were reviewed, including Berkel [38], Biswas and Cooling [39], Lim and Biswas [40], Kucukvar and Tatari [40], Onat et al. [16], Hossaini et al. [17], Dong and Ng [18], Kamali et al. [37], Pope et al. [42], Eggenberger and Partidário [43], and IISD [44]. The review revealed that these frameworks were based on either weak or strong sustainability concepts. The weak sustainability concepts are the assessment of the TBL sustainability objectives separately performed without integrating them and favour the trade-off between these objectives. Whereas, strong sustainability concept is the integration of three objectives (environmental, social, and economic) of sustainability leading to the ecologically focused development (Figure 1-1).

Chapter 2 confirmed that the existing literature on LCSA frameworks of buildings did not consider the influence of the service life of overall buildings and building components on the sustainability performance [24]. Because of the absence of service life of building components in the LCSA framework, the replacement and maintenance activities were not considered in the use stage of the buildings, which underestimated the true sustainability performance.

Therefore, this PhD research has adopted the concept of strong sustainability principle (Figure 1-1a) using multi-criteria hierarchal analysis and bottom-up approach, with the integration of service life of building components and overall building, to address the gaps in the existing sustainability assessment frameworks. Figure 3-2 illustrates the processes involved in the development of the LCSA framework for residential buildings. The process of the development of the LCSA framework started through a literature review of existing case studies on sustainability performance, building materials, and service life of buildings to identify the research gaps of existing LCSA frameworks.

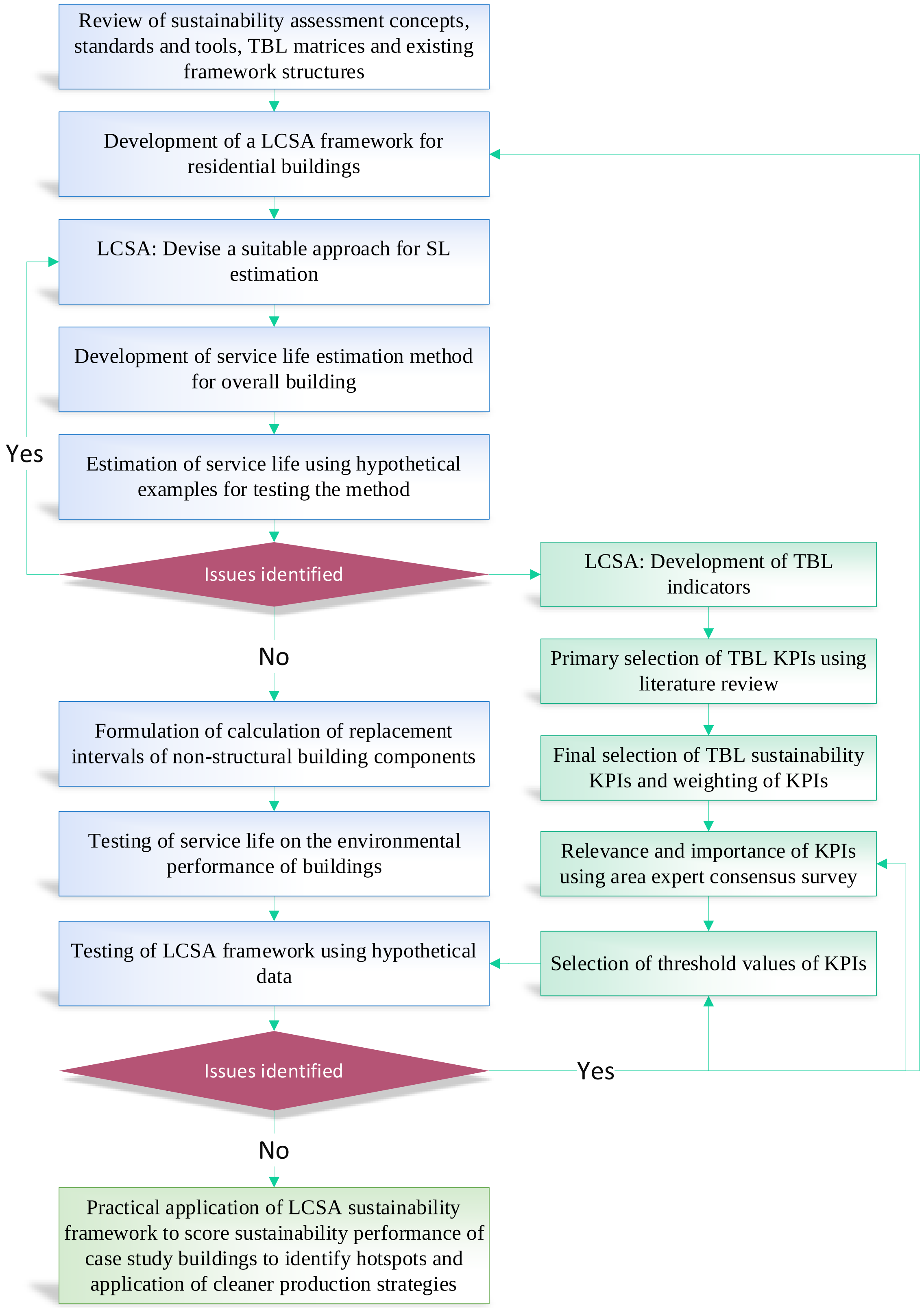


Figure 3-2: Development process of LCSA Framework for residential buildings [27]

The theoretical framework of the life cycle sustainability assessment was completed in two stages.

1. The formulae and procedures to estimate the service life of building and life cycle sustainability assessment were generated. The service life of a hypothetical case study building was estimated and then LCSA framework was applied to figure out the potential errors in the framework.

2. The TBL sustainability indicators were selected through a consensus survey. The relevance and importance in terms of rankings provided by the area experts were used to select and weight the key performance indicators (KPIs). Then the threshold values for each KPI were determined by reviewing existing case studies, sustainability standards, agreements to international treaties, and national statistics. The framework was then tested using hypothetical values to determine the accuracy of the framework prior to practical application.

3.2.1 Estimation of service life of residential buildings

Section 2 of Appendix 2 [24], described the methodology adopted in the LCSA framework. Firstly, the building was divided into three structural systems i.e., roof system, wall system, and footing system. Then the factor method of ISO 15686-8 [45] was used to estimate the service life of buildings. The estimation of service life was based on the material quality, design quality, level of workmanship, maintenance level, functional use, and internal and external exposure conditions of the building. In the factor method, the service life of a building component from some reliable existing data is considered as the reference service life and then it was multiplied by various factors to estimate the service life (Equation 3-1).

$$\boldsymbol{ESL = RSL * A * B * C * D * E * F * G} \qquad \textit{Equation 3-1}$$

Where,

ESL = Estimated service life

RSL = Reference service life

Factor A = Quality of components (e.g., manufacturing, storage, transport, protective coating)

Factor B = Design level (e.g., incorporation of design, sheltering by rest of the structure)

Factor C = Work execution level (e.g., site management, level of workmanship, climatic conditions during the execution of work)

Factor D = Indoor environment (e.g., aggressive environment, ventilation, condensation, humidity)

Factor E = Outdoor environment (e.g., elevation of building, micro-environmental conditions, and weathering factors)

Factor F = In-use conditions (mechanical impact, user category, and wear and tear)

Factor G = Maintenance level (quality and frequency of maintenance, and accessibility of maintenance)

Figure 3-3 presents the structural outline for estimation of service life of the overall building. In the first step, the ESL for components of building systems (i.e., roof, wall, and footing system) was estimated using the factor method. In the second step, the maximum of ESL of components of building systems was used as ESL of the building system. In the third step, the minimum ESL of building system was considered as the ESL of overall building to ensure the structural integrity of the building.

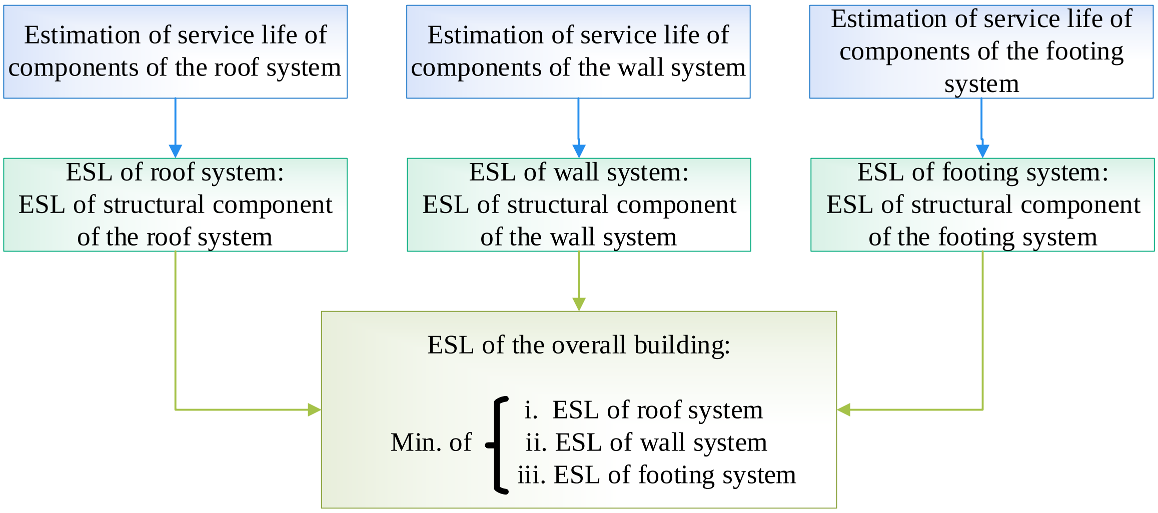


Figure 3-3: Procedure for service life estimation of the overall Building [27]

3.2.2 Life cycle sustainability assessment of residential buildings

The LCSA framework considered the cradle to gate approach (i.e., pre-use, use, and post-use stages) to assess the TBL sustainability performance of residential buildings. The framework used four steps of the ISO 14040-44 framework [30], including goal and scope definition, compilation of life cycle inventory (LCI), life cycle impact assessment, and interpretation. TBL sustainability KPIs were the smallest units of the TBL sustainability assessment of buildings. The KPIs were aggregated to impact categories and the impact categories were then aggregated to sustainability objectives (environmental, social, and economic), and then these objectives were integrated to determine the overall or single sustainability score of buildings. The scores of the level of importance of each of these KPIs given by the area experts in a consensus survey was converted to corresponding weight using Equation 3-2 [25]. The detailed methodology adopted for development of the KPIs of residential buildings and the selection of threshold values for each KPI has been explained in section 3.3 of this thesis.

$$\boldsymbol{w_i} = \frac{\sum_{R=1}^{N} \boldsymbol{S_{ri}}}{\boldsymbol{N} * \sum_{i=I_1}^{I_n} \boldsymbol{S_i}}$$ ***Equation 3-2***

Where,

w_i = Weight of KPI

N= Number of respondents

R = 1, 2, 3, …………. N; Responses of the respondents

S_{ri} = Score given by a respondent 'r' for an indicator 'i'

i = 1, 2, 3, ……….. I_n; Number of KPIs

S_i = Value of each score

The threshold value of each KPI was selected through a rigorous reviewing process and was given the highest position 5 on a 5-point Likert scale. KPIs achieving respective threshold values meant that sustainability performance has been achieved. The ELCA, SLCA, and LCCA used the numerical data of energy, material, transportation, and cost and qualitative data from the official reports of related government and semi-government organizations for all stages of building life cycle to determine the values of environmental, social and economic KPIs respectively. Equations 3-3 and 3-4 [25] were used to determine the position value of KPIs on a 5- point Likert scale.

$$P_{low} = \frac{\textbf{Threshold Value}}{\textbf{Calculated Value}} \times \mathbf{5}$$ ***Equation 3-3***

$$P_{high} = \frac{\textbf{Calculated Value}}{\textbf{Threshold Value}} \times \mathbf{5}$$ ***Equation 3-4***

Equation 3-3 was used to determine the position value of the KPIs where lower value lead to sustainability (e.g., carbon footprint, embodied energy, C&D waste), whereas, Equation 3-4 was used to determine the position value of KPIs where higher values reflect sustainability (e.g., net benefit, GDP, income). The gap 'G'– difference between the position value of KPI and its threshold value (i.e. 5 on a Likert scale) – was then multiplied by the corresponding weight to calculate the performance gap of the KPIs. To identify the hotspot, the possible performance gap for threshold value was determined by multiplying weight of KPI with threshold value (i.e., 5). Then the % performance gap of each KPI as a percentage of the performance gap for threshold was determined using Equation 3-5. A significant performance gap for KPI (≥ 50%) was identified, as the hotspot in the sustainability assessment of the building [27].

$$\%\ \boldsymbol{Performance\ gap\ of\ KPI} = \frac{\boldsymbol{Maximum\ performance\ gap\ of\ a\ KPI}}{\mathbf{5} * \boldsymbol{Weight\ of\ KPI}}\ \boldsymbol{X}\ \mathbf{100} \qquad \textit{Equation 3-5}$$

If the hotspots were identified, the CPS were applied to improve the sustainability performance, and a follow-up LCSA was carried out to calculate an improved/ revised sustainability scope. The revised performance gap of the KPIs after the application of CPS were then aggregated to the performance gap of impact categories, then to sustainability objectives, and finally to overall sustainability of the buildings. The sustainability score of the building is determined by subtracting the performance gap of the building from the maximum possible sustainability score (i.e., 5 on a 5-point Likert scale). The building with the highest sustainability score presents its highest level of TBL sustainability performance.

3.3 Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings

Figure 3-4 shows the hierarchical process adopted for the TBL sustainability assessment in the LCSA framework for residential buildings.

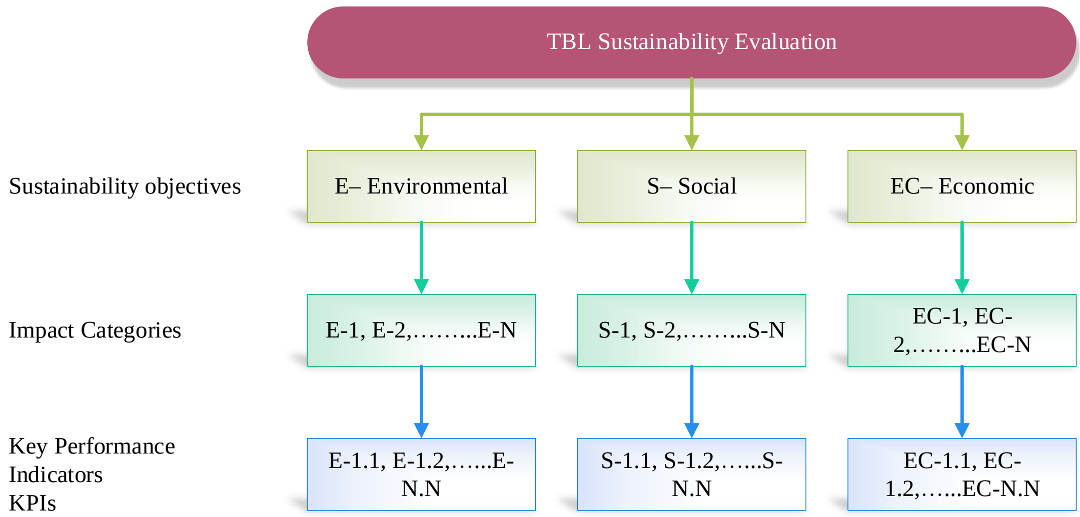


Figure 3-4: Hierarchy of TBL sustainability evaluation [26]

The TBL sustainability evaluation of building was segregated into sustainability objectives (environmental, social, and economic). Each sustainability objective was further subdivided into impact categories and each impact category was then segregated to key performance indicators (KPIs). KPIs were considered the smallest unit of the LCSA framework hierarchy. A participatory approach was adopted to select and develop the TBL sustainability indicators for residential buildings. The methodology involved four main steps; i) Primary selection of TBL sustainability KPIs, ii) Final selection of TBL sustainability KPIs, iii) Weighting of selected KPIs, and iv) Threshold values of KPIs (Figure 3-5).

i. Primary selection of TBL sustainability KPIs

  - After careful review of existing national and international literature, best practice guideline of life cycle impact assessment by Australian life cycle assessment society (ALCAS) and government official publications, a list of 17 KPIs under 12 impact categories for 3 sustainability objectives was prepared.
  - A questionnaire was designed to collect the area expert's response to the relevancy and importance of these KPIs. The questionnaire also had the provision for participants to provide feedback and suggest additional KPIs.
  - A mindful participant selection was made, taking into consideration the knowledge, area experience, judgement capacity and distinctive perception for sustainability assessment of building industries of Australia under four stakeholders' categories (Government and Engineers Australia, Academia, Practitioners, Structural engineers). The respondents were categorized and coded to keep the individual identity confidential as per Curtin's policy of human ethics and to avoid any potential bias.
  - Once Curtin University has approved the ethics application, potential participants were approached through emails to know their interest to participate in an online survey. The respondents who agreed to participate were sent a link of the online questionnaire and then their responses were recorded. The survey responses were truly anonymous to avoid bias. The respondents were aware of this and so they had agreed to provide opinion. The online survey took about three and a half months to complete. The responses were collected from an equal number of respondents for each stakeholder category (i.e., 40 respondents with 10 from each category).

ii. The responses were then compiled to determine the relevance and importance of the KPIs. All primarily selected KPIs were found relevant by the survey participants and few new

KPIs were suggested by the participants. A list of finally selected 22 KPIs included all 17 KPIs that were shortlisted before the survey and 5 new KPIs (recycling potential, loss of biodiversity, resilience and adaptation, noise, local material sourcing) which were suggested by the participants (Table 3-1). There were suggestions for including some more indicators which were not included due to following reasons [26]:

- These are way too broad i.e., shared amenity facility, modern slavery, water-wise landscaping, job creation, employee training, teleworking space and lifecycle contribution to local economy
- Some of these are beyond the scope of the proposed study i.e., adaptability, aesthetics, size of home, population density, site selection, occupancy and colour selection
- Some are strategies but not actually indicators i.e., water efficiency rating
- Some are like objectives of the study rather than the indicators i.e., sustainable materials, adaptability of building
- Some are overlapping with existing KPIs i.e., Cumulative embodied water consumption, indoor environmental quality, land use, circulatory indicator, social equity, resource depletion, eco-toxicity, social inclusion, and community/stakeholder input

iii. The weight of each KPI was determined based on the level of importance provided by the respondents using equation 3-2. The responses with no comments were excluded from weighting calculations and when the response for a KPI is ‘irrelevant’, its score was ‘0’. The scores for responses including somewhat important, moderately important, important, and most important were presented on a Likert scale were 2.5, 5, 7.5, and 10, respectively. The weights of all KPIs under one impact category were then aggregated to the weight of respective impact category. The weights of impact categories were aggregated to the weight of sustainability objectives (Table 3-2).

iv. The threshold values of the KPIs were ascertained by reviewing existing case studies, sustainability guidelines and standards, national and international agreement, and government statistics and reports. The values that were considered sustainable in the Australian context were selected as threshold values and were given a maximum score of 5 on a 5-point Likert scale.

v. Finally, the LCSA framework consisted of TBL sustainability KPIs was tested using hypothetical case study buildings to verify the applicability of the framework before practically implementing on the ground, as discussed in Chapter 5.

Table 3-1: Final list of TBL KPIs for building sustainability [26]

Sustainability objective	Category code	Impact category	KPI code	KPI
Environmental objective	E-1	Climate change	E-1.1	Carbon footprint (kg CO_2 eq/m^2/year)
			E-1.2	Resilience and adaptation (year)
	E-2	Air quality	E-2.1	Acidification (kg SO_2eq/m^2/year)
	E-3	Water quality	E-3.1	Eutrophication (kg PO_4 eq/m^2/year)
	E-4	Ecological footprint	E-4.1	Land use (Ha-a/m^2/year)
			E-4.2	Loss of biodiversity (BI Index/m^2/year)
	E-5	Water scarcity	E-5.1	Cumulative embodied water consumption (kl/m^2/year)
	E-6	Energy	E-6.1	Cumulative energy demand (GJ/m^2/year)
	E-7	Abiotic resource depletion	E-7.1	Cumulative fossil energy consumption (GJ/m^2/year)
	E-8	Waste generation	E-8.1	C&D waste (tonnes/m^2/year)
			E-8.2	Recycling potential (%/m^2/year)
Social objective	S-1	Intra-generational equity	S-1.1	House affordability (AUD/m^2/year)
			S-1.2	Indoor living conditions (AUD/m^2/year)
			S-1.3	Thermal comfort (AUD/m^2/year)
			S-1.4	Noise (STC)
			S-1.5	Local material sourcing (km)
	S-2	Inter-generational equity	S-2.1	Energy conservation (%/m^2/ year)
Economic objective	EC-1	User perspective	EC-1.1	Life cycle cost (AUD/m^2/year)
			EC-1.2	Potential savings (AUD/m^2/year)
			EC-1.3	Benefit-cost ratio
	EC-2	Developer perspective	EC-2.1	Net benefit (% /m^2/year)
			EC-2.2	Carbon tax saving (% /m^2/year)

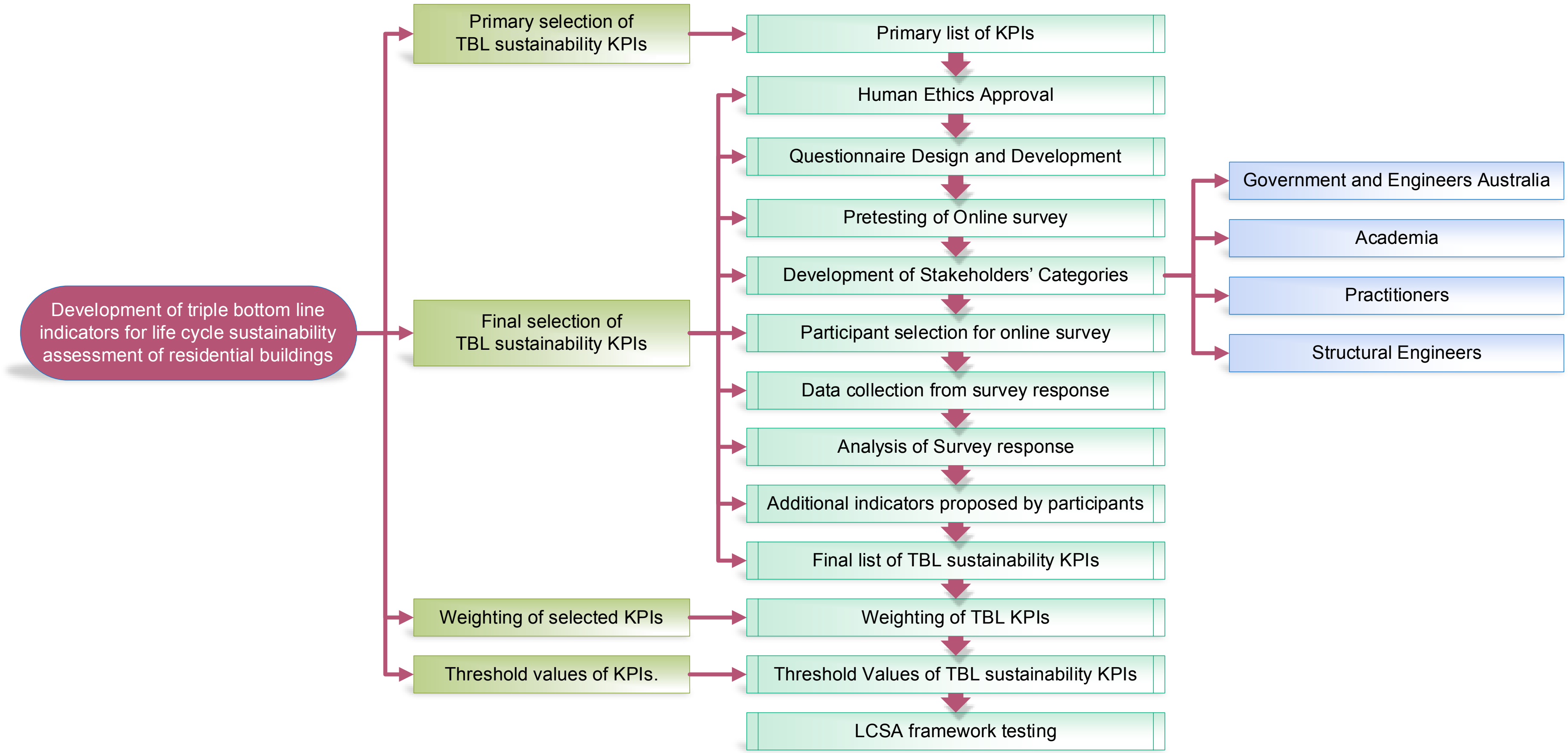


Figure 3-5: Hierarchy of TBL sustainability evaluation

Table 3-2: Weight of KPIs/ impact categories/ sustainability objective for residential buildings [26]

Impact Categories	KPIs	Total score	KPI weight	Impact category weight	Sustainability objective weight
E-1 Climate change	E-1.1	352.5	0.0741	0.0777	0.5000
	E-1.2	17.5	0.0037		
E-2 Air quality	E-2.1	227.5	0.0478	0.0478	
E-3 Water quality	E-3.1	215	0.0452	0.0452	
E-4 Ecological footprint	E-4.1	267.5	0.0562	0.0662	
	E-4.2	47.5	0.0100		
E-5 Water scarcity	E-5.1	297.5	0.0625	0.0625	
E-6 Energy	E-6.1	300	0.0630	0.0630	
E-7 Abiotic resource depletion	E-7.1	310	0.0651	0.0651	
E-8 Waste generation	E-8.1	300	0.0630	0.0725	
	E-8.2	45	0.0095		
S-1 Intra-generational equity	S-1.1	250	0.0525	0.1822	0.2463
	S-1.2	275	0.0578		
	S-1.3	310	0.0651		
	S-1.4	15	0.0032		
	S-1.5	17.5	0.0037		
S-2 Inter-generational equity	S-2.1	305	0.0641	0.0641	
EC-1 User perspective	EC-1.1	332.5	0.0699	0.1696	0.2537
	EC-1.2	230	0.0483		
	EC-1.3	245	0.0515		
EC-2 Developer perspective	EC-2.1	202.5	0.0425	0.0840	
	EC-2.2	197.5	0.0415		
	Total	4760	1.0000	1.0000	1.0000

Note: *E-1.1 Carbon footprint; E-1.2 Resilience and adaptation; E-2.1 Acidification; E-3.1 Eutrophication; E-4.1 Land use; E-4.2 Loss of biodiversity; E-5.1 Cumulative embodied water consumption; E-6.1 Cumulative energy demand; E-7.1 Cumulative fossil energy consumption; E-8.1 C&D waste; E-8.2 Recycling potential; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving*

CHAPTER 4: IMPACT OF SERVICE LIFE ON ENVIRONMENTAL PERFORMANCE OF BUILDINGS

4.1 Introduction

This chapter discussed the estimation of service life of building components and the overall building, determined of the potential replacement intervals of non-structural components in building systems and, the assessment of the impact of service life variation, and repair and replacement activities on the environmental performance of the building.

This chapter was published in '*Buildings*' as a journal article entitled, ***'Impact of Service Life on the Environmental Performance of Buildings'*** (Appendix-4, [22]).

4.2 Service life estimation

Initially, the article selected a single story detached house of 4 bedrooms and 2 bathrooms, typical to Western Australia. Keeping the area, architectural design, and location same, 12 building combinations were created by varying building materials of building systems (roof, wall, and footing system), while ensuring that the structural integrity of buildings was not compromised (Table 4-1).

Table 4-1: Building components and combinations [22]

Building	Building Specifications	Building Components		
		Roof Frame	Wall Frame	Slab footing
Building-50	TF-DB-CC	Timber frame	Double brick	Conventional concrete
1	TF-CB-CC	Timber frame	Concrete block	Conventional concrete
2	TF-CB-FAGC	Timber frame	Concrete block	30% FA Green concrete
3	TF-CB-GGBFS	Timber frame	Concrete block	30% GGBFS Green concrete
4	TF-DB-CC	Timber frame	Double brick	Conventional concrete
5	TF-DB-FAGC	Timber frame	Double brick	30% FA Green concrete
6	TF-DB-GGBFS	Timber frame	Double brick	30% GGBFS Green concrete
7	SF-CB-CC	Steel Frame	Concrete block	Conventional concrete
8	SF-CB-FAGC	Steel Frame	Concrete block	30% FA Green concrete
9	SF-CB-GGBFS	Steel Frame	Concrete block	30% GGBFS Green concrete
10	SF-DB-CC	Steel Frame	Double brick	Conventional concrete
11	SF-DB-FAGC	Steel Frame	Double brick	30% FA Green concrete
12	SF-DB-GGBFS	Steel Frame	Double brick	30% GGBFS Green concrete

The roof system consisted of roof covering of terracotta tiles, roof frame, and gypsum board ceiling. The wall system for case study buildings consisted of rendering, wall frame, and interior plaster. Similarly, the footing system for case study buildings included ceramic tile flooring and on-grade slab footing. A conventional building (Building-50) made of timber-framed roof, brick wall, and conventional concrete slab footing with a service life of 50 years, which is widely considered in the existing LCA literature was used as a reference building for this study for comparison purposes. Alternative 12 buildings were compared with this reference building in terms of sustainability performance.

The service life of case study buildings was estimated using the methodology adopted in Section 3.2.1 of this thesis. Table 3 of Appendix 4 [22] presents the factors used to estimate the service life of building components. After estimating service life of building components of roof, wall, and footing systems, the longest ESL of building components of the corresponding building system, was selected as ESL for the building systems. Then the minimum value of ESL for buildings systems was selected as the ESL of the overall building (Figure 3-3). The ESL of the building components was used to estimate the replacement intervals of non-structural components. Total replacements for each building component during ESL of a building were estimated considering replacement intervals. This study identified that a significant amount of useful life of building materials (20% to 35%) is wasted at the end of life of the building, due to larger variations during ESL of building components (Figure 4-1).

4.3 Environmental life cycle assessment

The ESL of 12 buildings varies as shown in Figure 4-1, which could potentially affect the environmental performance of these buildings. The ELCA of the case study buildings was carried out following the ISO 14040-44 framework [30] to determine the impact of ESL and the replacement and maintenance activities on the environmental performance of these buildings. The system boundary for the LCA was divided into four stages; 1) Pre-use stage, 2) Use stage, 3) Replacement stage and 4) Post-use stage. Although the repair and replacement activities were related to the use stage, the replacement stage was separated from the use stage to assess the impact of repair and replacement activities on the building during ESL of the building. The development of a life cycle inventory (LCI) for each of 12 buildings is a pre-requisite prior to the estimation of environmental impacts. The LCI consists of materials, energy, and the transportation used during the initial construction of the building and subsequent replacements of the non-structural components and disposal of construction and demolition wastes to landfill at the end of life for these case study buildings. The functional unit for this study was considered as '*per year per building*'. The annual operational energy demand including heating, cooling, lighting, and home appliances was kept constant for all buildings irrespective of the thermal properties of the building. Four performance indicators (cumulative energy demand, life cycle GHG emissions, land use, and water consumption) were selected for ELCA based on literature review, regional importance, and relevancy to the scope of the study just to test the impact of ESL on the environmental performance of buildings.

Based on the discussion in Section 4 of the published paper in Appendix-4 [26], it was concluded that the environmental performance of the buildings is linked to the ESL of the building and building components. Though the longer ESL increases the total operational energy demand of the building, the annual impacts of the use stage were not affected by ESL variations. The use stage had the highest environmental impacts on building performance. The longer ESL had reduced significantly the pre-use stage impacts of the buildings. The replacement stage had been proved to be the third most hotspot contributing to the environmental impacts of the building after use and pre-use stages. This study identified that the use of industrial by-products (fly ash, GGBFS) reduced the environmental impacts of the buildings. The building materials, like timber and brick, reduced the water footprint and the mineral-based materials (steel, concrete blocks) performed better for land use than concrete block buildings. The study concluded that the longer ESL of the buildings delivers sustainable output only if there are fewer replacements and reduced levels of wastage of useful materials and landfilling.

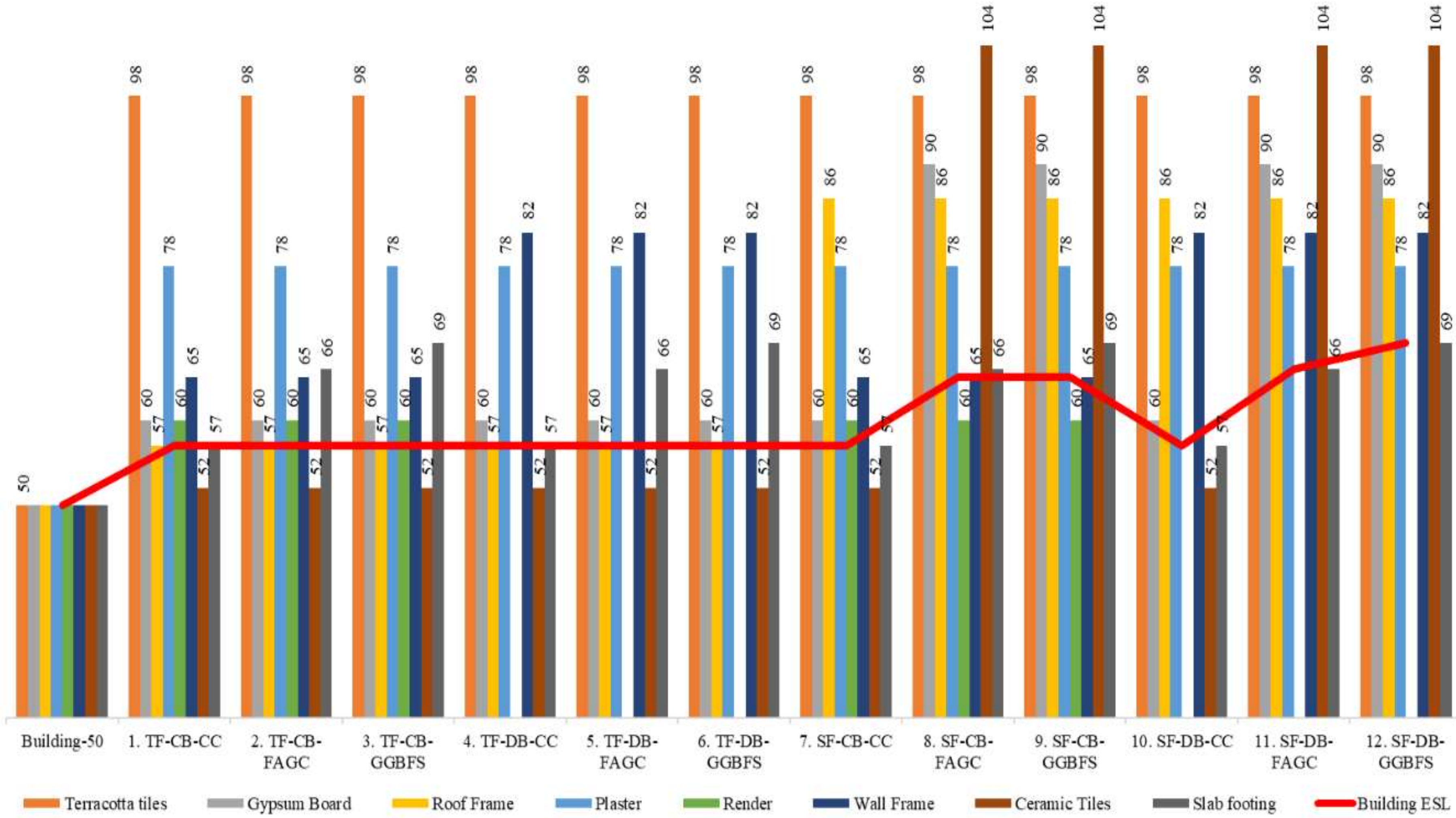


Figure 4-1: Estimated remaining life of building components at post-use stage [22]

CHAPTER 5: SUSTAINABILITY ASSESSMENT OF THE RESIDENTIAL BUILDINGS – A LIFE CYCLE SUSTAINABILITY ASSESSMENT APPROACH

5.1 Introduction

The objective of this chapter is to apply the LCSA framework to determine overall sustainability performance, and to identify the sustainability hotspots to determine the right cleaner production strategies to improve the sustainability performance of residential buildings. This chapter of the thesis has been accepted for publication by *Environmental and sustainability indicators* as a journal article entitled '***Sustainability implications of service life on residential buildings – An application of life cycle sustainability assessment framework***' (Appendix-5, [27]).

5.2 Case study

A typical single-story detached house of 4 bedrooms and 2 bathrooms of Western Australia with a service life of 50 years was selected as a reference house for this case study. As explained in section 3.2.1 of this thesis, the case study building was divided into three building systems (i.e., roof, wall, and footing). Keeping the location, orientation, architectural design, and size same, 14 building combinations were considered by varying the materials of building components of building systems. Table 5-1 presents the specifications of building systems for 14 case study buildings.

5.3 Estimation of service life of case study building components and overall building

In section 3.2 of paper 5 [27], the service life of the case study buildings was estimated following the methodology presented in Chapter 3: section 3.2.1 of this thesis. Estimation of service life included ESL of building components of building systems, ESL of building systems, ESL of buildings, and estimation of major repairs. The ESL of building components was estimated using the factor method of ISO 15686-8 [43]. Factors A-G considered to estimate the ESL of building components were ranked from 0.9 to 1.1 with 1.0 as not applicable or neutral. The manufacturer's technical sheets, materials databases (NAHB–National Association of home builders' database US, BOMA– Building Owners and Managers Association US), environmental product declaration sheets (EPDs), building codes and practices and government institution reports were used to rank the factors for each building component. The maximum value of ESL among ESL of building components of a system, was used as ESL of the corresponding building system and the minimum value of ESL among the ESL of building systems, was used as the ESL of buildings (Chapter 3: Figure 3-3).

Table 5-1: Building specifications of reference and 14 case study buildings [3]

Building #	Building Code	Roof System	Wall System	Footing System
Building-50	TF-DB-CC	Gypsum ceiling; Timber truss; Terracotta tiles	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
1	TF-CB-CC	Gypsum ceiling; Timber truss; Terracotta tiles	Rendering; Concrete blocks; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
2	TF-CB-FAGC	Gypsum ceiling; Timber truss; Terracotta tiles	Rendering; Concrete blocks; white set + Plaster	On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
3	TF-CB-GGBFS	Gypsum ceiling; Timber truss; Terracotta tiles	Rendering; Concrete blocks; white set + Plaster	On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
4	TF-DB-CC	Gypsum ceiling; Timber truss; Terracotta tiles	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
5	TF-DB-FAGC	Gypsum ceiling; Timber truss; Terracotta tiles	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
6	TF-DB-GGBFS	Gypsum ceiling; Timber truss; Terracotta tiles	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
7	SF-CB-CC	Gypsum ceiling; Steel truss; Terracotta tile	Rendering, Concrete blocks; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
8	SF-CB-FAGC	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
9	SF-CB-GGBFS	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
10	SF-DB-CC	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
11	SF-DB-FAGC	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
12	SF-DB-GGBFS	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
13	SF-DB-50% GGBFS+50 % RA	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 50% OPC replacement by GGBFS + 50% recycled aggregate; Ceramic tiles
14	SF-DB-50% GGBFS+100 %RA	Gypsum ceiling; Steel truss; Terracotta tile	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 50% OPC replacement by GGBFS+50% recycled aggregate; Ceramic tiles

The frequency of major repairs was estimated from ESL of building components. The number of replacements for each component during ESL or service life of the building was ascertained for inclusion in the LCI of buildings for life cycle assessment.

5.4 Life cycle sustainability assessment

Following the methodology of the LCSA framework (Figure 3-1), the sustainability assessment of the case study buildings was carried out. The goal and scope of this study, as discussed in section 3.3.1 of paper 5 [3], was to assess and improve the sustainability performance of buildings and to determine the effect of ESL of building and building components on their overall sustainability performance. The functional unit of this LSCA is '*per square meter per year*'. The system boundary of this study followed a cradle to grave approach, as per EN 16978, including three stages (pre-use, use, and post-use) for LCSA of buildings (Figure 5-1).

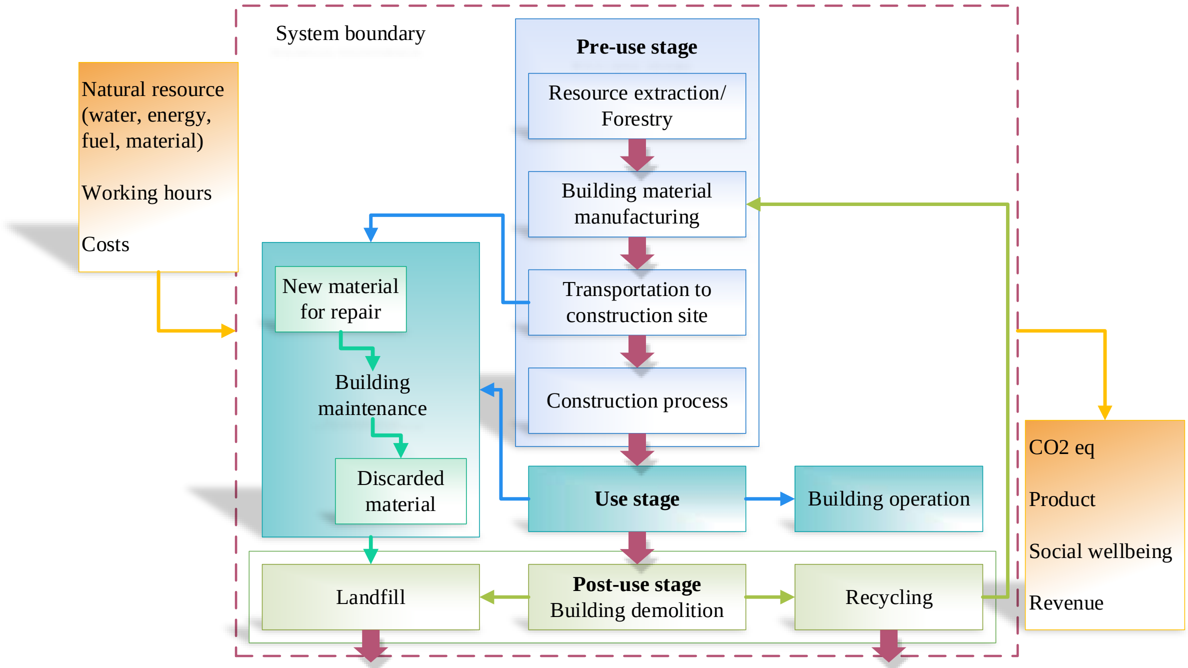


Figure 5-1: System boundary of LCSA framework

The drawing of 4×2 house (Figure 5-2) was used to estimate building materials to develop LCIs of buildings (Table 5-2). LCIs also include the information of energy consumption and transportation associated with building construction and use. Official publications of the Australian Bureau of Statistics, Rawlinson Western Australia, Alinta Energy Australia, Synergy Australia, Commonwealth Bank of Australia, Australian building codes, and construction material manufacturers and suppliers were used to collect quantitative and qualitative data used to calculate KPIs. Considering buildings specifications, materials, and orientation, the use stage operational energy demand (cooling/heating) was determined using an **AccuRate sustainability** software to capture the variation in region specific energy consumption [20]. Due to limited input material options for structural components of the building in this software, operational energy requirement was calculated for only brick wall and concrete block wall buildings.

Table 5-3 presents the system boundaries, where each system boundary consists of a number of stages. The amount of inputs used in these life cycle stages was used to develop LCIs to calculate KPIs values. The environmental KPIs were calculated using inputs from the material, energy, and transportation LCIs using ELCA software **SimaPro 8.4** [22]. Using the same LCIs that were used in ELCA, the life cycle costs of buildings were calculated in terms of present values (PVs). The PV was calculated for a discount rate of 7% and all present values of construction materials, operational costs, maintenance costs, and end of life costs were added [23]. All '*KPIs values'* were calculated for 1 m^2 of building gross floor area and divided by ESL of buildings to align the KPIs with the functional unit. The '*position values'* of each KPIs for all case study buildings were calculated using Equation 3-3 and Equation 3-4 as explained in Chapter 3. The '*gap'* between this positon value and the threshold value for each KPI was calculated and then multiplied by the corresponding weight (Table 3-2: Chapter 3) to determine the '*performance gap*' for the KPIs.

Figure 5-4 and Figure 5-5 showed that three KPIs, S-1.1, S-1.5, and EC-2.1 met the threshold values for all buildings (i.e. performance gap = 0). Section 3.3.6 of Paper 5 [27], discussed the LCSA results of case study buildings. The KPIs for the environmental objective performed the worst among sustainability KPIs with an average performance gap of 42%. KPIs for the economic objective performed average with an average KPI performance gap of 34.8%. The social KPIs performed the best with an average performance gap of 23.2%. Two KPIs for environmental objective E-5.1 (Cumulative embodied water consumption) and E-8.2 (Recycling potential) only met the threshold values of sustainability for 8 buildings and 4 buildings, respectively. One of the economic KPIs, EC-2.1 (Net benefit) were found to meet the sustainability threshold for all case study buildings and two social KPIs (S-1.1 (House affordability) and S-1.5 (Local material sourcing)) had met threshold values for all buildings. Overall, all case study buildings showed average sustainability performance with a sustainability score between 2.353 for Building 7 and 3.128 for Building 11. Buildings with brick walls (U-value = 1.58 W/m^{2}K) had better sustainability performance than building made of the block wall (U-value = 2.71 W/m^{2}K) due to lower annual energy consumption associated with lower U-value (12.1%). Buildings with longer service life showed lower pre-use stage TBL sustainability impacts due to higher durability.

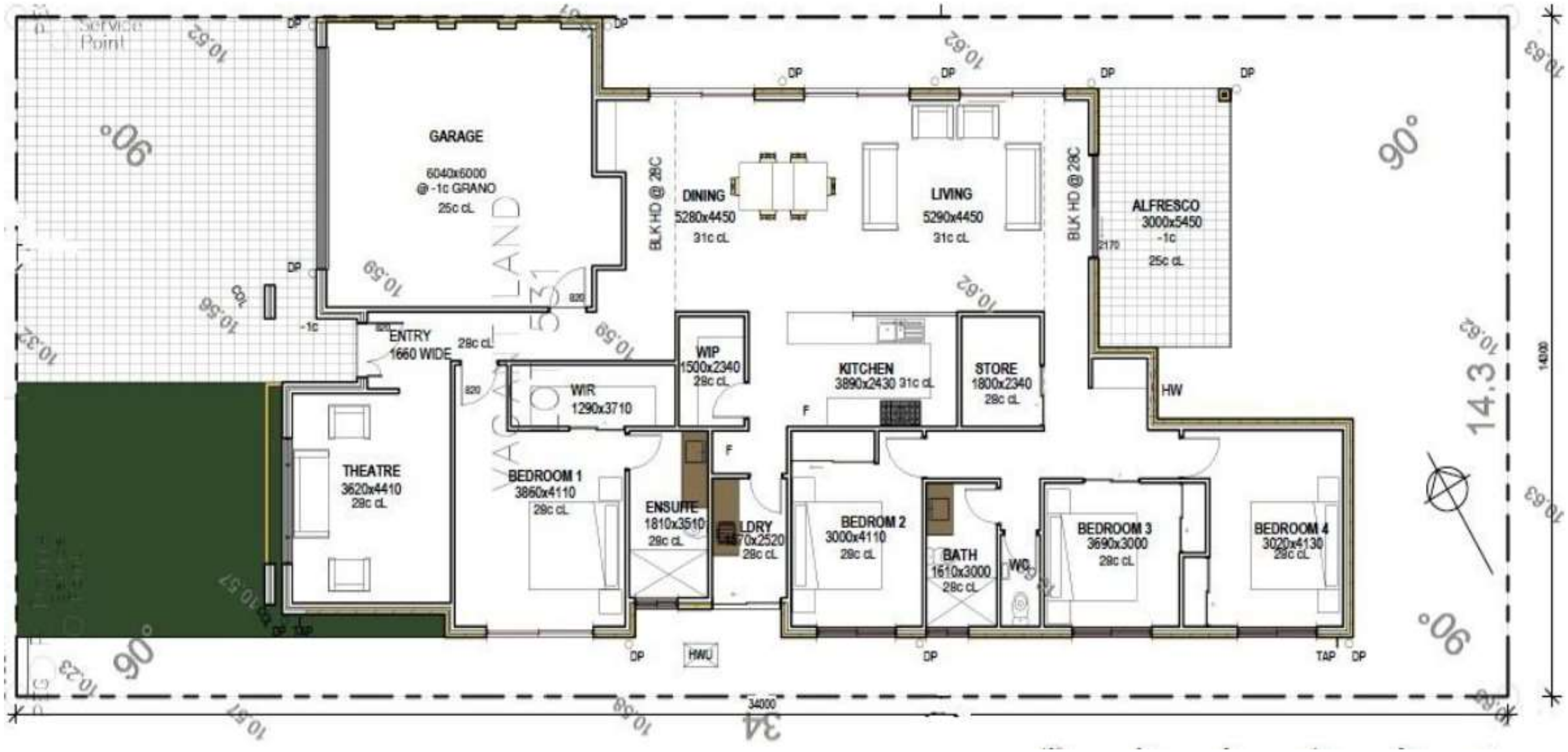


Figure 5-2: Layout of typical detached 4×2, single-story house [21]

Table 5-2: KPIs' Life cycle inventories of materials, transportation, and energy for Case study Buildings

	Buildings	Unit	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS +50%RA	14. SF-DB-50% GGBFS +100%RA
Construction Materials	Excavation of foundation	t	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83
	Sub base: sand	t	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01
	water proofing membrane- 0.2mm	t	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Mesh reinforcement fabric- SL92	t	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
	OPC	t	11.19	11.19	7.83	7.83	11.19	7.83	7.83	11.19	7.83	7.83	11.19	7.83	7.83	5.60	5.60
	FA	t	x	x	3.36	x	x	3.36	x	x	3.36	x	x	3.36	x	x	x
	GGBFS	t	x	x	x	3.36	x	x	3.36	x	x	3.36	x	x	3.36	5.60	5.60
	Natural Aggregate-4	t	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	22.39	x
	Recycled Aggregate-4	t	x	x	x	x	x	x	x	x	x	x	x	x	x	22.39	44.78
	Natural Sand-2	t	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39
	Floor Tiles (Ceramic)	t	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
	Concrete Blocks- 190x190x390	t	x	36.49	36.49	36.49	x	x	x	36.49	36.49	36.49	x	x	x	x	x
	Concrete Blocks- 90x190x390	t	x	27.5	27.5	27.5	x	x	x	27.5	27.5	27.5	x	x	x	x	x
	Face Bricks- 230x110x76	t	33.3	x	x	x	33.3	33.3	33.3	x	x	x	33.3	33.3	33.3	33.3	33.3
	Utility Bricks-290x90x90 (Ext. wall)	t	29.32	x	x	x	29.32	29.32	29.32	x	x	x	29.32	29.32	29.32	29.32	29.32
	Utility Bricks-290x90x90 (Int. Wall)	t	32.01	x	x	x	32.01	32.01	32.01	x	x	x	32.01	32.01	32.01	32.01	32.01
	rendering (5:1:1): Cement, plaster sand, lime	t	x	3.32	3.32	3.32	x	x	x	3.32	3.32	3.32	x	x	x	x	x
	plaster	t	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54
	Mortar: cement, brickie sand, lime	t	11.48	10.33	10.33	10.33	11.48	11.48	11.48	10.33	10.33	10.33	11.48	11.48	11.48	11.48	11.48
	Steel rebar, 12mm @ 1.25m c/c	t	x	0.19	0.19	0.19	x	x	x	0.19	0.19	0.19	x	x	x	x	x
	Metal lintels, columns, bracings, wall ties, structural fixtures	t	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
	Wall tiles	t	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
	Suspended ceiling	t	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19

	Buildings	Unit	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS +50%RA	14. SF-DB-50% GGBFS +100%RA
Construction Materials	Bat insulation for roof	t	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
	Roof Timber	t	4.13	4.13	4.13	4.13	4.13	4.13	4.13	x	x	x	x	x	x	x	x
	Roof Steel	t	x	x	x	x	x	x	x	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
	terracotta roof tiles	t	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55
	Metal door frames-12 no.	t	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	Door shutters-12no.	t	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
	Aluminium windows-SG	t	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Replacement Materials	Floor Tiles (Ceramic) @ 52 years	t	x	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
	Suspended ceiling @ 30 years	t	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	4.38	4.38	2.19	4.38	4.38	4.38	4.38
	Render @ 15 years	t	x	9.96	9.96	9.96	x	x	x	9.96	9.96	9.96	x	x	x	x	x
	Plaster @ 25 years	t	10.54	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08
	terracotta roof tiles @ 49 years	t	x	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55
	Aluminium windows-SG @ 23 years	t	1.43	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86
	Metal Frame, wood Door @ 23 years	t	0.55	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Construction Carriage	Dirt to Landfill	tkm	1341	1341	1341	1341	1341	1341	1341	1341	1341	1341	1341	1341	1341	1341	1341
	Sand for levelling	tkm	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300
	Material to site	tkm	6840	6000	6000	6000	6840	6840	6840	5932	5932	5932	6780	6780	6780	6780	6780
	Construction Waste	tkm	342	300	300	300	342	342	342	296.6	296.6	296.6	339	339	339	339	339
	Demolition waste to Landfill/ recycling	tkm	11414	10000	10000	10000	11414	11414	11414	9886	9886	9886	11300	11300	11300	11300	11300
Replacement Carriage	Material to site	tkm	441.3	1417	1417	1417	1118	1118	1118	1417	1942	1942	1118	1543	1543	1543	1543
	Construction Waste	tkm	22.06	70.86	70.86	70.86	55.92	55.92	55.92	70.86	97.08	97.08	55.92	77.16	77.16	77.16	77.16
	Demolition waste to Landfill/ recycling	tkm	735.5	2362	2362	2362	1864	1864	1864	2362	3236	3236	1864	2572	2572	2572	2572

	Buildings	Unit	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS +50%RA	14. SF-DB-50% GGBFS +100%RA
Energy	Energy consumption for plants and tools during construction activities	GJ	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23
	Energy consumption for heating, cooling, lighting, home appliances, and hot water during use stage	GJ	2688	3457	3457	3457	3064	3064	3064	3457	3942	3942	3064	3548	3548	3387	3225
	Energy consumption for plants and tools during end of life demolition activities	GJ	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072

Table 5-3: System boundaries including LCA stages of KPIs of TBL objectives [27]

Code	KPIs	Stages of LCA	Input
E-1.1	Carbon footprint	Pre-use, use, post-use	Materials, Energy, Transportation
E-1.2	Resilience and adaptation	Pre-use, use	Materials
E-2.1	Acidification	Pre-use, use, post-use	Materials, Energy, Transportation
E-3.1	Eutrophication	Pre-use, use, post-use	Materials, Energy, Transportation
E-4.1	Land use	Pre-use, use, post-use	Materials, Energy, Transportation
E-4.2	Loss of biodiversity	Pre-use, use, post-use	Materials, Energy, Transportation
E-5.1	Cumulative embodied water consumption	Pre-use, use, post-use	Materials, Energy, Transportation
E-6.1	Cumulative energy demand	Pre-use, use, post-use	Materials, Energy, Transportation
E-7.1	Cumulative fossil energy consumption	Pre-use, use, post-use	Materials, Energy, Transportation
E-8.1	C & D waste	Pre-use, use, post-use	Materials, Energy, Transportation
E-8.2	Recycling potential	Post-use	Materials
S-1.1	House affordability	Pre-use	Materials, Costs
S-1.2	Indoor living conditions	Use stage (Maintenance)	Materials, Costs
S-1.3	Thermal comfort	Use stage (Operation)	Energy, Costs
S-1.4	Noise	Pre-use stage (Construction), use stage	Materials
S-1.5	Local material sourcing	Pre-use stage (Transportation), use stage (Maintenance)	Materials, Transportation
S-2.1	Energy conservation	Pre-use, use, post-use	Materials, Energy, Transportation
EC-1.1	Life cycle cost	Pre-use, use, post-use	Costs, Energy, Materials
EC-1.2	Potential savings	Use stage (Operation)	Energy, Costs
EC-1.3	Benefit cost ratio	Pre-use, use, post-use	Costs
EC-2.1	Net benefit	Pre-use stage	Costs
EC-2.2	Carbon tax saving	Pre-use, use, post-use	Materials, Energy, Transportation

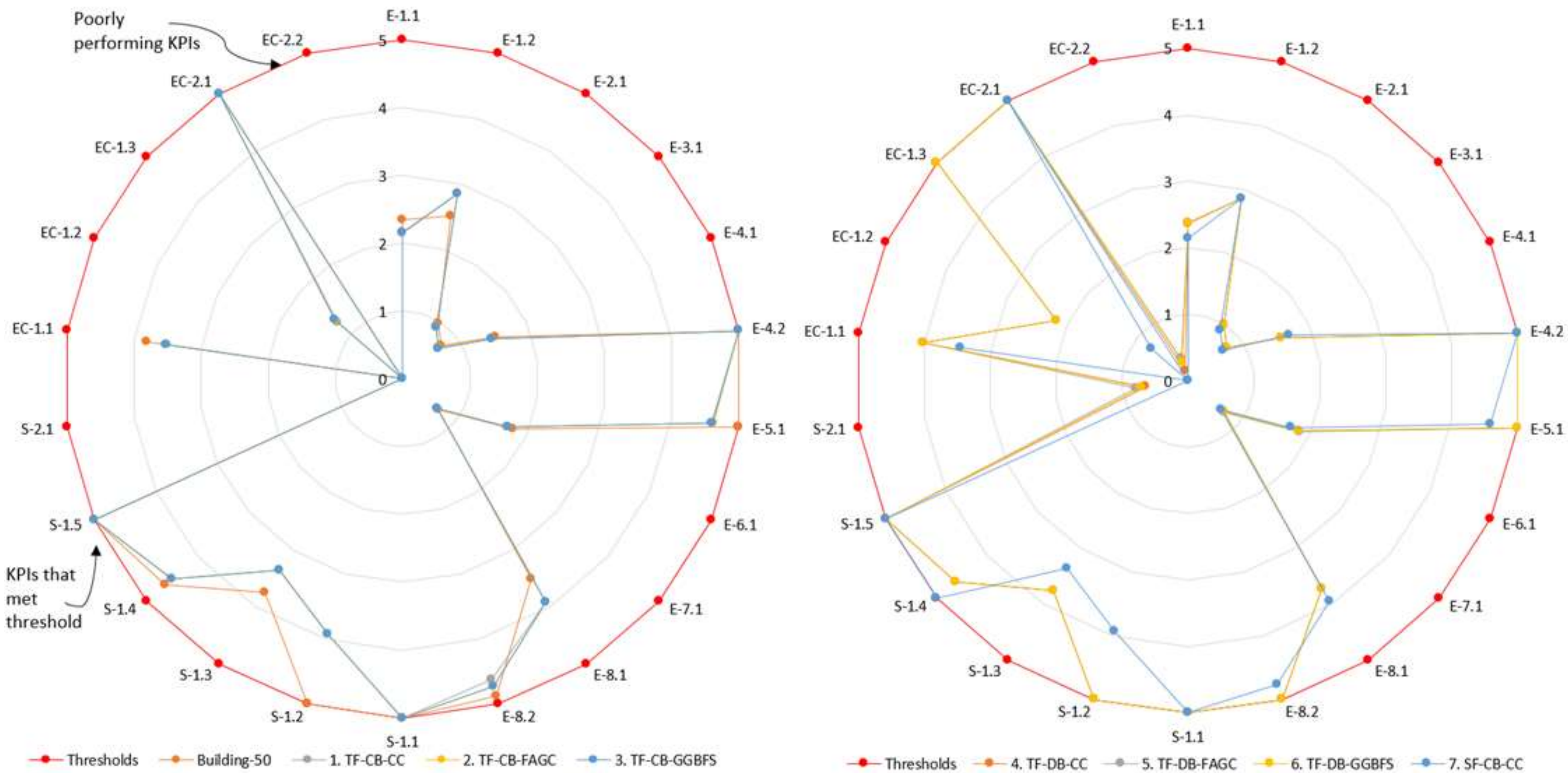


Figure 5-3: KPIs' position on 5-point scale for Case study building 1 - 3 [Left]; KPIs' position on 5-point scale for Case study building 4 -7 [Right] [27]

[E-1.1 Carbon footprint; E-1.2 Resilience and adaptation; E-2.1 Acidification; E-3.1 Eutrophication; E-4.1 Land use; E-4.2 Loss of biodiversity; E-5.1 Cumulative embodied water consumption; E-6.1 Cumulative energy demand; E-7.1 Cumulative fossil energy consumption; E-8.1 C&D waste; E-8.2 Recycling potential; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving]

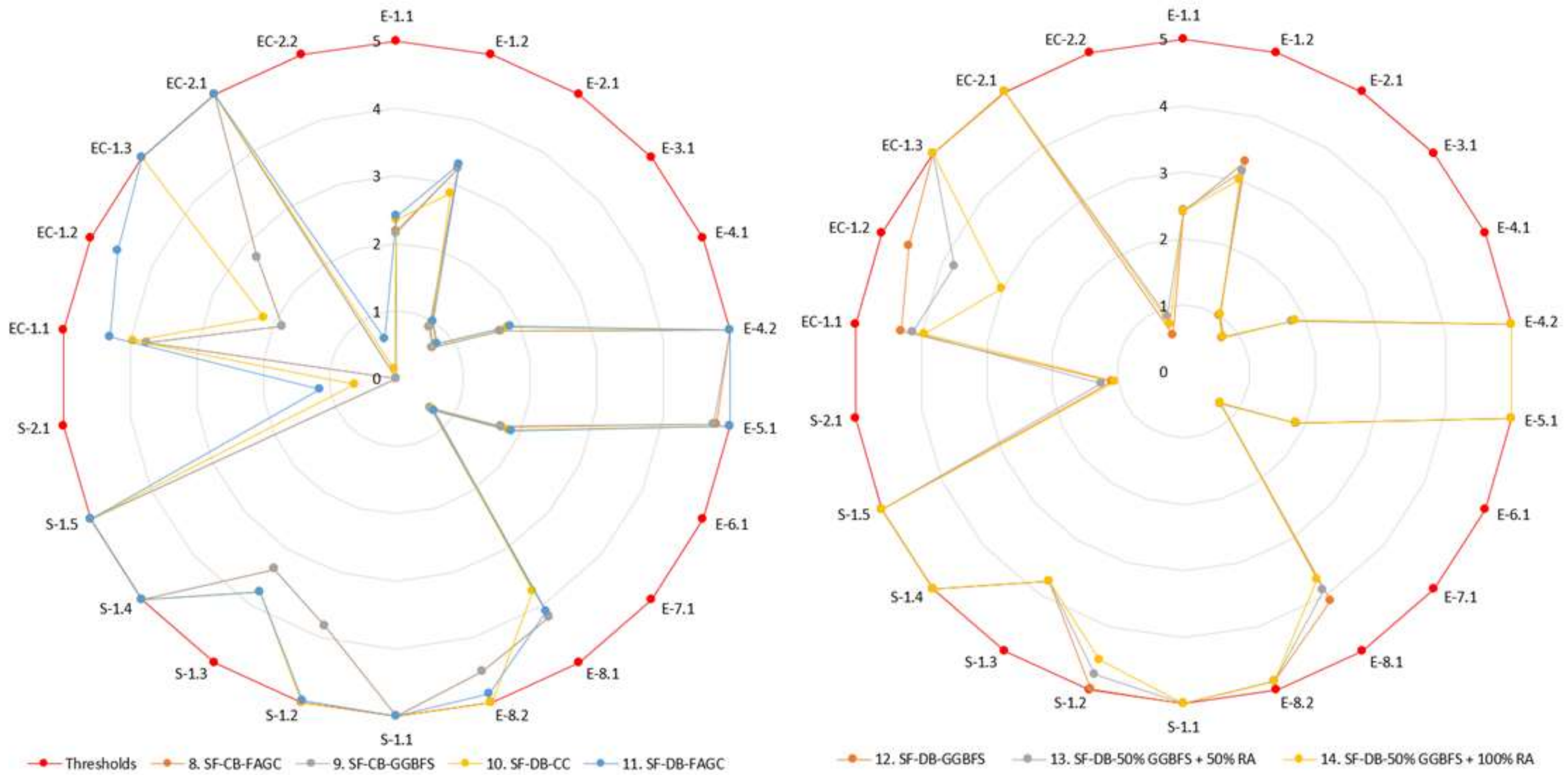


Figure 5-4: KPIs' position on 5-point scale for Case study building 8 - 11 [Left]; KPIs' position on 5-point scale for Case study building 12 - 14 [Right][27]

[E-1.1 Carbon footprint; E-1.2 Resilience and adaptation; E-2.1 Acidification; E-3.1 Eutrophication; E-4.1 Land use; E-4.2 Loss of biodiversity; E-5.1 Cumulative embodied water consumption; E-6.1 Cumulative energy demand; E-7.1 Cumulative fossil energy consumption; E-8.1 C&D waste; E-8.2 Recycling potential; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving]

Table 5-4: KPIs' Performance gap of case study buildings [27]

Code	KPIs	KPI Weight	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA	% Performance gap	Hotspot
E-1.1	Carbon Footprint	0.0741	0.19675	0.21	0.21	0.21	0.2	0.19	0.19	0.21	0.21	0.21	0.2	0.19	0.19	0.19	0.19	**57%**	1
E-1.2	Resilience and adaptation	0.0037	0.00925	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**43%**	
E-2.1	Acidification	0.0478	0.192349	0.2	0.2	0.2	0.19	0.19	0.19	0.2	0.2	0.2	0.19	0.19	0.19	0.19	0.19	**82%**	2
E-3.1	Eutrophication	0.0452	0.192002	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	**86%**	3
E-4.1	Land Use	0.0562	0.196676	0.2	0.2	0.2	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	**71%**	4
E-4.2	Loss of Biodiversity	0.01	2.71E-07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0%**	
E-5.1	Cumulative Embodied Water Consumption	0.0625	0	0.03	0.02	0.02	0	0	0	0.03	0.01	0.02	0	0	0	0	0	**8%**	
E-6.1	Cumulative Energy Demand	0.063	0.202905	0.21	0.21	0.21	0.2	0.2	0.2	0.21	0.21	0.21	0.2	0.2	0.2	0.2	0.2	**66%**	5
E-7.1	Cumulative Fossil Energy Consumption	0.0651	0.279982	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	**87%**	6
E-8.1	C & D waste	0.063	0.09386	0.07	0.07	0.07	0.08	0.08	0.08	0.07	0.05	0.05	0.08	0.06	0.06	0.07	0.08	**26%**	
E-8.2	Recycling potential	0.0095	0.001134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10%**	
S-1.1	House Affordability	0.0525	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0%**	
S-1.2	Indoor Living Conditions	0.0578	0	0.06	0.06	0.06	0	0	0	0.06	0.07	0.07	0	0	0	0.01	0.03	**24%**	
S-1.3	Thermal Comfort	0.0651	0.081267	0.11	0.11	0.11	0.08	0.08	0.08	0.11	0.11	0.11	0.08	0.08	0.08	0.08	0.08	**33%**	
S-1.4	Noise	0.0032	0.001173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10%**	
S-1.5	Local material sourcing	0.0037	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0%**	
S-2.1	Energy Conservation	0.0641	0.3205	0.32	0.32	0.32	0.28	0.27	0.28	0.32	0.32	0.32	0.28	0.25	0.25	0.24	0.25	**100%**	7
EC-1.1	Life Cycle Cost	0.0699	0.082752	0.1	0.1	0.1	0.07	0.07	0.07	0.11	0.09	0.09	0.07	0.05	0.05	0.06	0.07	**31%**	
EC-1.2	Potential Savings	0.0483	0.2415	0.24	0.24	0.24	0.14	0.14	0.14	0.24	0.15	0.15	0.14	0.02	0.02	0.06	0.1	**100%**	8
EC-1.3	Benefit Cost ratio	0.0515	0.2575	0.19	0.19	0.19	0	0	0	0.22	0.12	0.12	0	0	0	0	0	**85%**	9
EC-2.1	Net benefit	0.0425	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0%**	
EC-2.2	Carbon Tax Saving	0.0415	0.2075	0.21	0.21	0.21	0.2	0.19	0.2	0.21	0.21	0.21	0.2	0.18	0.18	0.17	0.18	**100%**	10

Note: Red colour bars represent the range of the performance gap for KPIs (Longer the colour bar, higher the value and vice versa)

5.5 Sustainability improvement strategies

The performance gaps for KPIs were used to identify the sustainability hotspot during the sustainability assessment of buildings. Threshold values for KPIs were given a score of 5 on a 5-point Likert scale. For each KPI, a performance gap for threshold was calculated by multiplying the weight of each KPI with the threshold value (i.e., 5). The difference of maximum calculated performance gaps of each KPI from the performance gap for threshold for respective KPI was then calculated using Equation 3-5 in terms of percentage. A KPI with a higher % value for performance gap (≥ 50%) was identified as the hotspot in the sustainability assessment of the building (Table 5-4).

Two of 22 KPIs (EC-1.2, EC-1.3) performed poorly for concrete block wall buildings. Whereas, eight KPIs (E-1.1, E-2.1, E-3.1, E-4.1, E-6.1, E-7.1, S-2.1, EC- 2.2) performed poorly for all buildings. The LCSA results showed that the use stage has contributed significantly to lower the sustainability performance of these KPIs. Therefore cleaner production strategies (CPS) [24], including product modification and technology modification, were proposed to reduce the impact during the use stage as it was identified as the hotspot (Table 5-5).

Table 5-5: Summary of CPS used for treating hotspots [3]

Hotspots		CPS	Options recommended
Appliances and lighting	34-39% of annual energy consumption	Technology modification	Use of the solar photovoltaic system
Water heater	37-42% of annual energy consumption	Technology modification	Use of solar water heater
Heating and cooling	19-28% of annual energy consumption	Product modification	Replacement of single glazed windows with double glazed windows
Energy-intensive building material	0.8-1.0% of construction material	Product modification	Replacement of virgin steel trusses for roof frame with 90% recycled steel

After incorporating the CPS (Table 5-5), the LCIs were updated with revised values of materials and energy inputs for all buildings. The energy demand was reduced by 51% for concrete block building (Building 1-3, 7-9) and 57% for brick wall buildings (Building 4-6, 10-14) due to application of these strategies. The change in the input values in the LCIs of buildings were considered when conducting follow-up LCSAs. The values of KPIs were updated by using these data in the revised LCIs. The revised performance gaps for KPIs, impact categories, and sustainability objectives were calculated. In revised sustainability assessment of case study buildings, six more KPIs (E-5.1, S-1.3, S-2.1, EC-1.2, EC-1.3, and EC-2.2) met the threshold, these included four of the ten KPIs (EC-1.2, EC-1.3, S-2.1, EC- 2.2) that initially performed poorly in sustainability assessment. Remaining six of the ten KPIs (E-1.1, E-2.1, E-3.1, E-4.1, E-6.1, E-7.1) improved significantly after the implementation of CPS (refer section 3.4, Paper 5 [3]). Reduced energy demand during the use stage due to application of technology modification strategy resulted in the reduced performance gap of KPI for life cycle cost with a performance gap reduction of 76% for Building 11 (SF-DB-FAGC) and Building 12 (SF-DB-GGBFS). The sustainability score of the case study buildings showed an average improvement of 30% for Buildings 11, 31% for Building 13, 33% for Building 14, 34% for Building 4-6, 35% for Building 10, 41% for Building 8-9, 48% for Buildings 1-3, and 49% for Building 7 (Figure 5-5).

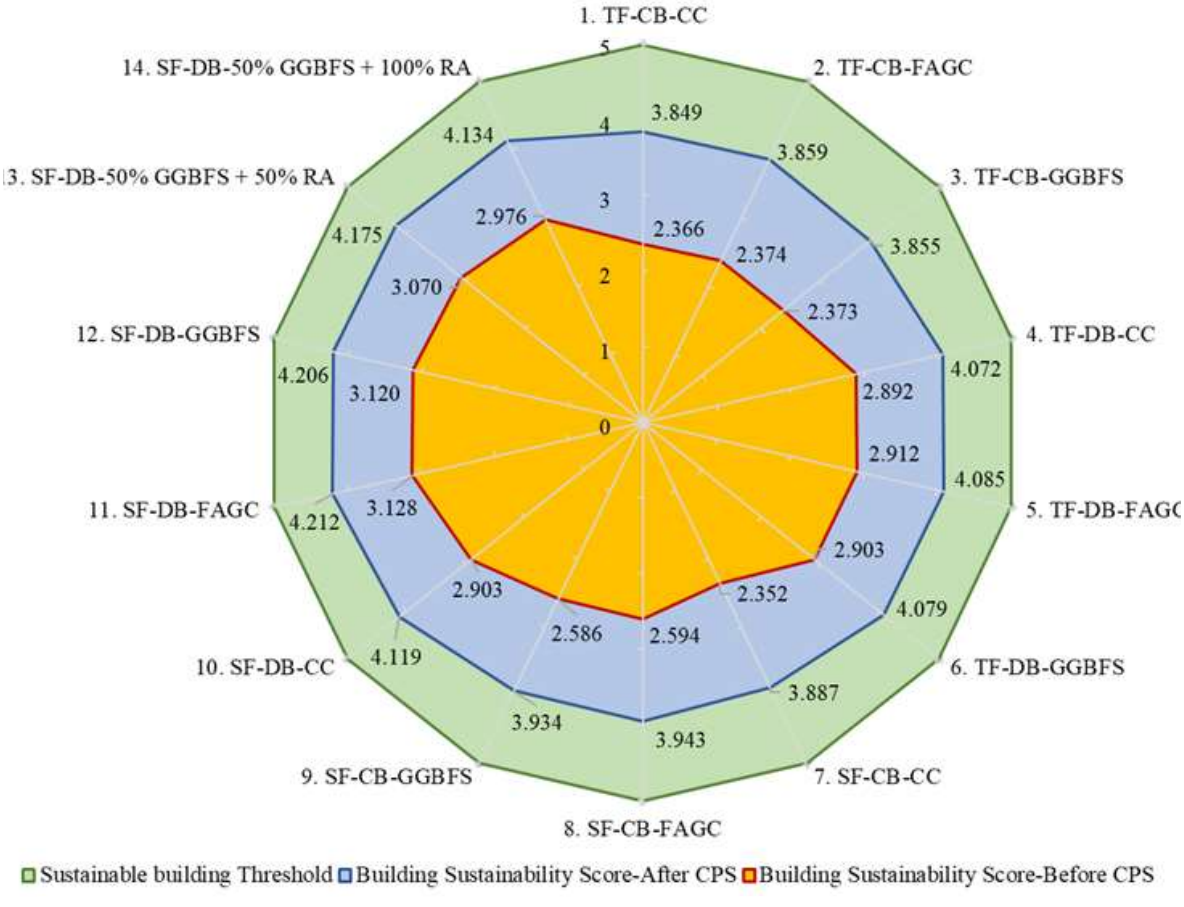


Figure 5-5: Sustainability score of case study buildings: before and after applying CPS [3]

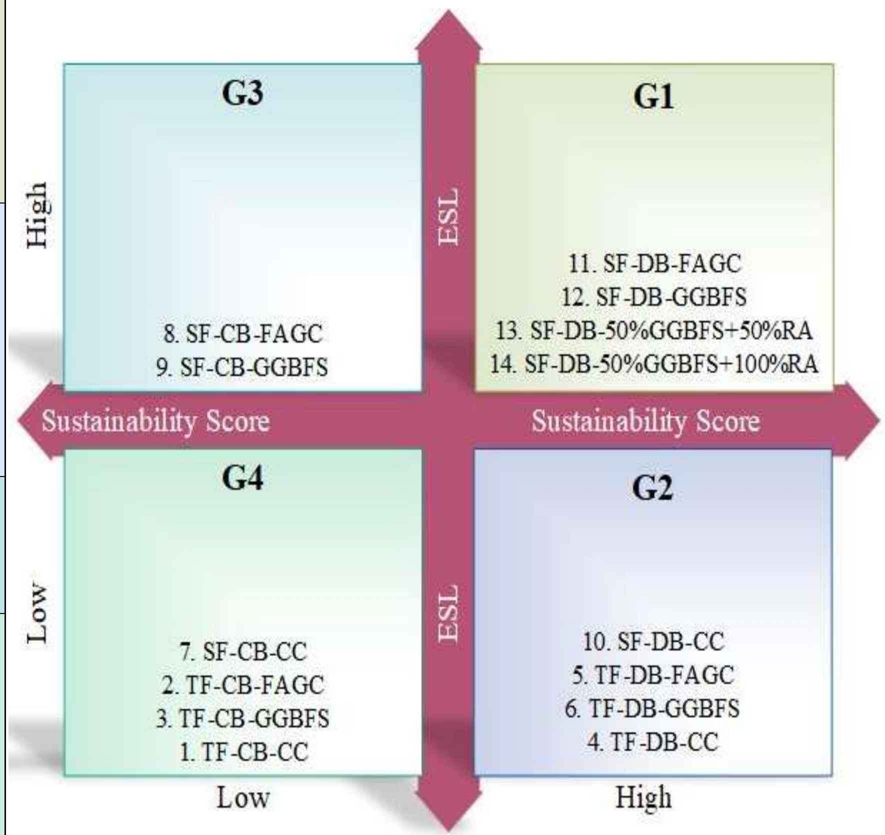
5.6 ESL- Sustainability quadrant

After calculation of sustainability scores, the case study buildings were ranked from 1-14, with sustainability rank-1 for building with the highest sustainability score (Table 5-6). Based on the ESL and sustainability score of the buildings, an 'ESL-sustainability quadrant' was made to classify the buildings in terms of TBL sustainability score and corresponding ESL.

1. Group G1 of the ESL-sustainability quadrant included Buildings 11-14 with ESL between 60-66 years and sustainability ranking from 1 to 4. G1 buildings have high sustainability scores and longer ESL among case study buildings. The impacts during pre-use stage and use stage maintenance of these buildings were reduced due to longer ESL. The use of industrial by-products and recycled materials reduced the environmental impacts of buildings. The use of bricks, with high thermal mass and lower heat transmission tendency (U-Value = 1.58W/m2K), in building envelope, lowered the use stage energy demand (24.63%) of buildings.
2. Group G2 of the ESL-sustainability quadrant included Buildings 10, 4-6 with high sustainability score, and shorter ESL of 57 years. Pre-use stage impacts of the buildings increased due to the use of plant-based materials (i.e., timber) in Building 4-6 and virgin materials (i.e., 100 % OPC conventional concrete, virgin steel) in Building 10. Also the frequent replacements of less durable non-structural components (i.e., ceramic tiles, roof covering, windows, doors, plaster) resulted in increased use stage of these buildings. However, the operational energy demand and costs of these buildings were significantly reduced thanks to the thermal performance of the brick walls (U-Value= 1.58W/m2K).
3. Group G3 of the ESL-sustainability quadrant included Buildings 8-9 with a lower sustainability score and longer ESL of 65 years. The use of concrete blocks of lower thermal mass and higher coefficient of heat transmission (U-Value =2.71 W/m2K) contributed to higher operational energy demand (24.63%), thus increasing TBL sustainability impacts. Rendering (ESL–16 years) applied to concrete block walls as an extra measure to reduce the porosity of concrete blocks, has also contributed adversely to the sustainability performance of the building by increasing the overall energy consumption.
4. Group G4 of the ESL-sustainability quadrant included Buildings 7, 1-3 with lower sustainability score, and shorter ESL of 57 years. The annual pre-use impacts of TBL sustainability were increased due to shorter ESL of these buildings. The shorter ESL is due to lower service life of timber framed roof and footing made of conventional concrete. Use of virgin materials, higher operational energy demand (24.63%) due to use of concrete block walls (U-Value =2.71 W/m2K) and frequent replacements of non-structural components (ceramic tiles, roof covering, windows, doors, plaster, rendering) increased the TBL impacts of G4 buildings.

The sustainability performance of the buildings with longer ESL (57-66 years) was found much higher (57.2% - 72%) as compared to the reference building (service life = 50 years; sustainability score = 2.449). This study has specifically identified that other factors like ***thermal performance of the building, and durability of non-structural components, use of industrial by-products and recycled materials, and maintenance activities played important roles in the sustainability performance of buildings.***

Table 5-6: Sustainability Ranking/ Matrix of case study buildings based on sustainability score and ESL [3]

Ranking	Buildings	ESL	Sustainability Score	Group	Quadrant Matrix
1	11. SF-DB-FAGC	66	4.212	G1	
2	12. SF-DB-GGBFS	66	4.206		
3	13. SF-DB-50%GGBFS+50% RA	63	4.175		
4	14. SF-DB-50%GGBFS+100% RA	60	4.134		
5	10. SF-DB-CC	57	4.119	G2	
6	5. TF-DB-FAGC	57	4.085		
7	6. TF-DB-GGBFS	57	4.079		
8	4. TF-DB-CC	57	4.072		
9	8. SF-CB-FAGC	65	3.943	G3	
10	9. SF-CB-GGBFS	65	3.934		
11	7. SF-CB-CC	57	3.887	G4	
12	2. TF-CB-FAGC	57	3.859		
13	3. TF-CB-GGBFS	57	3.855		
14	1. TF-CB-CC	57	3.849		

CHAPTER 6: CONCLUSIONS

6.1 Introduction

This chapter summarises the results that were determined to address the research objectives (ROs) as stated in Chapter 1. This study has developed a holistic life cycle sustainability assessment framework for residential buildings to address these objectives. To achieve the aim of this research, the understanding of existing theories, practices, standards, tools, and case studies particular to sustainable structures was indispensable. In this research, a holistic LCSA framework was developed, tested, and verified by applying this to residential buildings in Western Australia in order to achieve ROs. Figure 6-1 gives a snapshot of how the research objectives were achieved through five research articles during the PhD research period.

6.2 Outcome of research objectives

The outcomes of four research objectives of this PhD study are as follows:

6.2.1 Review of sustainability performance of the residential buildings

The literature review of the sustainability performance of the residential buildings concluded that there exist avenues for improvement in the sustainability assessment of residential buildings [RO1; Figure 6-1]. The frameworks so far developed prior to this PhD research hardly considered the integration of TBL sustainability objectives, selection of region-specific KPIs, involvement of key stakeholders in the selection and weighting of TBL indicators and the identification of TBL hotspots for incorporating sustainability improvement strategies in the residential buildings. In addition, this research has identified the most significant research gap by integrating the service life (SL) of buildings and building components into the LCSA framework as the exclusion of SL either underestimate or overestimate the sustainability performance of buildings or any civil infrastructure projects. These identified research gaps were addressed in order to establish the novelty of this PhD work.

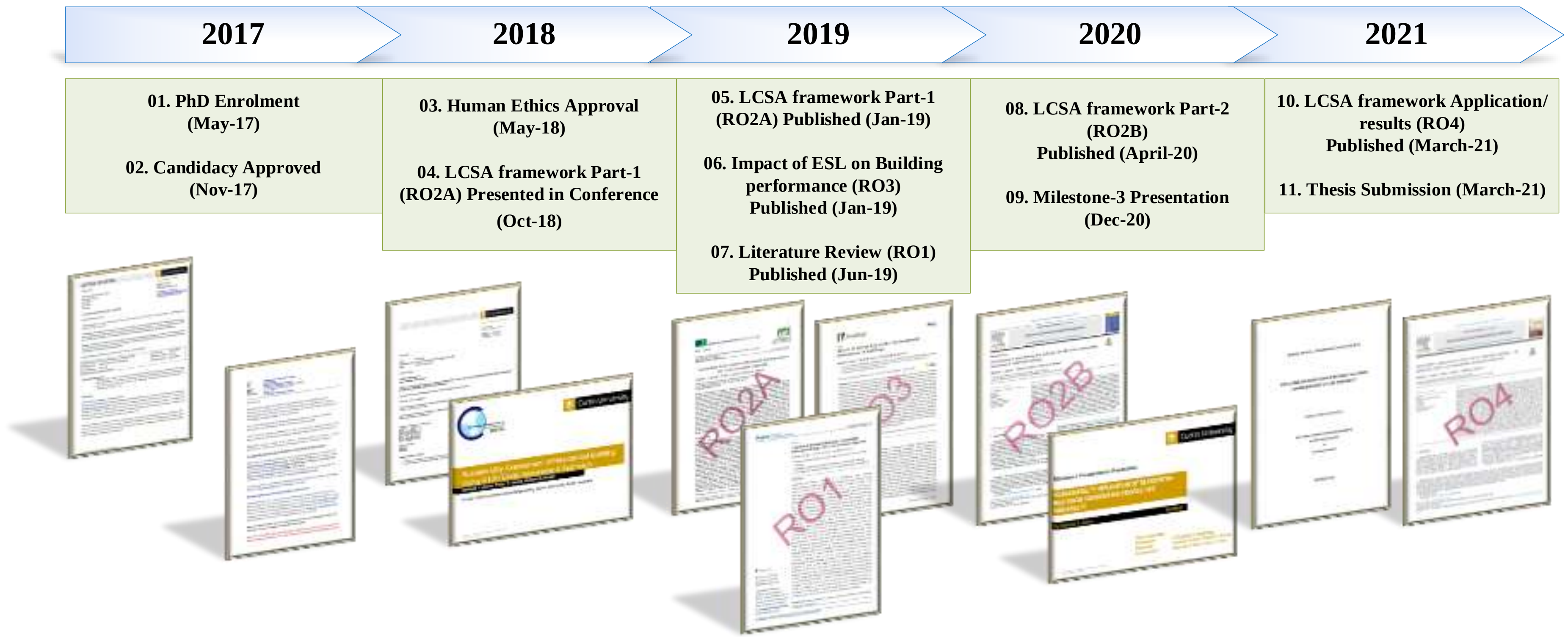


Figure 6-1: Timeline of PhD Research [RO – Research Objectives]

6.2.2 The development of a holistic life cycle sustainability assessment framework

The LCSA framework for residential buildings was developed in two phases [RO2A, RO2B; Figure 6-1]. Firstly, after a rigorous literature review, an LCSA framework based on strong sustainability concepts was developed following a bottom-up hierarchical approach. This approach consists of KPIs, impact categories, and sustainability objectives in a sequential manner to assess the sustainability performance of buildings. Mathematical equations were developed to integrate service life of residential buildings into the LCSA framework, to calculate the performance gaps, to identify hotspots, for further improvement and to obtain an overall sustainability score of the residential buildings.

In the second phase, the 22 KPIs for the LCSA framework were developed through a participatory approach by involving four categories of participants including Government and Engineers Australia, academia, industry practitioners, and structural engineers. The weight of each KPI was determined based on the level of importance provided by same participants. The threshold values for the KPIs were fixed by reviewing existing case studies and reports published by the Australian government and semi-government organizations. All these KPIs should have the same values as these threshold values to achieve the sustainability performance.

6.2.3 Impact of service life on environmental performance of buildings

This objective of the research was achieved by integrating the ESL of building and building components in this LCSA framework as a base parameter [RO3; Figure 6-1]. The implication of ESL of building and building components and major repairs were studied in terms of their impact on the environmental performance of the case study buildings. It was found that the service life of a building is dependent on the service life of building components. This research demonstrated that service life of building varied significantly with building components, construction materials, location, size, architectural designs, structural design, functional requirements, quality of workmanship, internal and external exposure conditions, and subsequent damage mechanisms, and quality of maintenance. There existed complex inter-relationship between service life and environmental performance of buildings. The pre-use stage environmental impacts reduced considerably for buildings with longer service life. Due to excessive replacement of non-structural components with lower durability, the environmental impacts of buildings increased with longer service life. The results concluded that the longer ESL of the buildings can only deliver environmentally sustainable output provided there are fewer replacements and a reduced level of wastage of useful materials and landfilling.

6.2.4 The application of LCSA framework

The LCSA framework has successfully been applied to assess the sustainability performance of the 14 case study buildings typical for Western Australia [RO4; Figure 6-1]. Building 11 (SF-DB-FAGC) performed the best among the case study buildings with a sustainability score of 3.128, due to having relatively lower coefficient of heat transmission (U-value of 1.58 W/m^2K) as compared to concrete block walls having lower thermal efficiency (U-value= 2.71 W/m^2K), use of less energy intensive materials (i.e. by-products), and ESL of building systems aligned with that of overall building. The operational energy and maintenance activities in the use stage were mainly found to affect the sustainability performance of residential buildings. Therefore, technology modification and product modification strategies were applied to reduce 34-39% of electricity consumption by incorporating solar photovoltaic system, and 37-42% of the energy consumption for heating and cooling by replacing single glazed windows with double glazed windows and gas water with solar water heater The follow-up LCSA after incorporating these energy conservation measures showed that the sustainability performance of the case study buildings can be improved by 30% to 49%.

This analysis demonstrates the flexibility of this LCSA framework as all indicators are interlinked and any change or improvement in one or some indicators affects others positively and negatively. The application of the LCSA framework in case study buildings concluded that the LCSA analysis could undergo a series of iterative processes by incorporating a range of suitable CPS or mitigation strategies until the sustainability performance of buildings is completely achieved (i.e., Sustainability score is 5).

6.3 Recommendation/ Future research

The study identified the following areas for future research:

- The framework has been used to assess the sustainability performance of the typical single-story case study buildings located in one climatic zone of Western Australia. The framework has enabled to incorporate the effects of climatic conditions on the overall sustainability performance of buildings. However this research did not consider the impact of climate change on the energy consumption during the use stage. The gradual increase in temperature during the building service life is likely to increase the cooling load, which can potentially be considered in the future research.

- The current study is limited to residential buildings only, however, the application of the framework can be extended to multi-storied buildings and also to the buildings in the commercial and industrial sectors.
- The estimation of service life could vary due to a number of factors including the extent of material deterioration due to exposure to specific environment, workmanship, and design and material quality. This research has used personal judgment based on available literature and manufacturers data sheets to estimate the service life of building components. The uncertainty of 20% in ESL of the overall building was found which could affect the sustainability performance to some extent. This uncertainty can be reduced if the materials service life is predicted using accelerated life testing method.
- This research used the AccuRate sustainability software to calculate the energy consumption in use stage. This software has material libraries for conventional materials used in building envelops only. This research highlighted that the thermal mass of both structural and non-structural components could affect the energy consumption during the use stage of the building. So there is an opportunity for upgrading the software by including more libraries for alternative building materials for structural and envelop components (e.g. roof frame, by-products and recycled materials).

REFERENCE

1. UNEP, *Towards zero-emission, efficient, and resilient buildings and construction sector*, in Global status report. 2018, Global Alliance for Buildings and Construction (GABC), United Nation Environment Programme, Paris, France. Available from: https://www.globalabc.org/uploads/media/default/0001/01/f64f6de67d55037cd9984cc29308f3609829797a.pdf Accessed: 30-06-2018.

2. UNEP, *Eco-Housing guidelines for Tropical regions*. 2006, Regional Resource Centre for Asia and the Pacific. United Nation Environment Programme, Bangkok, Thailand. Available from: www.rrcap.ait.ac.th. Accessed: 10-01-2019.

3. UNEP, *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication-A synthesis for Policy Makers*. St-Martin-Bellevue (France): United Nations Environment Programme; 2011. Available from: https://sustainabledevelopment.un.org/content/documents/126GER_synthesisen.pdf. Accessed: 25-12-2018.

4. Trimetric, GD-CN0004GO: Key Highlights from Global Construction Outlook 2021. 2018: London (UK): Construction Intelligence Centre, Timetric, London, UK.

5. Pickin, J., Randell, P., Trinh, J., Grant, B., *National Waste Report 2018*. 2018, Department of the Environment and Energy, Australia Victoria, Australia. Available from: http://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018 Accessed: 14-6-2019.

6. ABS, *Labour Force Region-SA4 Data*. 2018, Department of Jobs and Small Business-Australian Government, Australian Bureau of Statistics, Canberra Australia. Available from: http://lmip.gov.au/default.aspx?LMIP/Downloads/ABSLabourForceRegion Accessed: 10-06-2019.

7. ABS, *8731.0 - Building Approvals, Australia, Mar 2020*. 2020, Australian Bureau of Statistics Canberra Australia. Available from: https://www.abs.gov.au/ausstats/abs@.nsf/mf/8731.0 Accessed: 14-5-2020.

8. ABS, 3222.0 - *Population Projections, Australia, 2012 (Base) to 2101, Canberra*. 2013, Australian Bureau of Statistics Canberra Australia. Available from: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/3222.0main+features52012%20(base)%20to%202101 Accessed: 14-5-2020.

9. ABS, *8782.0.65.001 - Construction Activity: Chain Volume Measures, Australia, Mar 2019, Canberra.* 2019, Australian Bureau of Statistics, Canberra, Australia. Available from: https://www.abs.gov.au/ausstats/abs@.nsf/0/EDD60A6A5408DD1BCA2576B00014308C?Opendocument Accessed: 10-3-2020.
10. CCC, Fourth carbon budget review – part 2 the cost-effective path to the 2050 target, in UK: Committee on Climate Change. 2013, Available from: https://www.theccc.org.uk/publication/fourth-carbon-budget-review/. Accessed: 16-06-2019.
11. UNEP, *Transforming our World: The 2030 Agenda for Sustainable Development*, Paris agreement. United nations framework convention on climate change (UNFCCC), United nations. Le Bourget, Paris, France. https://unfccc.int 2015, Available from: https://unfccc.int › sites › default › files › english_paris_agreement. Accessed: 10-01-2019.
12. Brundtland GH. *Our Common Future: Report of the World Commission on Environment and Development*. 1987, World Commission on Environment and Development: New York, NY, USA. Available from: http://www.un-documents.net/wced-ocf.htm Accessed: 10-01-2019.
13. Akadiri PO. *Understanding barriers affecting the selection of sustainable materials in building projects*. Journal of Building Engineering, 2015. 4: p. 86-93. https://doi.org/10.1016/j.jobe.2015.08.006
14. Tayyab A, Thaheem MJ. *Developing a residential building-related social sustainability assessment framework and its implications for BIM*. Sustainable Cities and Society, 2017. 28: p. 1-15. https://doi.org/10.1016/j.scs.2016.08.002
15. Jeurissen R, Elkington J. Cannibals With Forks: The Triple Bottom Line of 21st Century Business. *Journal of Business Ethics* 23**,** 229–231 (2000). https://doi.org/10.1023/A:1006129603978
16. Onat NC, Kucukvar M, Tatari O. Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings. Int J Life Cycle Assess, 2014. 19: p. 1488-1505. https://doi.org/10.1007/s11367-014-0753-y
17. Hossaini N, Reza B, Akhtar S, Sadiq R, Hewage K. AHP based life cycle sustainability assessment (LCSA) framework: a case study of six story wood frame and concrete frame

buildings in Vancouver. Journal of Environmental planning and Management, 2015. 58(7): p. 1217-1241. https://doi.org/10.1080/09640568.2014.920704

18. Dong YH, Ng T. *A modeling framework to evaluate sustainability of building construction based on LCSA.* Int J Life Cycle Assess, 2016. 21: p. 555-568. https://doi.org/10.1007/s11367-016-1044-6

19. Balasbaneh A, Marsono AK, Khaleghi SJ. Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment. Journal of Building Engineering, 2018. 20: p. 235-247. https://doi.org/10.1016/j.jobe.2018.07.006

20. ISO 15686-1, Buildings and constructed assets - Service life planning, in Part-1: General principles and framework. 2011, International standards organization, Geneva, Switzerland.

21. Grant A, Ries R, Kibert C. *Life cycle assessment and service life prediction: A case study of building envelope materials.* Journal of Industrial Ecology, 2014. 18(2): p. 187-200. https://doi.org/10.1111/jiec.12089

22. Janjua SY, Sarker PK, Biswas WK. *Impact of Service Life on the Environmental Performance of Buildings.* Buildings, 2019. 9. https://doi.org/10.3390/buildings9010009

23. Rauf A, Crawford RH. *Building service life and its effect on the life cycle embodied energy of buildings.* Energy, 2015. 79: p. 140-148. https://doi.org/10.1016/j.energy.2014.10.093

24. Janjua SY, Sarker PK, Biswas WK. *A review of residential buildings' sustainability performance using a life cycle assessment approach.* J Sustainability Res, 2019. 1: p. e190006. https://doi.org/10.20900/jsr20190006

25. Janjua SY, Sarker PK, Biswas WK. *Sustainability Implication of a residential building using a lifecycle assessment approach.* Chemical Engineering Transactions, 2019. 72: p. 19-24. https://doi.org/10.3303/CET1972004.

26. Janjua SY, Sarker PK, Biswas WK. *Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings.* Journal of Environmental Management, 2020. 264:110476. https://doi.org/10.1016/j.jenvman.2020.110476

27. Janjua SY, Sarker PK, Biswas WK. Sustainability Implications of the service life of residential buildings – An application of Life Cycle Sustainability Assessment framework.

Environmental and sustainability indicators. 2021. 10, 100109, http://doi.org/10.1016/j.indic.2021.100109

28. Guinée, J. Chapter 3: Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges?, in Taking Stock of Industrial Ecology, Clift R, Druckman A (Ed). 2015, Springer Cham: Heidelberg New York, Dordrecht, London.

29. ISO, ISO 15686-2: Buildings and constructed assets - Service life Planning, in Part-2: Service life prediction procedures. 2012, International standards organization, Geneva, Switzerland.

30. ISO, ISO-14040: Environmental management - Life cycle assessment - Principles and framework. 2006, International standards organization, Geneva, Switzerland.

31. Chastas P, Theodosiou T, Kontoleon K J and Bikas D 2018 Normalising and assessing carbon emissions in the building sector: A review on the embodied CO2 emissions of residential buildings. Build Environ. 130 212–26. https://link.springer.com/article/10.1007/s11367-012-0509-5

32. Blengini GA, Di CT. *The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings.* Energy and Buildings, 2009. 42: p. 869-80. https://doi.org/10.1016/j.enbuild.2009.12.009

33. Christen, M., J. Schroeder, and H. Wallbaum. 2014. "Evaluation of Strategic Building Maintenance and Refurbishment Budgeting Method Schroeder." International Journal of Strategic Property Management, 18 (4). https://doi.org/10.3846/1648715X.2014.971917

34. Kreiner, H., A. Passer, and H. Wallbaum. 2015. "A New Systemic Approach to Improve the Sustainability Performance of Office Buildings in the Early Design Stage." Energy and Buildings 109. https://doi.org/10.1016/j.enbuild.2015.09.040

35. Klöppfer W, *Life Cycle Sustainability assessment of products.* Int J Life Cycle Assess, 2008. 13: p. 89-95.

36. Azeem S, Naeem MA, Waheed A, Thaheem MJ. *Examining barriers and measures to promote the adoption of green building practices in Pakistan.* Smart and Sustainable Built Environment, 2017. 6(3): p. 86-100. https://doi.org/10.1108/SASBE-06-2017-0023

37. Kamali M, Hewage K, Milani AS. Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices. Building and Environment, 2018. 138: p. 21-41. https://doi.org/10.1016/j.buildenv.2018.04.019

38. Berkel RV. *Cleaner production and eco-efficiency initiatives in Western Australia 1996-2004.* Journal of Cleaner Production, 2006. 15: p. 741-55. https://doi.org/10.1016/j.jclepro.2006.06.012

39. Biswas WK, Cooling D. *Sustainability Assessment of Red Sand as a Substitute for Virgin Sand and Crushed Limestone.* Journal of Industrial Ecology, 2013. 17(5): p. 756-762. https://doi.org/10.1111/jiec.12030

40. Lim CI, Biswas WK. *Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry.* Clean Technologies and Environmental Policy, 2018. 20: p. 539-560. https://doi.org/10.1007/s10098-017-1453-7

41. Kucukvar M, Tatari O. *Towards a triple bottom-line sustainability assessment of the U.S. construction industry.* The international journal of life cycle assessment, 2013. 18: p. 958-72. https://doi.org/10.1007/s11367-013-0545-9

42. Pope J, Annandale D, Morrison-Saunders A. *Conceptualising sustainability assessment.* Environmental Impact Assessment Review, 2004. 24(6): p. 595-616. https://doi.org/10.1016/j.eiar.2004.03.001

43. Eggenberger M, Partidário MR. *Development of a framework to assist the integration of environmental, social and economic issues in spatial planning.* Impact Assessment and Project Appraisal, 2000. 18(3): p. 201-207. https://doi.org/10.3152/147154600781767448

44. IISD, Seven questions to sustainability: how to assess the contribution of mining and minerals activities. 2002: Winnipeg.

45. ISO, ISO 15685-8: Buildings and constructed assets - Service-life planning, in Part 8: Reference service life and service-life estimation. 2008, International Standards Organisation, Geneva, Switzerland.

46. Buyle M, Braet J, Audenaert A. *Life cycle assessment in the construction sector: A review.* Renewable and Sustainable Energy review, 2013. 26: p. 379-388. https://doi.org/10.1016/j.rser.2013.05.001

47. Vieira, M. *Hotspot analysis in the PEF approach*. Quantifying sustainability 2016; Available from: https://www.pre-sustainability.com/news/pef-series-hotspot-analysis-in-the-pef-approach.Accessed: 10-05-2020.

48. Chen Z. *Accurate Sustainability Tool Version 2.3.3.13 SP4*. 2018, CSIRO Land & Water Flagship and distributed by Energy Inspection Pty Ltd. Australia.

49. Lawania KK. Improving the Sustainability Performance of Western Australian House Construction: A Life Cycle Management Approach, in School of Civil and Mechanical Engineering. 2016, PhD Thesis, Curtin University, Perth, Australia.

50. PRe'-Consultants, *SimaPro 8.4 LCA software*. 2016, Pre' Consultants, The Netherlands.

51. Pelzeter A. *Building Optimization with Life Cycle Costs- the influence of calculation methods*. Journal of Facilities Management, 2007. 5(2): p. 115-128. https://doi.org/10.1108/14725960710751861

52. UNEP, *Introduction to Cleaner Production Concepts and Practices*. 2015, Division of Technology, Industry and Economic: Institute of Environmental Engineering (APINI) Kaunas University of Technology, Lithuanis. Available from: http://www.un.org/esa/sustdev/sdissues/technology/cleanerproduction.pdf Accessed: 05-01-2020.

APPENDICES

APPENDIX-1: PAPER-1

Janjua SY, Sarker PK, Biswas WK, A review of residential buildings' sustainability performance using a life cycle assessment approach. J Sustainability Res. 2019, 1:e190006 https://doi.org/10.20900/jsr20190006

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STATEMENT OF CONTRIBUTION

To Whom It May Concern,

I, Janjua SY, contributed to literature review, method formulation, result discussions, analysis and writing (80%) of the paper/publication entitled:

Janjua SY, Sarker PK, Biswas WK. A review of residential buildings' sustainability performance using a life cycle assessment approach. J Sustainability Res, 2019, 1:e190006 https://doi.org/10.20900/jsr20190006

The remaining 20% of this paper/ publication was contributed by A/Prof. Wahidul K. Biswas (10%) and A/Prof. Prabir K. Sarker (10%).

Signature: Date: 01 March 2021

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 01 March 2021

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Review

A Review of Residential Buildings' Sustainability Performance Using a Life Cycle Assessment Approach

Shahana Y. Janjua [1,*], Prabir K. Sarker [1], Wahidul K. Biswas [2]

[1] School of Civil and Mechanical Engineering, Curtin University, Perth, 6102, Australia

[2] Sustainable Engineering Group, Curtin University, Perth, 6102, Australia

* Correspondence: Shahana Y. Janjua, Email: s.janjua@postgrad.curtin.edu.au.

ABSTRACT

Achieving sustainable buildings is a challenging task. Building sustainability involves "green building" design and construction, taking account of both environmental elements and economic benefits, along with social obligations to the society we live in. This article aims to critically review and analyse studies of the building and construction industry that deal with aspects of sustainability, including environmental life cycle assessment, life cycle costing, social life cycle assessment and cleaner production strategies, and to examine the research gaps in order to generate recommendations for further research. About 807 refereed research articles on residential buildings published over the last 10 years (2009–2019), were downloaded, having been searched from online databases (including Scopus, Web of Science, ScienceDirect and Compendex) using keywords. Building materials, embodied energy and operating energy were found to contribute chiefly to the environmental and socio-economic objectives of the construction industry. Many studies covered only the life cycle tools (such as environmental life cycle assessment, life cycle costing, and social lifecycle assessment) used in the sustainability assessment process. The "carbon footprint" concept is the most commonly used indicator in building sustainability assessments, underlining the urgent need to deploy more diverse environmental impact categories in order to avoid trade-offs among environmental, social and economic objectives. The social life cycle assessment tool needs a methodological breakthrough to improve its application in the building industry. In most of the studies, only an approximate evaluation of buildings' service life is the main consideration in life cycle assessments, while the important factor of the quality of the materials used in buildings is often neglected. However, a methodological approach to estimate the service life of structures that considers the durability of different building components would provide a more realistic life cycle assessment. Hence it would be judicious to address the thematic and methodological gaps identified in this paper, thereby optimising the understanding and communication of life cycle outcomes in building sustainability.

KEYWORDS: sustainability; life cycle assessment; building; sustainability indicators; service life

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ABBREVIATIONS

AHP, analytical hierarchy process; BIM, building information modelling; C & D waste, construction and demolition waste; CLT, cross-laminated timber; CMoC, cost model of construction; ELCA, environmental life cycle assessment; EMoC, environmental model of construction; EPD, environmental product declaration; GHG, greenhouse gas; GWP, global warming potential; HVAC, heat, ventilation and air-conditioning; LC3, limestone calcined clay cement; LCA, life cycle assessment; LCC, life cycle cost; LCI, life cycle inventory; LCSA, life cycle sustainability assessment; PET, Polyethylene terephthalate; PFA, pulverised fuel ash or fly ash; SL, service life; SLCA, social life cycle assessment; SMoC, social impact model of construction. TBL, triple bottom line

INTRODUCTION

Sustainability has for some time been a field of interest to researchers, one which is predominantly driven by environmental deterioration, social advancement and community engagement. Sustainability has thus become a key topic among scholars, regulators, and businesses. Systematic studies of sustainability have helped enterprises to adopt strategies to meet the expectations of stakeholders, as well insure, sustain and embellish social assets and natural resources for future generations [1]. Sustainability is an ecologically focused development that enhances our capacity to conserve resources for future generations. Current economic and human activities are unsustainable as their economic benefits are not aligned with social and environmental benefits. The complex and interlinked structure of sustainability entails wise natural resource utilisation, social sensitivity and economic realism as we try to turn this crisis into a positive challenge for the future.

The construction sector, which promotes economic growth and enhances society's wellbeing by providing shelter and employment, also contributes significantly to resource depletion, and to associated greenhouse gas (GHG) emissions [2–4]. World-wide, the annual energy consumption and GHG emissions of buildings and the building construction sector are 30% and 25% respectively [5]. The construction sector alone contributes significantly to global and local economic growth, to the tune of more than $8.8 trillion per year [6]. The sector uses about one third of global resources and generates approximately 40% of all solid wastes [7]. Building construction consumes 25% of wood, 16% of water and 40% of aggregate per year, according to some reports [8]. Some of the most commonly used construction materials, like aluminium, steel, glass, plastic, and cement, are energy-intensive materials [8]. The building industry is Australia's fastest growing industry, consuming about 21% of energy and generating 20 million tonnes of construction and demolition (C&D) waste per year—*i.e.*, 30% of the nation's annual waste generation [9]. On the other hand, the construction industry creates more than one million job opportunities annually and contributes 8% of Australia's GDP [10].

It is estimated that the construction industry will consume 21% of global energy and 32% of operational energy for buildings by 2040, due to urbanisation in non-OECD countries. About 60% of the total planned infrastructure needs to be built by 2050, which will deplete earth's resources exponentially [11]. Yet the building sector has great potential to reduce GHG emissions in a short period [12]. Green building, sustainable building, and smart building concepts are emerging globally, designed to ensure buildings' sustainability performance. Life cycle assessment (LCA) has been widely used across the globe to assess the economic and environmental impacts of the building sector. Life cycle sustainability assessment (LCSA) is a comprehensive LCA tool used to assess the overall sustainability performance of buildings by integrating environmental, economic and social measures [11]. Sustainability indicators facilitate the measurement of buildings' sustainability performance and set criteria for that performance. All these assessments have been based on the average service life of the buildings concerned [13,14]; hence this additional review has now been carried out to determine whether this consideration of average service life may affect the sustainability assessment process.

Although buildings are one of humankind's basic needs, they are also responsible for environmental degradation, including air, water and land pollution, localised health issues and resource depletion. The objective of the sustainable development of buildings is to comply with environmental, social and economic standards. A sustainable building expresses a design philosophy that strives to enhance effective resource efficiency, and reduce negative impacts on human wellbeing and dignity, in a cost-effective manner. A comprehensive framework is required to assess the triple bottom line (TBL) objectives of sustainability over the entire life span of buildings. In this paper, the current state of sustainability assessment tools for assessing residential buildings over their entire life has been reviewed from both the environmental and socio-economic perspectives. Additionally, this paper discusses sustainability indicators for the three main objectives of sustainability assessment, and aims to identify research gaps, formulate research questions, and develop an improved sustainability framework for the building industry.

METHOD OF REVIEW

A meticulous literature review was conducted on the topics of the sustainability assessment of residential buildings, construction materials, and assessment tools such as environmental life cycle assessment (ELCA), life cycle costing (LCC), social life cycle assessment (SLCA), indicator-based performance of buildings, and cleaner production strategies. Secondly, a review of the service life of buildings was conducted, as this parameter has a significant bearing on the conservation of natural resources. Thirdly, buildings made of both conventional (brick, timber, steel, concrete blocks) and by-product based materials (green concretes with partial replacement by 30% fly ash and 30% ground granulated blast slag) were investigated to determine how the choice of materials affects buildings' service life and their sustainability performance [15]. The literature review consisted of four steps:

1. Keywords and the criteria for searching available databases were determined.
2. The collected papers were then listed using excel sheets, and duplicates were removed from the list.
3. The abstracts of the articles that were found through search engines were thoroughly reviewed to conduct an initial screening process.
4. The final list of articles related to residential buildings at all stages of life cycle assessment was then categorised into two sections: building materials and service life, and sustainability of residential buildings from the TBL perspective.

The literature review was based on the latest research findings published during 2009–2019, with the aim of identifying the gaps in the existing research on the sustainability assessment of residential buildings. The review was conducted using four research databases: Scopus, Web of Science, ScienceDirect and Compendex. The keywords used when operating the search engines were: *sustainability*; *residential buildings*; *life cycle assessment*; *life cycle sustainability assessment*; *social life cycle assessment*; *sustainability assessment*; *sustainability indicators*; *triple bottom line*; *sustainability performance*; *environmental certification*; *service life*; *life-span* and *re-use in construction*. The scope was then narrowed down by using the following criteria to include publications in the survey:

- Scientific research publications and documents published by recognised bodies (e.g., government departments, United Nations Environment Programme (UNEP), over the past 10 years (2009–2019));
- Peer reviewed articles (refereed journals, and conference proceedings, and guidelines published by recognised bodies (e.g., ISO));
- Published in English.

A total of 807 publications were found to address sustainability aspects of residential buildings during the past decade, at different levels. Of these publications, only three were on SLCA and only five on LCSA as applied to residential buildings, while 80.4% of the publications discussed ELCA and 18.6% addressed both the environmental and economic aspects of sustainability using ELCA and LCC respectively.

BUILDING MATERIALS AND SERVICE LIFE

Building Materials

Building sustainability is difficult to quantify and define when reviewing a wide variety of construction methods, installation techniques, raw materials and manufacturing systems. Naturally, building materials are the main element in life cycle assessments, right from their initial extraction in raw-produce form to their final disposal to landfill or recycling after a building's life has ended. The assessment process takes into account every input or output involved in materials production, consumption and disposal, from energy, people and money, to environmental impacts. Almost all building materials come from nature, whether directly (natural materials) or indirectly (synthetic materials). A material closer to nature is more sustainable, because it involves less processing, less transportation, less energy consumption and fewer harmful chemicals [16]. Besides considerations of environmental impacts, building material sustainability also depends on factors like renewability, price, life span, resource availability, local availability, non-toxicity, thermal resistance and recycling potential. At the early design stage, the designer should be aware of the traditional perceptions of the characteristics of materials—such as tactile, thermal, acoustic, visual and olfactory *etc.* [17]. Technically, there are other factors to be considered in building design, such as cost, durability, market trends, availability, reliability, stakeholders, aesthetics, indoor quality and comfort, cultural aspects, social concerns, and end-user emotions [17–21]. Materials selection means weighing up social, economic and environmental factors alongside technical aspects of construction [22]. Materials manufacturers are now investing in sustainable products with minimal environmental impact, yet also capable of enabling advanced technology [23].

The growth of the construction and building industries as urban development proceeds has led to increased demand for materials, resulting in natural resource exploitation [24]. In addition to low carbon materials, researchers are also focused on renewable materials, including bamboo, stone, wool, and straw bale [25–27]. Ajayi *et al.* [28] suggested that sustainable materials could reduce the impact of operational energy due to their energy conserving nature. De Luca *et al.* [29] supported the importance of the innovative use of materials like cement, wood, glass and ceramics in reducing the environmental impact of the building industry. A study by Harish and Kumar [30] estimated that 20%–50% of the usual energy expenditure can be saved by proper materials selection for a building envelope. Lawania and Biswas [31] studied 60 building envelope options for a typical West Australian house and showed that a building envelope with cast-in-situ sandwich walls containing Polyethylene terephthalate (PET) foam core, concrete tile roof cladding and double-glazed windows, offers the lowest embodied energy consumption and GHG emissions. A study of reinforced concrete buildings with limestone calcined clay cement (LC3) and pulverised fuel ash or fly ash (PFA) showed that LC3 and PFA have a significantly lower carbon footprint than conventional concrete systems [32]. A case study for four Brazilian residential buildings showed that steel, concrete and ceramic tiles have the highest environmental impacts [13]. Huang *et al.* [33] and

Glover *et al.* [34] also concluded that concrete and steel have the highest embodied energy among wood, steel and concrete. Petrovic *et al.* [35], studied a single-family house in Sweden, over a 100-year period, and concluded that concrete slab has the highest carbon footprint, while wood and cellulose have the lowest environmental impact. A study of multi-storey residential buildings with structural material options of cross-laminated timber (CLT), prefabricated timber modules (modular) and precast concrete demonstrated that CLT and modular buildings offer 37% and 17% lower life-cycle primary energy consumption respectively compared to precast concrete [36].

Increased construction activity is exacerbating raw materials scarcity and emissions associated with the transportation and manufacturing of building materials [37]. Industrial by-products and waste materials like waste foundry sand [38,39], ground granulated blast furnace slag [40,41], steel slag [42,43], imperial smelting furnace slag [44], copper slag [45,46], bottom ash [47,48], class F type fly ash [48,49], silica fumes [50], palm oil clinker [51], rice husk ash [52,53], bagasse [54,55] and composites [56] have been found to improve buildings' structural and environmental performance when used instead of fine aggregates. Apart from generating industrial by-products, the recycling of C&D waste can also help reduce environmental impact and costs attributable to building materials [57]: recycled materials like ceramic and PET reduce the porosity of mortar, for example [58,59]. Research has shown that the addition of both industrial by-products and recycled aggregates can reduce a building's carbon footprint [37,49,60]. However, the transportation of these materials sometimes increases the carbon footprint [61–64]. This is why such materials need to be sourced locally, a critical factor for materials sustainability.

Materials selection should be based on TBL (economic, social and environmental aspects of impact) implications as well as structural stability. Industrial by-products and recycled construction materials provide a way to reduce the pressure on the natural resource extraction currently necessary to meet the increasing demand of the construction sector, yet the local sourcing of these materials is important to reduce the indirect TBL impacts on the building project.

Building Service Life

The service life (SL) of buildings plays a significant role in their LCSA. The building and building components deteriorate naturally with age. Knowledge of deterioration mechanisms and degradation agents helps to predict the service life of a building and its components. LCAs are carried out based on the life span of buildings. However, most LCA studies have considered a life span to be between 30 and 70 years, with the most common assumption being 50 years [15,65,66]. Out of 807 articles reviewed, only two [15,65] have used the estimated SL of buildings in order to assess the environmental impacts of residential buildings. This discrepancy in defining life span, due to assumptions about a building's end of life and incorrectly recorded intervals of repair and maintenance, has created uncertainty in LCA results.

The SL of a building can be estimated by theoretical or empirical methods [67]. Empirical methods deploy simple and robust tools, using the deterioration and degradation of materials to predict a building's SL. Different SL assessment approaches have been used for building materials and components. Grant *et al.* [65] advocated the empirical method as the most accurate. The "factor method" is a deterministic method devised to estimate the SL of buildings. It uses seven factors to estimate the SL of the building and building components under particular conditions, considering climatic conditions and the building's location [68]. Various studies have used SL prediction methods to estimate the SL of building materials. Madrigal *et al.* [69] used a factor method to estimate the SL of building envelopes. Emidio *et al.* [70] analysed 269 stone claddings in Portugal using the factor method and concluded that SL varies according to user demands, building use and funds availability for repair work. Souza *et al.* [71] applied the factor method to estimate the SL of ceramic tiling in Brazil, using both deterministic and probabilistic approaches. The study found that depending on the data quality, and the materials' exposure to the environment, both (deterministic and probabilistic) approaches produce consistent results. Pillai *et al.* [32] used accelerated tests to determine the SL of LC3 and compared the annual carbon footprint of conventional concrete with LC3 concrete. The LC3 concrete's annual footprint was found to be much lower than that of conventional concrete, owing to lower clinker quantity and a significantly high SL.

Nath *et al.* [49], used a deterministic method to predict the SL of conventional concrete and concretes containing 30% and 40% cement replacement by a Class F fly ash, and concluded that the fly ash increases the SL, and reduces both the carbon footprint and the embodied energy of the concrete. Another study proposed an SL prediction model using an accelerated test to study the effects of the intensity and wavelength of light on photovoltaic laminate material [72]. Ligotski *et al.* [73] investigated the SL of adsorptive heat, ventilation and air-conditioning (HVAC) filters used to improve indoor air quality, using a probabilistic method. Three activated carbon-based filter media were studied, and good agreement was found between the prediction data and the relevant S-curve. The SL of 100 churches was studied by Prieto *et al.* [74], using multiple linear regression and fuzzy logic models to determine a maintenance and preventive conservation action plan for cultural heritage buildings. Rauf and Crawford [75–77] studied the impact of SL variation on the environmental assessment of buildings. This study found that the embodied energy of a building may increase by one third due to maintenance and replacement activities, if the building's SL is not considered at the early design stage of a project. Grant *et al.* [65] studied the SL of building envelopes to make annual comparisons of the environmental impacts and concluded that environmental impacts are primarily dependent on the intensity and frequency of maintenance, and on the indicators used. Janjua *et al.* [15], used the factor method to determine the SL of buildings and building components and conducted an ELCA study of 12 buildings made of different building materials, to investigate the relationship between SL and the environmental impacts of buildings. This study concluded that the longevity of a building's SL can produce sustainable results if all the building components have a comparatively similar SL, thanks to a lower level of building component replacements.

The SL of a building plays an important role in the assessment of TBL sustainability impacts after the building actually comes into use, as buildings made of different materials behave differently in terms of durability and are capable of reducing or enhancing the TBL impacts. The SL prediction tool has been widely applied to building materials and building components, but there is still a gap in the literature when it comes to the application of SL prediction to life cycle assessments.

SUSTAINABILITY IN RESIDENTIAL BUILDINGS

Sustainability is the ultimate objective of all product development. According to the Klöppfer [78], sustainability has three main aspects: economic, social and environmental, known as the TBL objectives. An LCSA is a comprehensive assessment of these three crucial impacts attributable to a product [78].

Environmental Life Cycle Assessment

"Life cycle assessment (LCA) is a tool to assess the environmental objectives and potential impacts associated with the prediction and use of a product/system, by developing an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases" [79]. With the development of tools like SLCA and LCSA, environmental life cycle assessment is now known as ELCA. Based on the ISO guidelines series 14040-44 [79], the ELCA process scrutinises the environmental inputs/outputs of products at all life cycle stages, including: (1) the pre-use stage (extraction of raw materials for materials manufacturing, transportation to construction sites, construction), (2) the use stage, and (3) the demolition and disposal stage. The process also requires four prescribed steps: defining goals and scope; creating a life cycle inventory; assessing the environmental impacts, and interpreting the results [14,80].

The idea of sustainability assessment started in 1960, when there was already research on LCA, then mainly used to compare products at the manufacturing stage. In 1969, the first LCA study (unpublished) was conducted by Midwest Research Institute for the Coca Cola Company, examining emissions, resources, and waste generation for different beverage containers [81]. In the construction sector, LCA was first introduced by Bekker, identifying the need for renewable energy [82]. The environmental implications of building materials were first assessed using an LCA tool [83]. UNEP and the Society of Environmental Toxicology and Chemistry (SETAC) introduced the life cycle concept to expedite the use of LCA. An Environmental Product Declaration (EPD), is one of the life cycle concept applications based on LCA. EPDs are statements of quantified, verified and registered environmental data about a product, intended to provide transparent and reliable information on a product's environmental impact throughout its life. EPDs are helpful in the selection of eco-friendly materials for sustainable building design [84]. Environmental certifications are another application of the life cycle concept in the building sector, created to measure, quantify and assess the sustainability performance of buildings. CASBEE (Japan); Green Star (Oceania); HK-Beam (Hong Kong); Passivhaus (Sweden); LEED (America); BREEAM (Europe), and DGNB (Germany) are just a few examples of certification systems using ELCA [85–88].

ELCA has been used to assess and improve buildings' performance through the pre-use, use and post-use stages of its life. The pre-use stage includes the extraction, manufacturing and transportation to site of materials. The use stage is the occupancy phase, while post-use involves demolition, and recycling of materials. ELCA studies mostly focus on the various life cycle stages independently, instead of holistically considering all stages together. Only one third of the reviewed studies on ELCA covered all stages of the LCA, with the remaining two thirds focused exclusively on only one stage: 25% on the pre-use stage; 29% on the use stage, and 13% on the post-use stage. For a long time, LCA studies of buildings have focused primarily on energy efficiency and emissions associated with the use stage [89], leading to extensive research into the energy-efficient operation of buildings. Owing to a recent research focus on buildings' operational stage, attention has shifted to the extraction and manufacturing of construction materials, and the construction stage [90]. Building materials, embodied energy, operating energy and C&D waste are the common sustainability indicators used in sustainability assessments of the construction industry, with the carbon footprint measure found in 97.6% of articles on ELCA.

Most of the studies of buildings over the past decade have assumed an SL of 50 years for the building and building components, regardless of the materials actually used [91]. Due to this assumption on SL data, few studies have addressed the energy consumption and subsequent GHG emissions resulting from maintenance or refurbishment activity at the buildings. The energy consumed during repair, refurbishment or maintenance activities can substantially exceed initial embodied energy, if an assessment of the durability of the building materials used is neglected at the design stage [75]. Rauf and Crawford [77] have shown that the energy calculations may vary by 30% if there is no consideration of estimated SL.

Building material properties play an important role in the sustainable design of buildings [92]. ELCA helps to determine the cumulative effects of building materials on building performance. A thorough LCA study comparing recycled and ordinary concrete of the same strength has showed that recycled concrete is only slightly better in terms of carbon emissions. The ELCA tool helps to determine the differing energy and environmental performance of buildings using different building materials, whether consisting of virgin materials and/or by-product sources [93]. Gámez-García *et al.* [94] assessed 20 types of the external wall system that is conventional at the pre-use stage for residential buildings in Spain and concluded that the physical specifications of components, along with the materials selection process, contribute decisively to a building's environmental optimisation. The thermal performance of buildings has been assessed based on the building materials used, by Maalouf [95], Lawania [14], and Intini [96]. These studies examined polystyrene fibre products made from PET bottle flakes, unanimously showing that waste-product materials such as PET can reduce environmental impact across the life cycle of a product, and minimise the damage created by the system under study. An ELCA study of the structural systems of residential buildings in Sweden concluded that pre-engineered buildings have less energy impact in the pre-use and use stages, compared with the impact of conventional concrete systems; the study also found that a combination of sustainable structural materials and an efficient energy supply system results in the best building design [36]. Schmidt and Crawford [97] proposed an integrated framework for life cycle costs and GHG emissions in their study of different glazing options for a typical Australian detached house. The framework demonstrated the prevalent trade-off between cost and environmental impact in design decisions. Vivian Tam *et al.* conducted a review of LCA software designed for environmental assessments. GaBi and SimaPro were found to be the most widely used software programs, along with green energy rating tools. None of these software programs had yet been found capable of revealing the errors in environmental impact assessments [98]. The selection of material databases to use in LCA is vital to the assessment of environmental impacts, in order to reduce the uncertainties in findings that may result from a project's location and the database source. GaBi Database and Ecoinvent are two European databases that stand out for their broad range of materials data, usability, and integrity [99]. Ecoinvent has been found to be the most suitable database for construction projects, for all categories of construction materials [100,101]. GaBi Database is a cradle-to-gate database and includes all categories of construction materials, with regular annual updates [102].

The demolition and disposal of buildings increase the environmental burden due to C&D waste. However, recycling and re-use can help recover the embodied energy by 32%–42% [76,103,104]. A study of LCA for the end-of life stage of residential buildings showed that with steel recycling alone, it is possible to reduce the global warming impact by 89% and the minerals extraction impact by 73% [105]. Ghose *et al.* [106], found that the re-use of building materials in New Zealand could reduce environmental impact by 15%–25% as compared to using recycled materials (5%).

Although ELCA can determine impact in different environmental impact categories, life cycle energy consumption and carbon footprint are the most commonly assessed environmental impacts for the building sector [107,108]. Most of the studies use an assumed SL to assess the whole life cycle impacts of buildings (boundary conditions were defined by the particular objectives of each study). Finally, the ELCA tool was found useful to identify improvement strategies that can reduce environmental impacts. This form of LCA can also be used to discern the economic and social implications of environmental options, for overall sustainability assessment.

Life Cycle Costing

Life cycle costing (LCC) is a salient indicator for measuring the economic performance of a project. Klöppfer [78] described LCC as "a logical counterpart of LCA for the economic assessment". The LCC tool was developed before LCA [109], hence its relationship with LCA is quite recent. LCC was used in the 1960s for cost analysis during the proposal phase of a project to safeguard investment. However, right from the beginning of the 21st century, the LCC has become as crucial as ELCA to a structure's sustainability. LCC is useful to determine the relative cost-effectiveness/cost-competitiveness of various environmentally-friendly options [110]. LCC can be conducted using the same system boundaries as ELCA [111]. Due to its lack of computational structure, the use of LCC for sustainability assessment is quite often criticised [112]. LCC is challenging because many stakeholders are involved in any product life cycle; hence it is difficult to differentiate between physical and financial costs, resulting in double counting among TBL dimensions. In the building industry, LCC deals with embryonic capital, settlement, operational and disposal costs, and uses the same material and energy inventories as for ELCA. A number of research studies have developed models and frameworks to assess the economic performance of the built environment including examinations of transportation projects [113], residential buildings [114], and industrial buildings [111,115]. The concept of "green buildings" is constrained by the high costs entailed in attaining environmental and social sustainability [116,117]. The LCC process provides an important checklist for assessing the economic sustainability of a building project [118]. Ahmad and Thaheem [119] proposed an economic sustainability framework for residential buildings that considered LCC to be a "traditional indicator", while they characterised affordability, adaptability and manageability factors as "non-traditional indicators". Their framework was tested on three residential buildings and used the building information modelling

(BIM) tool to assess the cost perceptions underpinning the project as part of the process toward ensuring eco-friendly buildings. Babaizadeh *et al.* [120], used LCC along with LCA to assess the sustainability performance of exterior window shades/shutters in different climatic zones of the USA, concluding that timber shades were an eco-efficient option with reduced cost and lower environmental impact. Allacker *et al.* [121] concluded after studying the LCC of 16 low-energy residential buildings in Belgium that external environmental costs contribute only 5%–10% of such buildings' LCC; they found that this refutes the view that making a 'green choice' may render housing unaffordable. A study in Hong Kong considered LCC in its quest to find a sustainable maintenance option for building repairs and the retrofitting of residential buildings, identifying materials with a low carbon footprint and employing local labour resources [122]. Mahmoud Dawood [123] proposed a framework integrating genetic algorithms and BIM to discover the building components with the least LCC at the building design stage. Another study used LCC to determine the feasibility of using water conservation components in mass housing projects, and concluded that the feasibility of green construction depends on the incentives and policies of the relevant government and varies according to geographic location and climatic zone [124]. Tam *et al.* [125] used LCC analysis to study green building materials, conducting a detailed analysis of different timber types used in residential building construction in the Australian context. This study presents a methodology for finding the best materials for green buildings that also entail minimal cost. Lawania and Biswas [111] studied 20 building envelope options using LCC along with ELCA to compare conventional buildings with those designed with integrated solar photovoltaic systems and solar water heating. This study concluded that a GHG emission reduction of up to 50%, as well as cost savings of approximately 8.5%, could be achieved by using renewable resources in the use stage of a building. Yoshida and Sugiura [126] studied the effect of green factors (planting, long life span, energy efficiency and resource efficiency) on green buildings, using LCC to compare the investment return or pay-back period for such green factors. This study found that green building designs command a price premium thanks to these buildings' long-life span.

With the development of the green building concept, LCC has gained importance in green building certification systems [127]. There are cost implications in the environmental improvement of buildings. LCC could be used to come up with least-cost green building options and to identify avenues where incentives/economic instruments can be applied to make a green building project more cost-competitive and eco-efficient. However, ensuring a win-win situation that involves the selection of cost-effective but also environmentally friendly options is a challenge.

Social Life Cycle Assessment

Social life cycle assessment (SLCA) determines the social objectives of the sustainability of a product. It particularly addresses the requirements of various stakeholders in the life cycle stages of a building, including the end-user, suppliers, community, builders and designers. SLCA follows the four steps of ELCA including goal and scope definition, compilation of inventory, impact assessment, and interpretation of results. In 1996, O'Brien *et al.* [128] extended ELCA for the first time by incorporating the new factor of political and social influences on environmental impacts. The idea of integrating SLCA with LCC and LCA emerged in 1999 at a SETAC conference where social welfare was suggested as a social impact factor in ELCA studies [129]. In 2009, UNEP/SETAC published methodological sheets and guidelines for the SLCA of products [129]. This tool successfully identified social hotspots in various industrial cases by interviewing stakeholders for cradle-to-grave life cycle studies of specific products, such as laptop computers (e.g., workers' benefits, security and safety, and healthy living conditions for the local community)[130]; vehicle fuels (e.g., child labour, health and safety, and fair salary)[131]; palm oil biodiesel products (e.g., exploitative labour relations, wellbeing of the local community)[132]; palm oil industry products (e.g., employment opportunities, fair salary and access to information)[133]; bamboo bicycle frames (e.g., child labour, working hours, and local employment)[134]; waste management (e.g., illegal waste deposits)[135]; and fertilisers (e.g., labour laws, occupational hazards and accidents, and local community deaths due to air pollution)[136].

The SLCA tool has not often been used in the building sector. A very limited number of SLCA studies have been conducted on residential buildings, in which mainly social welfare dimensions such as employment and human health were considered [137,138]. Hosseinijou *et al.* [137] used SLCA to compare the social impacts of concrete and steel, and identified the social hotspots using material flow analysis and a participatory approach. This study concluded that the social impacts are linked more to company management than to the processes and materials used. Santos *et al.* [139] used health and comfort of the European Standard EN 16309:2014 methodology [140] to assess how five building characteristics—the building's thermal and acoustic profiles, its indoor air quality, visual comfort and spatial aspects—affect the social performance of three experimental buildings in Portugal with varying layout, design and area coverage. Liu and Qian [141] proposed a social sustainability framework for buildings that identified workers, occupants, the local community and society as the main stakeholders, to assess two types of construction: prefabricated prefinished volumetric construction and semi-prefabricated construction. The study concluded that the former outperforms the latter because it boasts the better worker protection scheme, and sophisticated technologies. An SLCA conducted by Dong and Ng [138] for the construction of precast buildings found that precast structures had negatively impacted local employment because the precast concrete components (including the façade, slab, and staircase) were imported rather than locally sourced. As in previous studies, this study also found that the inclusion of eco-efficiency practices could improve the social performance of building construction.

SLCA is an emerging tool, experiencing challenges in terms of life cycle inventory (LCI) compilation and analysis. Most of the SLCA articles reviewed considered generic national data [130], except for a few studies that used site-specific data [137]. There is not a single agreed approach to the selection of impact indicators, with UNEP/SETAC guidelines suggesting a top-down method for social LCI [129], and some other studies suggesting a participatory approach to indicator selection [142]. Stakeholder selection for SLCA depends on the research objectives, stakeholder behaviour, and confidentiality agreements signed with the company [136].

Life Cycle Sustainability Assessment

LCSA considers socio-economic and environmental impacts to assess a product as a single entity, in order to make well-informed decisions that are sustainable throughout the product’s life [11]. LCSA is an emerging technique and few studies have been conducted on the LCSA of buildings. In the building sector, ELCA, LCC and SLCA have been covered individually and separately rather than collectively by most of the studies [143]. Only five studies out of 807 were found to address the TBL sustainability implications of residential buildings. A building is a complex product encompassing groups of components. Unlike other products, buildings cannot be produced based on prototype models. Each building is unique in its functional use, materials, geographic location and design. Therefore, conducting the LCSA of buildings is a complex process, due to the variability in materials, design, workmanship, location, stakeholders, and deterioration mechanisms. A sustainability assessment thus results in larger uncertainties and impacts on the reliability of results in the absence of building SL data [77]. A long-life building requires repeated component replacement and maintenance while short-life buildings eventually entail the rebuilding of the whole building, thus worsening the sustainability scenario [144]. Variation in a building’s SL affects the building environmentally, socially and economically. Therefore, materials, construction methods, and building energy sources need to be selected wisely at the design phase to reduce these TBL effects. Sustainable development is an economic development conducted to fulfil the needs of the present generation without compromising future generations' ability to fulfil their needs, at the same time as conserving the earth's ecosystems and its life support capabilities [145]. The concept of sustainable performance has usually been found to be entwined with environmental performance.

The indicator-based approach is the approach that has most commonly been used to assess the sustainability performance of a product or system

[146]. The purpose of an indicator-based approach is "to provide a measure of current performance, a clear statement of what might be achieved in terms of future performance targets and a yardstick for measurement of progress along the way" [147]. The selection of the right performance indicators, covering validity, relevance, sensitivity and measurability, is important in the sustainability assessment of a project [148]. Selecting key indicators for TBL objectives is a brainstorming task, but it makes the assessment process easier, cheaper and more time-efficient, while a larger set of indicators increases complexity and makes the assessment a time-consuming, expensive and data-intensive process [149]. Thus, an optimum number of key indicators that are aligned with sustainability objectives and standards, should be determined. Kamali *et al.* [150] employed LCSA based on the analytical hierarchy process (AHP) of multi-criteria decision analysis to assess modular residential buildings in British Columbia, Canada, based on 12 environmental indicators, 9 economic indicators and 12 social indicators. The authors conducted indicator selection through a group decision-making process. The indicators list was lengthened by breaking single indicators into multi-indicators based on LCA stages like operational cost, maintenance cost, end-of-life cost, design and construction costs that could be covered by the LCC process. In this paper, a few management strategies (e.g., site disruption) and appropriate strategies and objectives (e.g., renewable and environmentally preferable products), are used as indicators that could contribute to the complexities and intermixing of indicator impacts. The paper has documented the application of a proposed framework for assessing the environmental performance of a case study building with an assumed SL. Although the authors conducted a comprehensive study on the environmental performance of modular residential buildings, the study did not highlight the hotspots for modular buildings to help decide further improvement strategies. The authors also did not explain the capability of their framework to investigate modular buildings and draw comparisons with other building systems.

The types of TBL indicators deployed vary with the objectives and regional perspectives of the product/system under consideration. Onat *et al.* [151] have used an integrated input-output hybrid LCA model to assess TBL sustainability in the residential and commercial building industries of the USA (2002), using system boundaries that include all stages of a product. The study considered 16 macro-level indicators: foreign purchase, business profit, income, government tax, injuries, fishery, grazing, forestry, cropland, carbon fossil fuel, carbon electricity, total GHG, total energy, water, and hazardous waste, categorised under TBL objectives. The authors have used only quantitative data for 2002, obtained from publicly available sources like the US Bureau of Economic Analysis, the Department of Energy, the Energy Information Administration, and the Federal Highway Administration, *etc.* The social aspects of sustainability should be assessed using qualitative and quantitative data, which need to be generic and site-specific. Site-specific qualitative data are collected through face-to-face interviews and direct observations, which also provide a clear picture of the prevalent condition of affected people that cannot easily be measured or quantified.

System boundaries in LCSA studies vary with the scope of the study. However, the three LCSA objectives, *i.e.*, the environmental, social and economic factors, should be studied using the same system boundaries. An LCSA framework should be robust enough to analyse the TBL objectives simultaneously and explain the interdependencies among the environmental, social and economic aspects being impacted. Another study of the sustainability of residential buildings, done by Dong and Ng [143], examined only the pre-use stage of a multi-residential building, including materials extraction and manufacturing, and on-site construction. This study has proposed an LCSA framework combining three life cycle assessment approaches, *i.e.*, the environmental model of construction (EMoC), the cost model of construction (CMoC), and the social-impact model of construction (SMoC); the study has also used human health, the ecosystem, resources, materials, workers, local community and society as TBL impact categories for assessing a building's sustainability performance. The LCSA framework was based on a weak sustainability concept and the TBL objectives were discussed and interpreted independently of each other. The authors concluded that extraction and manufacturing of materials contribute more than 90% to environmental impacts and 60% to economic impacts, a far greater impact than that of actual construction activity. The SMoC showed overall positive social impacts on all stakeholders due to the project's provision of employment and its low levels of dust and noise pollution thanks to the use of precast building components that were transported and installed on-site.

The incorporation of precise building SL data in an LCSA has a significant bearing on the building's sustainability performance assessment, ultimately complementing the accuracy of LCSA results. However, none of the LCSA frameworks has addressed the variability associated with SL in the sustainability assessment process. For instance, Balasbaneh *et al.* [152] studied the sustainability assessment of hybrid timber-frame buildings in Malaysia, considering the following factors as sustainability indicators: global warming potential (GWP); fossil depletion potential; acidification and eutrophication; human toxicity potential; LCC; present value; wages of the foreman, and job creation. Although the authors have presented a comprehensive study on five types of hybrid timber buildings, the indicator selection for economic and social objectives is very limited. Biodiversity, land use, water consumption, and inter-generational equity, factors which are critical to natural resource assessment, were not considered in this study, which has used a fixed assumed SL of 50 years for all case study buildings, disregarding building materials properties. Another LCSA framework for residential buildings, proposed by Hossaini *et al.* [153], is based on the AHP approach and has used an assumed SL of 60 years. This framework was applied to two six-story residential buildings in Vancouver, Canada. One building was timber-framed, while the second one was a concrete structure. The framework used 18 sustainability indicators to assess the buildings' sustainability, including GWP, acidification and eutrophication, fossil fuel, habitat alteration, resources use, waste management, smog potential, and human health respiratory impact, as environmental criteria; with indoor air, occupant comfort, safety and affordability, as social criteria; and total cost as the economic criterion. This study concluded that building sustainability performance is linked to SL energy rather than construction materials. The SL was assumed to be the same for both buildings.

None of the above LCSA studies has adequately reflected on sustainability implications of residential buildings in terms of the selection of stakeholders, indicators development, site-specific data collection, nor the variation of the estimated SL of construction materials in the LCA. Contemporary LCA frameworks are not adequate for assessing all TBL objectives simultaneously. Firstly, there are several inadequacies in terms of SL assumptions, uncertainties in data quality (e.g., data collected from life cycle stakeholders), and insufficient TBL impact indicators in LCSA frameworks. None of these studies has integrated TBL objectives or provided for the application of TBL improvement strategies. Therefore, a fully holistic LCSA framework moderated by practical evaluation is essential to a comprehensive TBL sustainability assessment.

LESSONS LEARNT AND FUTURE RESEARCH DIRECTION

After a thorough review of the published literature on the sustainability performance of residential buildings, it emerges that:

1. The LCSA of residential buildings can be further improved by selecting key stakeholders, developing relevant TBL indicators, and gathering site-specific data to compile TBL inventories for sustainability assessment.
2. Few studies have been conducted to assess the TBL sustainability performance of residential buildings.
3. The sustainability assessment frameworks used so far lack a comprehensive approach to address the above-mentioned gaps. Therefore, a holistic LCSA framework is required to integrate the environmental, social and economic objectives of sustainability.
4. The system boundaries set need to consider the life cycle of all the building components and of the building itself, in order to assess the impacts of the building throughout its entire life cycle.
5. An assumed SL is the most commonly used factor when conducting life cycle assessments of buildings. This results in uncertainties in LCA assessments because the assumed maintenance and repair intervals and use stages could differ according to the building materials used.

6. TBL indicators in existing studies found in the literature surveyed did not necessarily take into account region-specific variations. Sustainability scenarios may vary across different locations. A sustainability impact indicator, like water scarcity, child labour *etc.*, that is considered the most important in one country may not necessarily be useful in another country.

Therefore, TBL indicator selection should be based on the factors in the region studied, and the LCSA framework should be flexible enough to handle the variation in region-specific impact indicators. This review thus confirms that there is a need to conduct LCSA studies that consider all stages of a building's life cycle and address the above-mentioned gaps, by developing a holistic TBL sustainability assessment framework for residential buildings.

CONCLUSIONS

This review confirms that LCA has been widely used to separately assess the environmental, social, and economic performance aspects of the building industry. A limited number of studies have applied LCA to determine all three TBL objectives in order to assess the overall sustainability performance of buildings. The existing frameworks were not designed to compare the sustainability performance of different buildings. Firstly, there is a need to integrate examination of the three objectives of sustainability, to obtain an overall score which will allow comparison between buildings. Secondly, this framework needs to be designed in a way that allows the identification of sustainability hotspots in order to formulate relevant improvement strategies. Thirdly, TBL indicator selection plays a crucial role as indicators vary with places, and with the socio-economic status of a region. It is therefore important to conduct a consensus survey, to select region-specific indicators that can help determine buildings' overall sustainability performance. Most importantly, the buildings' SL has a significant bearing on the sustainability of buildings constructed from varying and different materials. There are still avenues for improving the existing assessment process, in terms of developing indicators, and the integration of TBL indicators and the objectives for assessing buildings' sustainability performances. A building sustainability assessment tool should be able to handle the flexibility and complexity associated with the interaction among the three sustainability objectives in the building industry. If the industry is to improve the quality of sustainability assessments, a comprehensive sustainability framework must be developed by defining the relevant and region-specific sustainability indicators that can be measured by an LCA approach, taking into account the SL variabilities of different types of buildings made of conventional or alternative materials.

AUTHOR CONTRIBUTIONS

Conceptualisation and methodology: SYJ, PKS and WKB; analysis: SYJ; investigation: SYJ; data curation: SYJ; original draft: SYJ; visualization: SYJ; writing review and editing: SYJ, PKS and WKB; Supervision: PKS and WKB.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1. Business Council for Sustainable Development; Deloitte & Touche; International Institute for Sustainable Development. Business strategy for sustainable development: leadership and accountability for the '90s. Winnipeg (Canada): International Institute for Sustainable Development; 1992.
2. Love PED, Irani Z. An exploratory study of information technology evaluation and benefits management practices of SMEs in the construction industry. Inf Manag. 2004;42(1):227-42.
3. Zuo J, Zhao ZY. Green building research current status and future agenda: A review. Renew Sustain Energy Rev. 2014;30:271-81.
4. Ma M, Cai W. Do commercial building sector-derived carbon emissions decouple from the economic growth in Tertiary Industry? A case study of four municipalities in China. Sci Total Environ. 2019;560(1):822-34.
5. Dean B, Dulac J, Petrichenko K, Graham P. Towards zero-emission efficient and resilient buildings. Global Status Report 2016. Paris (France): Global Allience for Buildings and Construction (GABC); 2016.
6. Trimetric. Key Highlights from Global Construction Outlook 2021. London (UK): Construction Intelligence Centre, Timetric; 2018. Report Code: GD-CN0004GO.
7. United Nations Environment Programme. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication-A synthesis for Policy Makers. St-Martin-Bellevue (France): United Nations Environment Programme; 2011. Available from: https://sustainabledevelopment.un.org/content/documents/126GER_synthesisen.pdf. Accessed 2018 Dec 25.
8. Joseph P, Tretsiakova-McNally S. Sustainable Non-metallic Building Materials. Sustainability. 2010;2(2):400-27.
9. Pickin J, Randell P. National Waste report 2016. Victoria (Australia): Department of the Environment and Energy; 2017. Available from: https://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2016. Accessed 2018 Dec 18.
10. Australian Bureau of Statics. Labour Force Region-SA4 Data. Canberra (Australia): Department of Jobs and Small Business—Australian Government;

2018. Available from: http://lmip.gov.au/default.aspx?LMIP/Downloads/ABSLabourForceRegion. Accessed 2019 Jan 16.

11. United Nations Environment Programme. Towards a Life Cycle Sustainability Assessment. Making informed choices on Products. Paris (France): Life Cycle initiative; 2012. Available from: https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/life-cycle-sustainability-assessment. Accessed 2018 Jun 30.
12. Committee on Climate Change. Fourth carbon budget review—part 2: the cost-effective path to the 2050 target. London (UK): Committee on Climate Change; 2013. Available from: https://www.theccc.org.uk/publication/fourth-carbon-budget-review/. Accessed 2019 Jun 16.
13. Evangelista PPA, Kiperstock A, Torres EA, Gonçalves JP. Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA). Constr Build Mater. 2018;169:748-61.
14. Lawania K, Biswas WK. Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia. Int J Life Cycle Assess. 2018;23:204-24.
15. Janjua SY, Sarker PK, Biswas WK. Impact of Service Life on the Environmental Performance of Buildings. Buidings. 2019;9:9. doi: 10.3390/buildings9010009
16. Lombard R. It's not easy being green: Difficulties in sourcing sustainable building materials. QScience Connect. 2017;2:1. doi: https://doi.org/10.5339/connect.2017.qgbc.10
17. Hegger M, Drexler H, Zeumer M. Basics Materials. Basel (Switzerland): Birkhauser; 2007.
18. Ashby M, Johnson K. Materials and Design: the Art and Science of Material Selection in Product Design. 1st ed. Oxford (UK): Butterworth-Heinemann; 2002.
19. Crilly N, Moultrie J, Clarkson PJ. Seeing things: consumer response to the visual domain in product design. Des Stud. 2004;25(6):547-77.
20. Rao RV. A material selection model using graph theory and matrix approach. Mater Sci Eng A. 2006;431(1-2):248-55.
21. Abeysundara UG, Babel S, Gheewala S. A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka. Build Environ. 2009;44(5):997-1004.
22. Spiekermann C, Donath D. Digital support of material and product selection in the architectural design and planning process. In: Gürlebeck K, Könke C, editors. Proceeding of 17th International Conference on the Applications of Computer Science and Mathematics in Architecture and Civil Engineering; 2006 Jul 12-14; Weimar, Germany. Weimar (Germany): Bauhaus-University Weimar; 2006. p. 1-10.
23. Huang H, Zhang L, Liu Z, Sutherland JW. Multi-criteria decision making and uncertainty analysis for materials selection in environmentally conscious design. Int J Adv Manuf Technol. 2011;52(5-8):421-32.
24. Cheng K, Hsu SC, Li WM, Ma HW. Quantifying potential anthropogenic resources of buildings through hot spot analysis. Resour Conserv Recycl. 2018;133:10-20.

25. Iffa E, Tariku F. Hygrothermal performance assessment of ICF walls with different moisture control strategies and wall designs. J. Green Build. 2017;12(4):35-53.
26. Uçtuğ FG, Ağralı S. Simple nonlinear optimization-based selection of insulation material and window type in Turkey: effect of heating and cooling base temperatures. J Green Build. 2017;9(6):79-94.
27. Wang J, Pan W. Influencing parameters of the life cycle cost-energy relationship of buildings. J Green Build. 2018;13(4):103-21.
28. Ajayia S, Oyedele LO, Ilori OM. Changing significance of embodied energy: A comparative study of material specifications and building energy sources. J Build Eng. 2019;23:324-33.
29. De Luca P, Carbone I, Nagy JB. Green building materials: a review of state of the art studies of innovative materials. J Green Build. 2017;12(4):141-61.
30. Harish VSKV, Kumar A. A review on modeling and simulation of building energy systems. Renew Sust Ener Rev. 2016;56:1272-92.
31. Lawania K, Biswas WK. Achieving environmental friendly building envelope for Western Australia's housing sector: A life cycle assessment approach. Int J Sust Built Environ. 2016;5(2):210-24.
32. Pillai RG, Gettu R, Santhanam M, Rengaraju S, Basavaraj AS. Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3). Cem Concr Res. 2019;118:111-9.
33. Huang B, Chen Y, McDowall W, Türkeli S, Geng Y. Embodied GHG emissions of building materials in Shanghai. J Clean Prod. 2019;210:777-85.
34. Glover J, Whilte DO, Langrish TAG. Wood versus concrete and steel in house construction. J For. 2002;100(8):34-41.
35. Petrovic B, Myhren JA, Zhang X, Wallhagen M, Eriksson O. Life Cycle Assessment of Building Materials for a Single-family House in Sweden. Energy Procedia. 2019;158:3547-52.
36. Tettey UYA, Dodoo A, Gustavsson L. Effect of different frame materials on the primary energy use of a multi storey residential building in a life cycle perspective. Energy Build. 2019;185(15):259-71.
37. Göswein V, Goncalves AB, Silvestre JD, Freire F, Kurda R. Transportation matters—does it? GIS-based comparative environmental assessment of concrete mixes with cement, fly ash, natural and recycled aggregates. Resour Conserv Recycl. 2018;137:1-10.
38. Siddique R, Singh G, Belarbi R, Ait-Mokhtar K, Kunal. Comparative investigation on the influence of spent foundry sand as partial replacement of fine aggregates on the properties of two grades of concrete. Constr Build Mater. 2015;83:216-22.
39. Bhardwaj B, Kumar P. Waste foundry sand in concrete: A review. Constr Build Mater. 2017;156:661-74.
40. Nath P, Sarker PK. Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Constr Build Mater. 2014;66:163-71.

41. Durgun MY, Sevinc AH. High temperature resistance of concretes with GGBFS, waste glass powder, and colemanite ore wastes after different cooling conditions. Constr Build Mater. 2019;196:66-81.
42. Wang Y, Suraneni P. Experimental methods to determine the feasibility of steel slag as supplementary cementitious materials. Constr Build Mater. 2019;204:458-67.
43. Guo Y, Xie J, Zhao J, Zuo K. Utilization of unprocessed steel slag as fine aggregate in normal- and high-strength concrete. Constr Build Mater. 2019;204:41-9.
44. Tripathi B, Misra A, Chaudhary S. Strength and abrasion characteristics of ISF slag concrete. J Mater Civ Eng. 2013;25(11):1611-8.
45. Lori AR, Hassani A, Sedghi R. Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate. Constr Build Mater. 2019;197:130-42.
46. Prem PR, Verma M, Ambily PS. Sustainable cleaner production of concrete with high volume copper slag. J Clean Prod. 2018;193:43-58.
47. Abdulmatin A, Tangchirapat W, Jaturapitakkul C. An investigation of bottom ash as a pozzolanic material. Constr Build Mater. 2018;186:155-62.
48. Ghosh A, Ghosh A, Neogi S. Reuse of fly ash and bottom ash in mortars with improved thermal conductivity performance for buildings. Heliyon. 2018;4(11):e00934.
49. Nath P, Sarker PK, Biswas WK. Effect of fly ash on the service life, carbon footprint and embodied energy of high strength concrete in the marine environment. Energy Build. 2018;158:1694-702.
50. Tamimi A, Hassan NM, Fattah K, Talachi A. Performance of cementitious materials produced by incorporating surface treated multiwall carbon nanotubes and silica fume. Constr Build Mater. 2016;114:934-45.
51. Muthusamy K, Mirza J, Zamri NA, Hussin MW, Budiea AMA. Properties of high strength palm oil clinker lightweight concrete containing palm oil fuel ash in tropical climate. Constr Build Mater. 2018;199:163-77.
52. Qin L, Gao X, Chen T. Recycling of raw rice husk to manufacture magnesium oxysulfate cement based lightweight building materials. J Clean Prod. 2018;191:220-32.
53. Umasabor RI, Okovido JO. Fire resistance evaluation of rice husk ash concrete. Heliyon. 2018;4(12):e01035.
54. Danso H. Properties of Coconut, Oil Palm and Bagasse Fibres: As Potential Building Materials. Procedia Eng. 2017;200:1-9.
55. Langade S, Gilke N, Patil K. Bagasse Ash for Manufacturing Construction Products. Materials Today Proceedings. 2018;5(9):19954-62.
56. Saccani A, Manzi S, Lancellotti I, Lipparini L. Composites obtained by recycling carbon fibre/epoxy composite wastes in building materials. Constr Build Mater. 2019;204:296-302.
57. Gómez-Soberón JM, Cabrera-Covarrubias FG, Almaral-Sánchez JL, Gómez-Soberón MC. Fresh-State Properties of Mortars with Recycled Glass Aggregates: Global Unification of Behavior. Adv Mater Sci Eng. 2018;2018:1386946. doi: 10.1155/2018/1386946

58. Mendivil-Escalante JM, Gómez-Soberón JM, Almaral-Sánchez JL, Cabrera-Covarrubias FG. Metamorphosis in the Porosity of Recycled Concretes Through the Use of a Recycled Polyethylene Terephthalate (PET) Additive. Correlations between the Porous Network and Concrete Properties. Materials. 2017;10:176.
59. Cabrera-Covarrubias FG, Gómez-Soberón JM, Almaral-Sánchez JL, Arredondo-Rea SP, Gómez-Soberón MC, Corral-Higuera R. An Experimental Study of Mortars with Recycled Ceramic Aggregates: Deduction and Prediction of the Stress-Strain. Materials. 2016;9(12):1029.
60. Lawania K, Sarker PK, Biswas WK. Global Warming Implications of the Use of By-Products and Recycled Materials in Western Australia's Housing Sector. Materials. 2015;8(10):6909-25.
61. Ding T, Xiao J, Tam VWY. A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. Waste Manag. 2016;56:367-75.
62. Hossain MU, Poon CS, Lo IC, Cheng JP. Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach. Int J Life Cycle Assess. 2016;21(1):70-84.
63. Braga AM, Silvestre JD, Brito JD. Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. J Clean Prod. 2017;162:529-43.
64. Yazdanbakhsh A, Bank LC, Baez T, Wernick I. Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area. Int J Life Cycle Assess. 2018;23(6):1163-73.
65. Grant A, Ries R, Kibert C. Life cycle assessment and service life prediction: A case study of building envelope materials. J Ind Ecol. 2014;18(2):187-200.
66. Maslesa E, Jensen PA, Birkved M. Indicators for quantifying environmental building performance: A systematic literature review. J Build Eng. 2018;19:552-60.
67. Gray J, Isaacs N, Kernohan D, McIndoe G. Building Evaluation techniques. Baird G, editor. New York (US): McGraw-Hill Co. Inc.; 1995.
68. ISO 15686-2, Buildings and constructed assets—Service life Planning. Part-2: Service life prediction procedures. Geneva (Switzerland): International Standards Organisation; 2012.
69. Madrigal LO, Bretones JF, Lanzarote BS. Proposed method of estimating the service life of building envelopes. J Constr. 2015;14(1):60-88.
70. Emídio F, Brito JD, Gaspar PL, Silva A. Application of the factor method to the estimation of the service life of natural stone cladding. Constr Build Mater. 2014;66:484-93.
71. Souza J, Silva A, Brito JD, Bauer E. Service life prediction of ceramic tiling systems in Brasília-Brazil using the factor method. Constr Build Mater. 2018;192:38-49.
72. Lyu Y, Kim JH, Gu X. Developing methodology for service life prediction of PV materials: Quantitative effects of light intensity and wavelength on discoloration of a glass/EVA/PPE laminate. Solar Energy. 2018;174:515-26.

73. Ligotski R, Sager U, Schneiderwind U, Asbach C, Schmidt F. Prediction of VOC adsorption performance for estimation of service life of activated carbon based filter media for indoor air purification. Build Environ. 2019;149:146-56.
74. Prieto AJ, Silva A, Brito JD, Macías-Bernal JM, Alejandre FJ. Multiple linear regression and fuzzy logic models applied to the functional service life prediction of cultural heritage. J Cult Herit. 2017;27:20-35.
75. Rauf A, Crawford RH. The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. Arch Sci Rev. 2013;56(3):252-61.
76. Rauf A, Crawford RH. The Effect of Material Service Life on the Life Cycle Embodied Energy of Multi-Unit Residential Buildings. Paper presented at: World Sustainable Buildings WSB14 Conference; 2014 Oct 28-30; Barcelona, Spain.
77. Rauf A, Crawford RH. Building service life and its effect on the life cycle embodied energy of buildings. Energy. 2015;79:140-8.
78. Klöppfer W. Life Cycle Sustainability assessment of products. Int J Life Cycle Assess. 2008;13:89-95.
79. ISO 14040: Environmental management—Life cycle assessment—Principles and framework. Geneva (Switzerland): International Standards Organization; 2006.
80. Counsoli F, Allen D, Boustead I, Fava J, Franklin W, Jensen A. SETAC (Society) and LCA "Code of Practice" Workshop (1993: Sesimbra, Portugal) Guidelines for life-cycle assessment: a "code of practice". 1st ed. Pensacola (US): Society of Environmental Toxicology and Chemistry (SETAC); 1993.
81. Guinee JB, Haes UD, Huppes G. Quantitative life cycle assessment of products: 1: goal definition and inventory. J Clean Prod. 1993;1(1):3-13.
82. Bekker PCF. A life cycle approach in building. Build Environ. 1982;17(1):3-13.
83. Coles RJ. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Build Environ. 1998;34(3): 335-48.
84. Fufa SM, Skaar C, Gradeci K, Labonnote N. Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA. J Clean Prod. 2018;44:319-33.
85. Marjaba GE, Chidiac SE. Sustainability and resiliency metrics for buildings—Critical review. Build Environ. 2016;101:116-25.
86. Rakha T, Moss TW, Shin D. A decade analysis of residential LEED buildings market share in the United States: Trends for transitioning sustainable societies. Sustain Cities Soc. 2018;39:568-77.
87. Saldaña-Márquez H, Gómez-Soberón JM, Arredondo-Rea SP, Rosell-Balada G. The passivhaus standard in the mediterranean climate: Evaluation, comparison and profitability. J Green Build. 2015;10(4):55-72.
88. Saldaña-Márquez H, Gómez-Soberón JM, Arredondo-Rea SP, Gámez-García DC, Corral-Higuera R. Sustainable social housing: The comparison of the Mexican funding program for housing solutions and building sustainability rating systems. Build Environ. 2018;133:103-22.

89. Fouquet M, Levasseur A, Margni M, Lebert A, Lasvaux S, Souyri B, *et al.* Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. Build Environ. 2015;90:51-9.
90. Motuziene V, Rogoža A, Lapinskiene V, Vilutiene T. Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: A case study. J Clean Prod. 2016;112:532-41.
91. Aneurin Grant RR. Impact of building service life models on life cycle assessment. Build Res Info. 2013;41(2):168-86.
92. Akadiri PO. Understanding barriers affecting the selection of sustainable materials in building projects. J Build Eng. 2015;4:86-93.
93. Ingrao C, Arcidiacono C, Bezama A, Ioppolo G, Schmid AG. Virtual Special Issue on sustainability issues of by-product and waste management systems to produce building material commodities. Resour Conserv Recycl. 2017;126:A4-5.
94. Gámez-García DC, Gómez-Soberón JM, Corral-Higuera R, Saldaña-Márquez H, Gómez-Soberón MC, Arredondo-Rea SP. A Cradle to Handover Life Cycle Assessment of External Walls: Choice of Materials and Prognosis of Elements. Sustainability. 2018;10(8):2748.
95. Maalouf C, Ingrao C, Scrucca F, Moussa T, Asdrubali F. An energy and carbon footprint assessment upon the usage of hemp-lime concrete and recycled-PET façades for office facilities in France and Italy. J Clean Prod. 2018;170:1640-53.
96. Intini F, Kühtz S. Recycling in buildings: an LCA case study of a thermal insulation panel made of polyester fiber, recycled from post-consumer PET bottles. Int J Life Cycle Assess. 2011;16(4):306-15.
97. Schmidt M, Crawford RH. A framework for the integrated optimisation of the life cycle greenhouse gas emissions and cost of buildings. Energy Build. 2018;171:155-67.
98. Tam WV, Le KN, Tran CN, Wang JY. A review on contemporary computational programs for Building's life-cycle energy consumption and greenhouse-gas emissions assessment: An empirical study in Australia. J Clean Prod. 2018;172:4220-30.
99. Martínez-Rocamora A, Solís-Guzmán J, Marrero M. LCA databases focused on construction materials: A review. Renew Sustain Energy Rev. 2016;58:565-73.
100. Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Heck T, et al. The ecoinvent database: Overview and methodological framework. Int J Life Cycle Assess. 2005;10(1):3-9.
101. Ecoinvent Centre. Ecoinvent Databases 2019. Available from: http://www.ecoinvent.org/database/database.html. Access 2019 Apr 28.
102. Thinkstep. GaBi Databases 2019. Available from: http://www.gabi-software.com/databases/gabi-databases/. Access 2019 Apr 28.
103. Crawford RH, Czerniakowski I, Fuller RJ. A comprehensive framework for assessing the life-cycle energy of building construction assemblies. Arch Sci Rev. 2010;53(3):288.

104. Blengini GA, Carlo TD. Energy-Saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy). Int J Life Cycle Assess. 2010;15(7):652-65.
105. Vitale P, Arena N, Gregorio F, Arena U. Life cycle assessment of the end-of-life phase of a residential building. Waste Manag. 2017;60:311-21.
106. Ghose A, Pizzol M, McLaren S. Consequential LCA modelling of building refurbishment in New Zealand—an evaluation of resource and waste management scenarios. J Clean Prod. 2017;165:119-33.
107. Zhou C, Dai X, Wang R, Huang J. Indicators for evaluating sustainable communities: A review. Acta Ecol Sin. 2011;31(16):4750-9.
108. Geng S, Wang Y, Zuo J, Zhou Z, Mao G. Building life cycle assessment research: A review by bibliometric analysis. Renew Sustain Energy Rev. 2017;76:176-84.
109. Settanni E, Tassielli G, Notarnicola B. Life Cycle Costing (LCC). In: Spellerberg I, Fogel DS, Fredericks SE, Butler Harrington LM, editors. Berkshire ENCYCLOpaedia of SUSTainability 6/10: Measurements, Indicators, and Research Methods for Sustainability. Great Barrington (US): Berkshire Publishing Group; 2012. p. 225-7.
110. HuaGoh B, Sun Y. The development of life-cycle costing for buildings. Build Res Inf. 2016;44(3):319-33.
111. Lawania K, Biswas WK. Cost-effective GHG mitigation strategies for Western Australia’s housing sector: A life cycle management approach. Clean Technol Environ Policy. 2016;18(8):2419-28.
112. Heijungs R, Settanni E, Guinée J. Toward a computational structure for life cycle sustainability analysis: Unifying LCA and LCC. Int J Life Cycle Assess. 2012;18(9):1722-33.
113. Singh D, Tion RK. Development of life cycle costing framework for highway bridges in Myanmar. Int J Project Manag. 2005;23(1):37-44.
114. Cuellar-Franca RM, Azapagic A. Life cycle cost analysis of the UK housing stock. Int J Life Cycle Assess. 2014;19:174-93.
115. Kovacic I, Waltenbereger L, Gourlis G. Tool for life cycle analysis of facade-systems for industrial buildings. J Clean Prod. 2016;130(1):260-72.
116. Azeem S, Naeem MA, Waheed A, Thaheem MJ. Examining barriers and measures to promote the adoption of green building practices in Pakistan. Smart Sustain Built Environ. 2017;6(3):86-100.
117. Persson J, Grönkvist S. Drivers for and barriers to low-energy buildings in Sweden. J Clean Prod. 2015;109:296-304.
118. Shen LY, Hao JL, Tam VW, Yao H. A checklist for assessing sustainability performance of construction projects. J Civil Eng Manag. 2007;13(4):273-81.
119. Ahmad T, Thaheem MJ. Economic sustainability assessment of residential buildings: A dedicated assessment framework and implications for BIM. Sustain Cities Soc. 2018;38:476-91.
120. Babaizadeh H, Haghighi N, Asadi A, Broun R, Riley D. Life cycle assessment of exterior window shadings in residential buildings in different climate zones. Build Environ. 2015;90:168-77.
121. Allacker K, Trigaux D, Troyer FD. An Approach For Handling Environmental And Economic Conflicts In The Context Of Sustainable Building. In: Passerini

G, Brebbia CA, editors. Environ Impact II. WIT Transactions on Ecology and the Environment. Southampton (UK): WIT Press; 2014. p. 79-90.

122. Chiang YH, Li J, Zhou L, Wong FK, Lam PT. The nexus among employment opportunities, life-cycle costs, and carbon emissions: A case study of sustainable building maintenance in Hong Kong. J Clean Prod. 2015;109: 326-35.
123. Dawood MH. BIM based optimal life cycle cost of sustainable house framework. In: Proceedings of 3rd MEC International Conference on Big Data and Smart City; 2016 Mar 15-16; Muscat, Oman. Piscataway (US): IEEE; 2016. doi: 10.1109/ICBDSC.2016.7460381
124. Sayed M, Sajid S, Sawant, Priyadarshi H. Financial feasibility analysis of water conservation components in mass housing projects: Suburban Indian Case review. J Arch Eng. 2016;22(2):e04016001-1.
125. Tam VWY, Senaratne S, Le KN, Shen LY, Perica J, Illankoon IMCS. Life-cycle cost analysis of green-building implementation using timber applications. J Clean Prod. 2017;147:458-69.
126. Yoshida J, Sugiura A. The Effects of Multiple Green Factors on Condominium Prices. J Real Estate Finan Econ. 2015;50(3):412-37.
127. Roh S, Tae S, Kim R. Development of a Streamlined Environmental Life Cycle Costing Model for Buildings in South Korea. Sustainability. 2018;10(6):1733.
128. O'Brien M, Doig A, Clift R. Social and environmental life cycle assessment (SELCA): approach and methodological development. Int J Life Cycle Assess 1996;1(4):231-37.
129. United Nations Environment Programme. Guidlines for Social Life Cycle Assessment of Products. Paris (France): Life Cycle initiative, 2009. Available from: https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca. Accessed 2018 Jun 30.
130. Ekener-Petersen E, Finnveden G. Potential hotspots identified by social LCA - Part 1: A case study of a laptop computer. Int J Life Cycle Assess. 2013;18(1):127-43.
131. Ekener E, Hansson J, Gustavsson M. Addressing positive impacts in social LCA discussing current and new approaches exemplified by the case of vehicle fuels. Int J Life Cycle Assess. 2018;23(3):556-68.
132. Manik Y, Leahy J, Halog A. Social life cycle assessment of palm oil biodiesel: A case study in Jambi Province of Indonesia. Int J Life Cycle Assess. 2013;18(7):1386-92.
133. Lim CI, Biswas WK. An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia. Sustainability. 2015;7: 16561-7. doi: 10.3390/su71215833
134. Agyekum EO, Fortuin K, Harst ED. Environmental and social life cycle assessment of bamboo bicycle frames made in Ghana. J Clean Prod. 2017;143:1069-80.
135. Santos AC, mendes P, Teixeira MR. Social life cycle analysis as a tool for sustainable management of illegal waste dumping in municipal services. J Clean Prod. 2019;210:1141-9.

136. Martínez-Blanco J, Lehmann A, Muñoz P, Antón A, Traverso M, Rieradevall J, et al. Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. J Clean Prod. 2014;69:34-48.
137. Hosseinijou SA, Mansour S, Shirazi MA. Social life cycle assessment for material selection: a case study of building materials. Int J Life Cycle Assess. 2014;19(3):620-45.
138. Dong YH, Ng ST. A social life cycle assessment model for building construction in Hong Kong. Int J Life Cycle Assess. 2015;20(8):1166-80.
139. Santos P, Pereira AC, Gervásio H, Bettencourt A, Mateus D. Assessment of health and comfort criteria in a life cycle social context: Application to buildings for higher education. J Clean Prod. 2017;123:625-48.
140. European Committee for Standardisation. EN 16309:2014+A1, Sustainability of Construction Works—Assessment of Social Performance of Buildings—Calculation Methodology. Brussels (Belgium): CEN—European Committee for Standardisation; 2014.
141. Liu S, Qian S. Evaluation of social life-cycle performance of buildings: Theoretical framework and impact assessment approach. J Clean Prod. 2019;213:792-807.
142. Mathe S. Integrating participatory approaches into social life cycle assessment. The SLCA participatory approach. Int J Life Cycle Assess. 2014;19(8):1506-14.
143. Dong YH, Ng ST. A modeling framework to evaluate sustainability of building construction based on LCSA. Int J Life Cycle Assess. 2016;21:555-68.
144. Fu F, Pan L, Ma L, Li Z. A simplified method to estimate the energy-saving potentials of frequent construction and demolition process in China. Energy. 2013;49:316-22.
145. Griggs D, Smith MS, Gaffney O, Rockström J, Öhman MC, Shyamsundar P, et al. Sustainable development goals for people and planet. Nature. 2013;495(7441):305-7.
146. Bragança L, Mateus R, Koukkari H. Building Sustainability Assessment. Sustainability. 2010;2:2101-23.
147. Alwaer H, Clements-Croome DJ. Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. Build Environ. 2010;45(4):799-807.
148. Dale VH, Beyeler SC. Challenges in the development and use of ecological indicators. Ecol Indic. 2001;1(1):3-10.
149. Lasvaux S, Achim F, Garat P, Peuportier B, Chevalier J, Habert G. Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: what matters? Ecol Indic. 2016;67:174-82.
150. Kamali M, Hewage K, Milani AS. Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices. Build Environ. 2018;138:21-41.
151. Onat NC, KucukvarM, Tatari O. Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings. Int J Life Cycle Assess. 2014;19:1488-505.

152. Balasbaneh AT, Bin Marsono AK, Kermanshahi KE. Balancing of life cycle carbon and cost appraisal on alternative wall and roof design verification for residential building. Constr Innovation. 2018;18(3):274-300.
153. Hossaini N, Reza B, Akhtar S, Sadiq R, Hewage K. AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. J Environ Plan Manag. 2015;58(7):1217-41.

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APPENDIX-2: PAPER-2

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STATEMENT OF CONTRIBUTION

To Whom It May Concern,

I, Janjua SY, contributed to literature review, method formulation, hypothetical data collection, result interpretation, discussions and writing (80%) of the paper/publication entitled:

Janjua SY, Sarker PK, Biswas WK. Sustainability Implication of a residential building using a lifecycle assessment approach. Chemical Engineering Transactions. 2019, 72:19-24 http://doi.org/10.3303/CET1972004

The remaining 20% of this paper/ publication was contributed by A/Prof. Wahidul K. Biswas (10%) and A/Prof. Prabir K. Sarker (10%).

Signature: Date: 01 March 2021

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 01 March 2021

Co-author 2: A/Prof Prabir K. Sarker Date: 01 March 2021

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> Student ID:18229848
> Email | s.janjua@postgrad.curtin.edu.au
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Sustainability Assessment of a Residential Building using a Life Cycle Assessment Approach

Shahana Y. Janjua[a,*], Prabir K. Sarker[a], Wahidul K. Biswas[b]

[a]School of Civil and Mechanical Engineering, Curtin University, Perth, Australia
[b]Sustainability Engineering Group, Curtin University, Perth, Australia
s.janjua@postgrad.curtin.edu.au

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).

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

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)

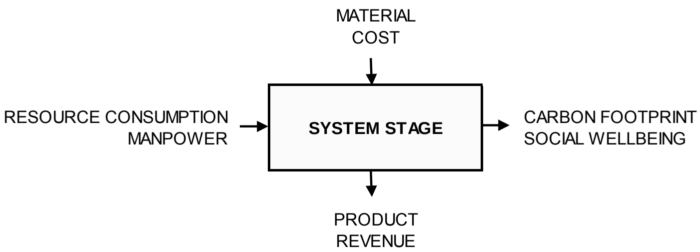

Figure 1: Life cycle assessment stage Inventory for LCSA of Buildings

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

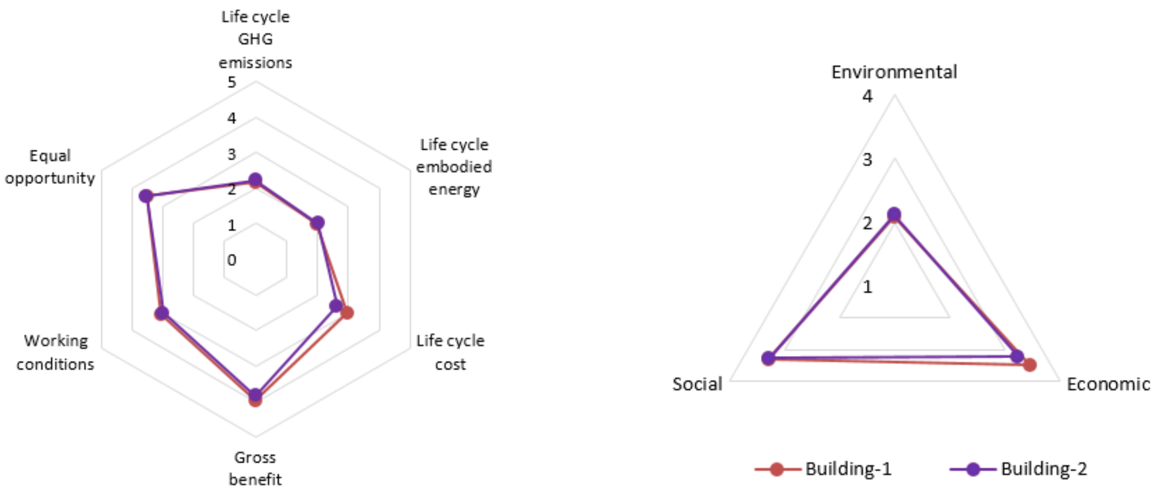

Figure 2: Score of sustainability indicators (Left), Score of sustainability objectives (Right)

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.

References

DOE, 2015, Australia’s 2030 emissions reduction target, Department of the Environment, Australian Government, Canberra, Australia.

Grant A, Robert R., Charles K., 2014, Life Cycle Assessment and Service Life Prediction, Journal of Industrial Energy, 18 (2), 187-200.

Hovde P.J., Konrad M., 2004, Performance based Methods for Service life Prediction, State of Art Reports, Report of CIB W080/RILEM 175-SLM: Service Life Methodologies, Norwegian University of Science and Technology (NTNU), Dept. of Building and Construction Engineering, Trondheim, Norway.

Lawania K., Biswas W.K., 2018, Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia, The International Journal of Life Cycle Assessment, 23, 204-224.

Lim C.I., Biswas W.K., 2015, An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia, Sustainability, 7, 16561–16587.

Madrigal L.O., José M.F.B., Begoña S.L., 2015, Proposed method of estimating the service life of building envelopes, Journal of Construction, 14(1), 60-88.

Matthias B., Johan B., Amaryllis A., 2013, Life cycle assessment in the construction sector: A review, Renewable and Sustainable Energy review, 26, 379-388.

Nath P., Sarker P.K., Biswas W.K., 2018, Effect of fly ash on the service life, carbon footprint and embodied energy of high strength concrete in the marine environment, Energy and Buildings, 158, 1694-1702.

Nemet A., Klemeš J.J., Kravanja Z., 2018, GHG emissions reduction by improving efficiency of utilities’ transport and use and cross-sectorial energy integration, Chemical Engineering Transactions, 63, 19-24.

NHSC, 2011, The key findings of 2011, The state of supply report, the Australian government. National Housing Supply Council, Australia, <https://treasury.gov.au/programs-initiatives-consumers-community/the-national-housing-supply-council/> accessed 13.05.2018.

Pelzeter A., 2007, Building Optimization with Life Cycle Costs- the Influence of Calculation Methods, Journal of Facilities Management, 5 (2), 115-128.

Rafieizonooz M., Salim M.R., Hussin M.H., Mirza J., Yunus S.M., Khankhaje E., 2017, Workability, compressive strength and leachability of coal ash concrete, Chemical Engineering Transactions, 56, 439-444.

Rauf A., Crawford H.C., 2013, The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia, Architectural Science Review, 56 (3), 252-261.

UNEP, 2012, Towards a Life Cycle Sustainability Assessment: Making informed choices on Products, United Nation environment Programme <https://www.lifecycleinitiative.org> accessed 01.07.2017.

APPENDIX-3: PAPER-3 + ESM

Janjua SY, Sarker PK, Biswas WK. Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings. Journal of Environmental Management. 2020, 264:110476. https://doi.org/10.1016/j.jenvman.2020.110476

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STATEMENT OF CONTRIBUTION

To Whom It May Concern,

I, Janjua SY, contributed to literature review, method formulation, survey development, result discussions, analysis and writing (80%) of the paper/publication entitled:

Janjua SY, Sarker PK, Biswas WK. Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings. Journal of Environmental Management. 2020, 264:110476. https://doi.org/10.1016/j.jenvman.2020.110476

The remaining 20% of this paper/ publication was contributed by A/Prof. Wahidul K. Biswas (10%) and A/Prof. Prabir K. Sarker (10%).

Signature: Date: 01 March 2021

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 01 March 2021

Co-author 2: A/Prof Prabir K. Sarker Date: 01 March 2021

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Author: Shahana Y. Janjua,Prabir K. Sarker,Wahidul K. Biswas

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Research article

Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings

Shahana Y. Janjua [a,*], Prabir K. Sarker [a], Wahidul K. Biswas [b]

[a] School of Civil and Mechanical Engineering, Curtin University, Perth, 6102, Australia
[b] Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Perth, 6102, Australia

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ABSTRACT

The growth of the building sector represents the progress of civilizations. There are environmental, social and economic implications, impeding the sustainability performance of buildings. A holistic life cycle sustainability assessment (LCSA) framework is inevitable to address the integrated sustainability performance of residential buildings. This paper aims to develop triple bottom line indicators to assess the sustainability performance of buildings, including sustainability objectives, impact categories and key performance indicators (KPIs) to implement in the life cycle sustainability assessment framework. The indicators have been developed through the consensus survey involving area experts from four key stakeholders' categories including, government and Engineers Australia, academia, practitioners, and structural engineers. A list of KPIs was compiled through a literature review, followed by an online census survey to collect feedback from the participants in terms of relevance and importance of initally selected KPIs. Secondly, a modified list of triple bottom line (TBL) KPIs and their weights was developed based on respondents' feedback. Finally, the threshold values were assigned to the selected KPIs and the LCSA framework was tested using a hypothetical case study. The LCSA framework using these scientifically valid KPIs would assist stakeholders to assess the sustainability performance of residential buildings and to identify the hotspots for proposing well-informed industry strategies in Western Australia.

1. Introduction

Sustainability is the goal that endeavors to attain a true balance between the environmental, social and economic objectives at local, national, regional, and global levels (UN, 2015a). People greatly influence sustainable development, as their activities cause environmental consequences and social inequity (Brundtland, 1987). The building industry plays an important role in the economic and social development of a nation (Ofori, 2006). For achieving these two pillars of sustainability, building construction activity makes extensive use of natural resources, energy, and water (Akadiri et al., 2012).

The design of a sustainable residential building thus also needs to consider the dignity and wellbeing of a family without compromising environmental and economic impacts (Ahmad and Thaheem, 2017). The efforts for a well designed, sustainable residential building require creating harmony between the environment, social and economic pillars of sustainability rather than a trade-off between TBL sustainability objectives. Along with structural and aesthetical criteria, occupants' comfort and expectations, environmental impacts, and economic pressures are to be taken into consideration in order to achieve sustainable building design (Cuéllar-Franca, 2012).

The construction industry is using 36% of global energy, producing 25% GHG emissions (UNEP, 2018), and responsible for 30% solid wastes and 20% of global freshwater consumption (UNEP, 2006). On the other hand, the building and construction sector has increasingly become the heart of economic development, providing 5–10% of employment, and

Abbreviations: **ABS**, Australian Bureau of statistics; **ALCAS**, Australian life cycle assessment society; **AUD**, Australian dollar; **BCA**, Building codes of Australia; **BCR**, Benefit-cost ratio; **BI**, Biodiversity Integrity index; **C&D**, Construction and demolition; **CED**, Cumulative energy demand; **CFEC**, Cumulative fossil energy consumption; **CO_2 eq**, Carbon dioxide equivalent; **E**, Environmental; **EC**, Economic; **ESL**, Estimated service life; **GHG**, Greenhouse gases; **GJ**, Gigajoules; **Ha_a**, Annual hectare; **IPEEC**, International Partnership for Energy Efficiency Cooperation; **ISO**, International standards organization; **kl**, Kilolitre; **km**, Kilometer; **KPI**, Key Performance Indicator; **LCSA**, Life cycle sustainability assessment; **PO_4 eq**, Phosphate equivalent; **S**, Social; **SL**, Service life; **SO_2 eq**, Sulphur dioxide equivalent; **STC**, Sound transmission class; **TBL**, Triple bottom line; **TS**, Technical specification; **UNEP**, United Nations Environment Program; **WWF**, Word Wide Fund for Nature.

* Corresponding author.
E-mail address: s.janjua@postgrad.curtin.edu.au (S.Y. Janjua).

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5–15% of national GDP world-wide (UNEP, 2006). Building and construction industry in Australia is growing at an alarming rate due to rapid urbanization (ABS, 2019; ABS, 2018). Buildings account for 59% of Australian construction activity and residential buildings are 65% of total buildings constructed per year (ABS, 2019). Being accounted for the major portion of the construction industry, the buildings have great potential to reduce the environmental impacts in a short period by using sustainable materials with reduced embodied energy consumption and increased service life (CCC, 2013). This sharp reduction of environmental impacts by the building sector could enhance inter-generational social equity through resource conservations.

Life cycle sustainability assessment (LCSA) is an emerging sustainability assessment tool to investigate the environmental, social and economic performance of a building throughout its lifespan. Until now, a few studies have used LCSA to assess building sustainability (Janjua et al., 2019a). Dong and Ng (2016) proposed a LCSA framework involving the environmental, social and economic assessment of buildings considering only cradle to gate stages. Onat et al. (2014), proposed an integrated input/output hybrid Life cycle assessment model utilizing generic data for buildings for quantitative assessment. Hossaini et al. (2015), came up with an analytic hierarchy process based sustainability framework of buildings of 60 years lifespan, with a limited focus on social implications. Kamali et al. (2018), proposed a TBL sustainability framework for modular buildings but assessed only environmental performance. Balasbaneh et al. (2018), studied the TBL sustainability performance of hybrid timber buildings of 50 years of service life and found the manufacturing stage as the hotspot. None of the above studies have considered the variation in building and building components' service life which in fact has a significant bearing on sustainability assessment of buildings (Janjua et al., 2019b). The TBL indicator selection in the existing literature was based on literature review, without involving stakeholders and region-specific variations. A comprehensive framework considering inter-disciplinary research and stakeholder involvement along with region-specific KPIs could be useful to evaluate the life cycle sustainability of residential buildings, as recently developed by the authors (Janjua et al., 2019a).

Janjua et al. (2019c), developed a comprehensive framework for the TBL sustainability assessment of residential buildings, considering the impact of estimated service life. The proposed framework was based on a multi-criteria hierarchical analysis using a top-down approach to assess the TBL objectives of sustainability. The TBL objectives of sustainability were divided into TBL impact categories, where each impact category was determined by aggregating a set of indicators (hereafter named as key performance indicators or KPIs). KPIs are the smallest units for sustainability assessment (Fig. 1). The impact of each KPI was divided by the estimated service life of building to acquire the per annum impact of KPIs. This framework was tested using a hypothetical example and indicators derived from the available literature. These KPIs have yet to be developed for successfully implementing the framework (Lim and Biswas, 2018). Though the proposed framework (Janjua et al., 2019c) was capable to overcome shortcomings of existing LCSA frameworks, a scientific approach to select the KPIs was deemed necessary.

This paper thus aims to develop KPIs for TBL sustainability assessment in a methodical manner specifically for assessing Australian buildings. Firstly, a rigorous literature review was conducted to compile a primary list of TBL KPIs for residential buildings. Secondly, an expert survey was conducted to finalize the selection of KPIs in a scientific manner through a participatory approach involving key experts in this area. Thirdly, the weight of each KPI was determined, based on the level of importance of these indicators provided by the same experts during the same survey. Finally, the threshold or optimum values of KPIs were assigned through a comprehensive literature review of documents on the sustainability of buildings in order to determine the sustainability gap. The gap means the level of effort which is required to meet the target achieving sustainable residential building design outcomes.

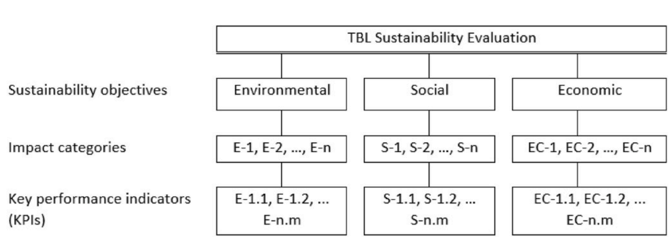

Fig. 1. Hierarchy of TBL sustainability evaluation (Janjua et al., 2019c); E−environmental; S- Social; EC- Economic.

2. Methodology

The selection and development of TBL Sustainability key performance indicators (KPIs) were carried out systematically in two main steps; 1) Primary selection of TBL sustainability KPIs, 2) Final selection of KPIs, as explained below:

2.1. Primary selection of TBL sustainability KPIs

Sustainability performance of conventional and alternative building options is measured against TBL objectives. In LCSA studies, TBL objectives are classified in terms of impact categories to assess sustainability objectives. Each impact category consists of a set of key performance indicators (KPIs), which is the smallest unit, for measuring TBL objectives. A primary list of impact categories and KPIs (Table 1) in this study were selected on the basis of existing national and international literature, sustainability standards, government report, and Best Practice Guide to life cycle impact assessment by Australian life cycle assessment society (ALCAS).

2.1.1. KPIs for environmental impact categories

The selection of Environmental KPIs was based on Brundtland's definition (Brundtland, 1987) on sustainable development, which is to meet the needs of the present generation by conserving the natural resources for the future generation to meet their needs. The environmental consequences of human intervention to the natural system degradation are; 1) energy and climate change, 2) loss of biodiversity, 3) pollution and soil erosion and 4) water stress (Brundtland, 1987; Greene, 1994; BBC, 2004; Lawn, 2006; Roosa, 2008). The associated impact categories resulting from these consequences are GHG emissions, abiotic and biotic resource depletion, energy intensity, ecological footprint, land use transformation, acidification, eutrophication, waste generation, deforestation, and water scarcity. Of these environmental impact categories, E−1) Climate change, E−2) Air quality, E−3) Water quality, E−4) Ecological footprint, E−5) Water scarcity, E−6) Energy, E−7) Abiotic Resource depletion, and E−8) Waste generation are relevant to buildings (Bragança et al., 2010).

2.1.1.1. E−1: Climate change. It is the impact category that quantifies the anthropogenic emissions on radioactive forcing of the atmosphere resulting in temperature rise, damage to the natural environment and human health. Australia is producing annual GHG emissions of 538MtCO_2-e (DOEE, 2019a) and Western Australia alone is responsible for 16.6% of these emissions (DOEE, 2019b). The construction industry is contributing 23% of the total GHG emissions of Australia, of which 55% originates from the building sector (ABS, 2018). Commonly accounted for GHGs include Carbon dioxide, methane, and nitrous oxides. KPI-*Carbon footprint* is used to measure the accumulated effect of these GHGs in terms of kg CO_2 eq/m^2/year.

2.1.1.2. E−2: Air quality. The air quality is deteriorated by the acidifying emissions (NO_x and SO_x) released from the power and transport

Table 1
Primary selection of TBL Sustainability Key Performance Indicators.

Sustainability Objectives		Impact Categories		KPIs	Unit
Environmental	E−1	Climate change	E−1.1	Carbon footprint	kg CO_2 eq/m^2/year
	E−2	Air quality	E−2.1	Acidification	kg SO_2 eq/m^2/year
	E−3	Water quality	E−3.1	Eutrophication	kg PO_4 eq/m^2/year
	E−4	Ecological footprint	E−4.1	Land use	Ha_a/m^2/year
	E−5	Water scarcity	E−5.1	Cumulative embodied water consumption	kl/m^2/year
	E−6	Energy	E−6.1	Cumulative energy demand	GJ/m^2/year
	E−7	Abiotic resource depletion	E−7.1	Cumulative fossil energy consumption	GJ/m^2/year
	E−8	Waste generation	E−8.1	C&D waste	tonnes/m^2/year
Social	S-1	Intra-generational equity	S-1.1	House affordability	AUD/m^2/year
			S-1.2	Indoor living conditions	AUD/m^2/year
			S-1.3	Thermal comfort	AUD/m^2/year
	S-2	Inter- generational equity	S-2.1	Energy conservation	%/m^2/year
Economic	EC-1	Users perspective	EC-1.1	Life cycle costs	AUD/m^2/year
			EC-1.2	Potential savings	AUD/m^2/year
			EC-1.3	Benefit cost ratio	BCR
	EC-2	Developer perspective	EC-2.1	Net benefit	%/m^2/year
			EC-2.2	Carbon tax saving	%/m^2/year

sectors. In Australia, 85% of the power is generated by using non-renewable resources (61% coal+ 21% natural gas+ 2% oil+ 6% renewable sources) (DOEE, 2018a; DOEE, 2018b). Power used during extraction and manufacturing of building materials, construction of the building, use stage and post-use stage is produced by coal-burning resulting in the production of Nitrogen (NOx) and Sulphur (SOx), ultimately impacting natural environment and human health. KPI- *Acidification*, is thus, the indicator to measure the air quality in terms of kg SO_2 eq/m^2/year.

2.1.1.3. Water quality. Macro-nutrients like nitrogen (N), phosphorus (P) and organic compounds (BOD^2), released due to agricultural, industrial processes and fuel combustion due to electricity generation and transportation, deteriorate water quality by eutrophying water bodies. All these processes are directly or indirectly related to buildings' life cycle from building material production, transportation to site and power use in construction, use, and post-use stages. Australian rivers receive approximately 141,000 tonnes of nitrogen and 19,000 tonnes of phosphorous annually (WWF, 2019a), destroying water quality, resulting in eutrophication. KPI-*Eutrophication* is thus considered as an indicator, which captures the impacts including accelerated algal growth, oxygen depletion and reduced sunlight penetration in water bodies resulting from the processes carried out within the system boundaries of buildings.

2.1.1.4. Ecological footprint. Deforestation leads to the loss of biodiversity, climate change, and soil infertility. Australia is identified as one of the top ten countries worldwide listed as global deforestation hotspots (WWF, 2019a). The upstream processes in building construction including mining of raw materials, industrialization, commercial plantation, and urban sprawl are the major contributing factors to deforestation (WWF, 2019b). The ecological footprint is the impact of human activities determined in terms of conversion of biologically productive land to commercial use. KPI-*Land use* is the aggregated land occupation for all processes within the system boundaries of buildings measured in Ha_a/m^2/year. It is a pre-curser of potential environmental impacts related to land use rather than just land occupation.

2.1.1.5. Water scarcity. Australia is the driest human-inhabited continent (Sawe, 2018). Water is the precious commodity for Australia and water scarcity is controlled by expensive and energy-consuming desalination of seawater (Radcliffe, 2018; Fenton and Gerofi, 1981). Buildings consume 20% of global water consumption, directly or indirectly in the form of embodied water in building materials, construction process, embodied water in the production of fuel and electricity being used in material transportation, construction, use and post-use stages (McCormack et al., 2007). KPI-*Cumulative embodied water consumption* is the summation of water consumption by all processes in the system boundary of buildings and helps identify and reduce water scarcity by using renewable resources.

2.1.1.6. Energy. Energy is consumed during the product's lifecycle, through processes the product undergoes. This energy includes non-renewable (fossil, nuclear) and/or renewable energy (wind, hydro, solar, biomass, geothermal). Building and construction industry consumes 36% of the global energy (UNEP, 2018). KPI, *Cumulative energy demand,* is the total energy absorbed by the building directly or indirectly in its entire lifespan (pre-use, use, post-use), and is measured in GJ/m^2/year. This KPI is an indirect measure of the total impacts (global warming, biotic/abiotic resource depletion) on earth due to the production of the energy required by the building.

2.1.1.7. Abiotic resources. Abiotic resources are created from incomplete oxidization of organic matter by chemical reactions over hundreds of millions of years. These resources are depleting faster than the rate of regeneration, such as oil, natural gas, and coal. Australia's annual fossil fuel consumption is 93.84% (5767.3 PJ) of total energy consumption (DOEE, 2018b). The building sector's consumption of fossil energy is approximately 82% of the final energy consumption (UNEP, 2018). In addition, fossil fuel energy consumption causes impacts on natural resources, natural environment, and human health. *Cumulative fossil energy consumption* is another relative KPI that represents the total fossil fuels consumed within the system boundaries of building in GJ/m^2/year.

2.1.1.8. Waste generation. Waste generation is the quantity of materials and/or products entering waste stream before further processing like composting, incineration, landfilling, re-use, or recycling (DOEE, 2012). The construction industry contributes 38% of the waste generated in Australia, with 67% recycled and 33% disposed to landfill (Pickin et al., 2018). KPI-*C&D Waste* is the pre-curser of the potential impacts of waste deposited towards the environment and measured in tonnes/m^2/year.

2.1.2. KPIs for social impact categories

As stated in Brundtland's report (Brundtland, 1987), sustainable development is underpinned by two elementary assumptions of equity, which are fairness and justice; 1) within a generation (i.e., intra-generational) and 2) across the generations (i.e., inter-generational). Intra-generational equity and inter-generational equity are considered in this study to assess the social objectives of sustainability.

2.1.2.1. Intra-generational equity. Intra-generational equity is the fair utilization of global resources among human beings of the same generation. The shelter is the basic need of all humans and it should be affordable by the low-income people. However, due to increased pressure on developers to build low energy-intensive buildings, the prices of houses increase, sometimes, making it difficult for the general public to buy houses and also increasing reliance on the mortgage. Also, there are maintenance costs of the house to achieve a liveable standard. The maintenance cost and energy utilization depend on the building materials. If an environmentally friendly material is used, the building will have thermal resistance and lower energy consumption to attain a liveable Indoor thermal environment. Similarly, these materials should require lower maintenance and repair or replacement activities, thus decreasing maintenance costs. *House affordability, indoor living conditions,* and *thermal comfort* are selected as KPIs to measure the social sustainability of building with reference to the median gross household income of a country (AHURI, 2016; Ofori, 2001; Nance, 2013).

2.1.2.2. Inter-generational equity. Inter-generational equity identifies the equality of opportunities to be benefitted by natural resources across the generations. Inter-generational equity asks for a balance between the production and utilization of natural resources to a good extent, which is a very concerning issue due to the growing degradation of the natural environment and resource depletion. KPI-*Energy conservation* is an indicator to measure the amount of energy conserved for future generations due to the selection of energy-efficient building materials (Barthel et al., 2005; Hunkeler, 2006; Biswas and Cooling, 2013; Dreyer et al., 2006).

2.1.3. Economic impact categories and KPIs

The economic sustainability objective of residential buildings mainly includes economic prosperity and capital investment (ISO, 2006). The economic implications of a building can be analyzed from both developer and user perspectives (Vale et al., 2017).

2.1.3.1. User perspective. The user perspective is assessing a building through a user point of view in terms of life cycle costs, potential savings (low maintenance and energy cost), secure and beneficial investment. The users are those who bear the costs of owning a building and experience either benefits or losses due to the use of the building. Economic sustainability is achieved by recovering investment through savings during use in a short period of time. Three *KPIs, life cycle costs, potential savings, and benefit-cost ratio are* used in this study to assess the economic impacts of buildings from the user perspective.

- KPI-*Life cycle cost* is the estimation of the total cost of a house for all LCA stages including material, labor, transportation, energy, and machinery to compare alternative investment options. It takes into account the variation in costs of materials, transportation, and operational energy and construction methods of different building specifications in this research (Wong et al., 2010; Sherif and Kolarik, 1981; Gluch and Baumann, 2004).
- KPI- *Potential savings* is the money saved during the use stage due to the consideration of efficient building materials and end-use appliances. It also justifies the basis for selecting high capital cost options to ultimately obtain long term economic benefits. It thus represents the probabilities for a lower payback period of a building (ISO, 2006).
- KPI- *Benefit-cost ratio (BCR),* indicates the effectiveness of investments in different types of buildings (Fernández-Membrive et al., 2015; Araújo et al., 2016). A house is a big investment from the user perspective, thus a BCR will identify the option enabling a significant return to recover the investment cost quickly.

2.1.3.2. Developer perspective. A developer is a person/group of people or organizations, who buys raw land, obtain approvals, prepare the land for building construction and sell buildings. Business continuity and resilience determine the economic sustainability of a business. Two KPIs, *Net Benefit* and *Carbon Tax* savings are used to assess the economic benefits from the developer perspective.

- KPI-*Net Benefit* is the estimated benefit from an investment, resulting from cost difference between conventional and alternative buildings, to sustain and continue construction business.
- KPI-*Carbon Tax saving* is the benefit of reduced carbon footprint resulting from the use of sustainable materials in buildings in terms of monetary values. In 2011, the Australian government introduced a clean energy act (COFA, 2011) to implement a carbon tax of $23 per tonne of CO_2 eq emissions on 500 biggest fossil energy consumers with a plan for tax rate increasing on yearly basis (COFA, 2011). Though the tax was suspended in July 2014, it reduced the carbon footprint dramatically in 2013 by 17 million tonnes (Milman, 2014), a record in 24 years. Whilst carbon tax is not currently applied in Australia, it is incorporated to capture the economic benefits associated with the use of environmentally friendly materials by the building industry.

2.2. Final selection of KPIs

A structured method has been adopted to select the aforementioned KPIs for the sustainability assessment of residential buildings. The development of KPIs involved the final selection of KPIs based on expert's opinions, ascertain their weights and threshold values. The research methodology consisted of the following eight steps;

2.2.1. Questionnaire design and development

An online questionnaire, using Google forms, was developed to conduct a consensus survey to gather the feedback of the stakeholders of building industries. The purpose of the questionnaire was to collect the expert's response within building industries about relevancy and importance of the KPIs discussed in the previous section (Table 1). The questionnaire also had a provision for respondents to suggest additional KPIs. The questionnaire was divided into three sections, each representing one sustainability objective.

The **first part** of each section consisted of three questions:

Question I: The respondent had to appraise the relevance of KPIs as relevant or not-relevant. If they were unsure, they had the option to tick the no-comments box in order to avoid either overtly or misjudgment.

Question II: If the respondent ticked the relevant box, then they had to tick one of the following boxes, in order to assess the level of importance.

- Somewhat important
- Least important
- Important
- Most important

Question III: If the respondent had ticked the not-relevant box, the next task for him/her was to provide reasoning in order for researchers to consider his/her opinion.

The **second part** of each section for TBL objectives consisted of the following three questions:

Question I: The respondent was given a provision to suggest KPI(s), which he/she thought worth incorporating.

Question II: The respondent had to provide reasoning for suggesting any KPIs.

Question III: The respondent suggesting additional KPIs had to rank the importance of each suggested KPI.

2.2.2. Pre-testing of online survey

After designing, the online questionnaire was pre-tested by sending it to a few colleagues, to identify the mistakes, to check its usability, complexity, and clarity for effective information collection. Once the pre-test has been successfully performed, the online survey link was sent to the potential participants.

2.2.3. Development of stakeholders' categories

For any consensus survey, it is a must to identify the right participants, who have sound knowledge, research track records and practical experience, and decision-making role and judgment authority in this field to some extent, in order to provide credible and enthusiastic responses (Linstone and Turroff, 1975). While selecting stakeholders for this survey, it was taken into account that the potential participants have knowledge, practical experience and judgment capacity in the field of building sustainability of Australia (UNEP, 2009). Australian Life Cycle Assessment Society (ALCAS) for the building industries, Engineers involved in structural engineering design and recognized bodies capable of influencing decisions and the local practitioners and researchers based on their published articles, were approached to find four broad categories of key stakeholders, including; 1) Government and Engineers Australia, 2) Academia, 3) Practitioners, and 4) Structural Engineers. These stakeholders perform a specific role with a distinctive perception of the building industry. A brief description of each stakeholder category is given in Table 2.

2.2.4. Participant selection for online survey

A contact list of 60 potential participants for stakeholder categories was selected with substantial expertise and contribution to Australian building industries. The list also allowed the breakdown of respondents into four equal numbers of stakeholders in order to obtain balanced responses. Following ethics approval from Curtin University, potential participants were emailed to participate in the survey. Of these listed participants, 46 initially agreed to participate in the online survey on a voluntary basis. After receiving the required number of responses, authors considered 40 responses in a way that each of 4 categories of area experts had an equal number of respondents (i.e. 10) to avoid biasness and to attain a balance of opinions. The online questionnaire link was then emailed to these participants. In the same email, the approved participant information sheet that shows the nature of the project and confidentiality aspects of information management by Ethics, Curtin Research Office was attached.

Table 2
Categories of stakeholders.

No.	Category	Type of participants	Background
1	Government and Engineers Australia	Officers, regulators of the Australian government departments and Engineers Australia.	Government officers/ regulators involved in policymaking, regulation and standard compliance related to building construction and the representatives of Engineers Australia who are directly involved in influencing the changes in policies and the code of conduct.
2	Academia	Researchers from Australian universities	Researchers researching and teaching engineering sustainability, built environment and green buildings.
3	Practitioners	Owners/Chief Executive Officers/Managers of consulting firms/ industries	Practitioners who are mostly involved in Life Cycle assessment, sustainable buildings, consulting and implementation of a sustainable project.
4	Structural Engineers	Chartered Professional Structural Engineers	Structural engineers those who are involved in implementing sustainable strategies in the design stage of the building and innovative structural design and new materials to build sustainable buildings.

2.2.5. Data collection from survey response

The whole process of the online survey took about three and a half months (January to April 2019). Potential participants from each stakeholder category were contacted in early January 2019 through email and telephone to know their interest to participate in an online survey. Weekly reminders were sent for three weeks and even direct phone contact was made to expedite the response collection. Once the participants had completed the survey, the response collected from the participants was deliberately managed to (25% for each category) to avoid partiality and imparity of results. Survey respondents were categorized and coded, keeping the individual identity confidential as per Curtin's human ethics requirements.

2.2.6. Analysis of survey responses

The responses of forty participants were then compiled to determine the level of relevance (Table A-1) and acceptance for each KPI (Table A-2).

The outcomes of the survey in the form of the relevance of KPIs are presented in Fig. 2:

- All KPIs were accepted as 89% of the respondents considered them as relevant. Only 9% of respondents considered 16 out of 17 KPIs as irrelevant and 2% of respondents did not comment on 9 KPIs.
- All environmental indicators except KPI- *Cumulative energy demand* found to be relevant by more than 90% of the respondents. KPI- *Carbon footprint* was found relevant by all respondents. KPI- *Cumulative energy demand* is considered irrelevant by 15% of respondents mainly from Practitioners and Government categories, advocating that this indicator does not necessarily take into account energy mixes (solar or coal). Despite this, authors and others (Huijbregts et al., 2006; Frischknecht et al., 2015) recognized this KPI as an important indicator from the building efficiency and energy management point of view.
- All social sustainability indicators were found relevant by more than 80% of the respondents. KPI- *House affordability* was considered irrelevant by 18% of respondents from Academia and Practitioner categories, due to the fact that the Australian present home loan situation has made houses more affordable than in the previous years. However, the authors could not ignore this KPI as government policies change over time.
- Economic sustainability indicators were found relevant by more than 75% of respondents. KPI- *Life cycle cost* was considered relevant by 97.5% of respondents. KPI- *Net benefit* was considered irrelevant by 17.5% of respondents from Practitioners and Government regulators while 7% of respondents from Academia and Structural engineers did not comment on this particular KPI. Some respondents (5%) suggested merging KPI- *Net benefit* with the KPI- *Benefit-cost ratio.* Authors have considered both KPIs independently in order to capture the benefits of energy savings associated with the use of green/ smart building materials. KPI- *Carbon tax saving* was considered irrelevant by only 17.5% of respondents from Practitioners, Government and Academia, due to the fact that the carbon tax was abolished in Australia in 2014 and 7% of respondents from Practitioners and Structural engineers did not comment on this KPI. However, authors have considered this KPI to determine cost savings associated with the design of energy-efficient buildings in a carbon-constrained economy.
- All KPIs were found 'important' by the two-third of participants. The environmental KPIs were considered as important by 93% of respondents and social KPIs by 89% of respondents (Fig. 3). Economic KPIs were not considered important by as many as participants who

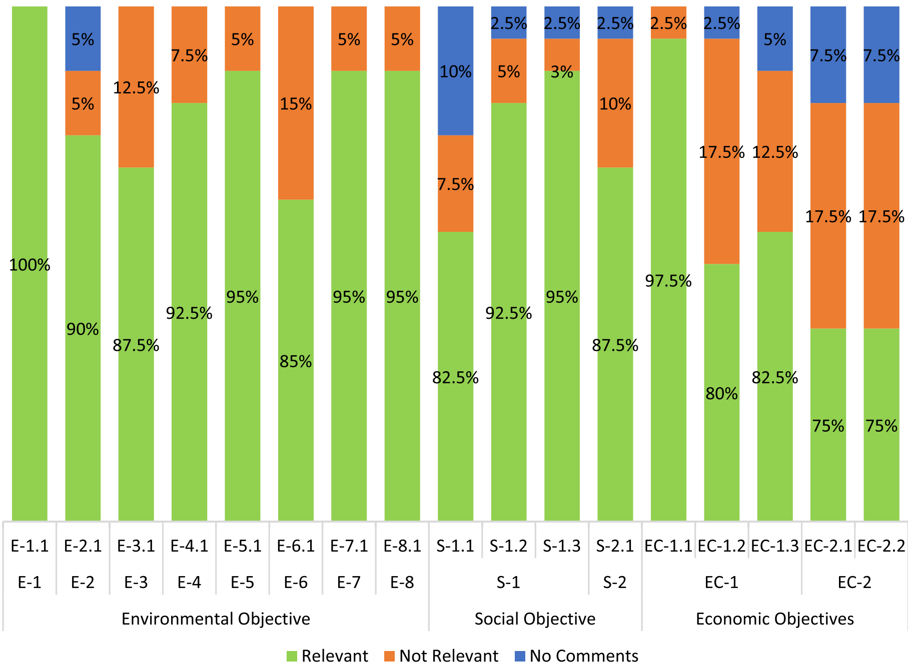

Fig. 2. Level of relevance for TBL KPIs (E−1 Climate change; E−2 Air quality; E−3 Water quality; E−4 Ecological footprint; E−5 Water scarcity; E−6 Energy; E−7 Abiotic resource depletion; E−8 Waste generation; S-1 Intra-generational equity; S-2 Inter-generational equity; EC-1 User perspective; EC-2 Developer perspective; E−1.1 Carbon footprint; E−2.1 Acidification; E−3.1 Eutrophication; E−4.1 Land use; E−5.1 Cumulative embodied water consumption; E−6.1 Cumulative energy demand; E−7.1 Cumulative fossil energy consumption; E−8.1 C&D waste; ; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving).

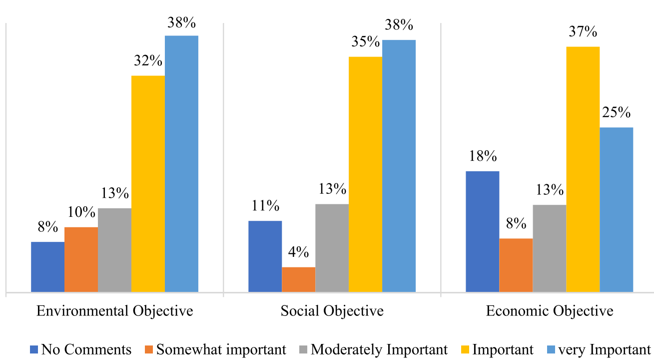

Fig. 3. Level of importance for TBL Objectives for Building Sustainability.

found environmental KPIs are important. It is mainly because the environmental problems (deforestation, GHG emissions, etc.) are arising due to rapid economic and population growth in Australia, thus it is challenging national commitments to climate changes and energy security issues (UN, 2015b).

2.2.7. *Additional indicators proposed by the participants*

About more than half of the respondents (i.e., 21) proposed the inclusion of 16 new KPIs, including adaptability of building, sustainable materials, recycling, and re-use, aesthetics, biodiversity, eco-toxicity, resource depletion, noise pollution, site selection, indoor environmental quality, community/stakeholder input, social equity, occupancy, teleworking space, social inclusion, circulatory indicator, water efficiency rating, population density, size of home, water-wise landscaping, job creation, employee training and lifecycle contribution to local economy.

After careful review of participants' feedback, the authors provided justification and reasoning for acceptance or rejection of these new indicators (Table A-3). Five of these suggested KPIs (recycling potential, loss of biodiversity, resilience and adaptation, noise, local material sourcing) were included for assessment. However, most of them were not considered due to the following reasons;

- Overlapping with existing KPIs i.e., Cumulative embodied water consumption, land use
- Way too broad i.e., shared amenity facility, modern slavery
- Beyond the scope of the proposed study i.e., adaptability, aesthetics, and color selection
- More like of strategies than indicators i.e., water efficiency rating
- Presentation of objectives of the study (sustainable materials)

2.2.8. *Final list of TBL key performance indicators*

The KPIs for the final list were selected based on the following criteria (Lim and Biswas, 2018);

1. The KPIs were accepted by more than 50% of respondents.
2. The additional KPIs proposed by respondents were;
   a. Not overlapped with existing KPIs and.
   b. Aligned with the objectives and scope of this study

Interestingly, all KPIs that were primarily selected were considered relevant by more than 75% of respondents and so were chosen as KPIs for assessing the sustainability performance of residential buildings (Table 3). Three environmental KPIs (*recycling potential* in impact category-waste generation, *loss of biodiversity* in impact category-ecological footprint; and *resilience and adaptation* in impact category-climate change), two social KPIs (*noise* and *local material sourcing* under intra-generational equity category) were selected from the KPIs proposed by the respondents, as these were not overlapping with existing KPIs and were aligned with the objectives and scope of the study (Table A-3). The revised list consists of 22 KPIs given in Table 3.

2.2.9. *Weighting of TBL sustainability key performance indicators*

Once the list of KPIs has been finalized, the level of importance provided to each KPI by the respondents was used to calculate their weights using equation (1) (Janjua et al., 2019c).

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

where, N= Number of respondents.

Table 3
Final list of TBL KPIs for building sustainability.

Sustainability objective	Category code	Impact category	KPI code	KPI
Environmental objective	E−1	Climate change	E−1.1	Carbon footprint (kg CO_2 eq/m^2/year)
			E−1.2	Resilience and adaptation (year)
	E−2	Air quality	E−2.1	Acidification (kg SO_2eq/m^2/year)
	E−3	Water quality	E−3.1	Eutrophication (kg PO_4 eq/m^2/year)
	E−4	Ecological footprint	E−4.1	Land use (Ha_a/m^2/year)
			E−4.2	Loss of biodiversity (BI Index/m^2/year)
	E−5	Water scarcity	E−5.1	Cumulative embodied water consumption (kl/m^2/year)
	E−6	Energy	E−6.1	Cumulative energy demand (GJ/m^2/year)
	E−7	Abiotic resource depletion	E−7.1	Cumulative fossil energy consumption (GJ/m^2/year)
	E−8	Waste generation	E−8.1	C&D waste (tonnes/m^2/year)
			E−8.2	Recycling potential (%/m^2/year)
Social objective	S-1	Intra-generational equity	S-1.1	House affordability (AUD/m^2/year)
			S-1.2	Indoor living conditions (AUD/m^2/year)
			S-1.3	Thermal comfort (AUD/m^2/year)
			S-1.4	Noise (STC)
			S-1.5	Local material sourcing (km)
	S-2	Inter-generational equity	S-2.1	Energy conservation (%/m^2/year)
Economic objective	EC-1	User perspective	EC-1.1	Life cycle cost (AUD/m^2/year)
			EC-1.2	Potential savings (AUD/m^2/year)
			EC-1.3	Benefit-cost ratio
	EC-2	Developer perspective	EC-2.1	Net benefit (%/m^2/year)
			EC-2.2	Carbon tax saving (%/m^2/year)

R = 1, 2 … … … … … N, responses of respondents
i = I1, I2 … … …. In, indicators for social, economic and environmental aspects
S_{ri} = Score given by a respondent 'r' for an indicator 'i'.
S_i = Value of each score

The responses with no comments were excluded for calculating the weight of each KPI. The responses saying 'irrelevant' to particular KPI are given a score '0'. The responses with somewhat important, moderately important, important and most important responses for a particular KPI, were scored 2.5, 5, 7.5 and 10 respectively. The weight of each KPI was calculated using equation (1). The weights of KPIs listed under one category were then aggregated to determine the total weight of that impact category. The weights of the impact categories of each sustainability objective were then summed to determine the weight of overall sustainability (Table A-5). Table 4 presents the weight of KPIs, impact categories and objectives based on participant's feedback.

3. Threshold values of TBL sustainability KPIs

The threshold values ascertain the intended sustainability performance. It is the maximum value (i.e., 5) on a 5-point Likert scale, to indicate the best sustainability performance of KPIs. The threshold values of the KPIs were ascertained by reviewing existing case studies on building sustainability, international agreement (Paris agreement, International Partnership for Energy Efficiency Cooperation (IPEEC), etc.), sustainability guidelines and standards (ISO-12720, ISO/TS 21929–1, etc.), and government statistics and reports (ABS, WWF Australia, Department of Environment and Energy, ALCAS, etc.). Only the values that are considered environmentally and socio-economically sustainable from the Australia's context were selected as threshold values as this research focuses on the sustainability performance of Western Australia's buildings.

3.1. E−1.1: Carbon footprint

GHG emissions from Australian buildings vary between 13.4 and 46.708 kg CO_2 eq/m^2/year (Janjua et al., 2019b; Lawania and Biswas, 2018; Maddox and Nunn, 2003; Carre, 2011; Carre and Crossin, 2015). These studies differ from each other in terms of building material, operational stage energy consumption, and service life of the building, construction methods and locations. Operational energy contributes 80–95% of life cycle GHG emissions in an energy-intensive building. The selection of environmentally friendly building materials and heating and cooling systems can reduce energy consumption reducing the subsequent GHG emissions. The average value of GHG emissions (**30.05 kg CO_2 eq/m^2/year)** that is achievable in Australia was thus considered as the threshold value.

Table 4
Weight of KPIs/impact categories/sustainability objective for residential buildings.

KPIs	Total score	KPI weight	Impact category weight	Sustainability objective weight
E−1.1	352.5	0.0741	0.0777	0.5000
E−1.2	17.5	0.0037		
E−2.1	227.5	0.0478	0.0478	
E−3.1	215	0.0452	0.0452	
E−4.1	267.5	0.0562	0.0662	
E−4.2	47.5	0.0100		
E−5.1	297.5	0.0625	0.0625	
E−6.1	300	0.0630	0.0630	
E−7.1	310	0.0651	0.0651	
E−8.1	300	0.0630	0.0725	
E−8.2	45	0.0095		
S-1.1	250	0.0525	0.1822	0.2463
S-1.2	275	0.0578		
S-1.3	310	0.0651		
S-1.4	15	0.0032		
S-1.5	17.5	0.0037		
S-2.1	305	0.0641	0.0641	
EC-1.1	332.5	0.0699	0.1696	0.2537
EC-1.2	230	0.0483		
EC-1.3	245	0.0515		
EC-2.1	202.5	0.0425	0.0840	
EC-2.2	197.5	0.0415		
Total	4760	1.0000	1.0000	1.0000

Note: E−1.1 Carbon footprint; E−1.2 Resilience and adaptation; E−2.1 Acidification; E−3.1 Eutrophication; E−4.1 Land use; E−4.2 Loss of biodiversity; E−5.1 Cumulative embodied water consumption; E−6.1 Cumulative energy demand; E−7.1 Cumulative fossil energy consumption; E−8.1 C&D waste; E−8.2 Recycling potential; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving).

3.2. E−1.2: Resilience and adaptation

Building resilience and adaptation is directly affected by the durability of building materials. The durability of a building is measured by estimating the useful life of the building and building components during which building performs the expected service without extensive repairs or replacements of building components. Both Australian houses and the information gathered from the existing literature suggest that the life span varies between 30 and 100 years (Janjua et al., 2019b; Atmaca, 2016; Cabeza et al., 2014). Therefore, the maximum achievable SL of **100 years** is considered as the threshold value for a building to be resilient and adaptive to climate change.

3.3. E−2.1: Acidification

Acidification produced by a building varies largely with the use of different types of building materials (Ede et al., 2014). Malaysian study calculated that about 0.302 kg SO_2 eq/m^2/year of acidification impacts can result from a building made of reinforced concrete frame and clay bricks (Rashid et al., 2017). The studies in UK, France, and Slovakia found that the acidification impacts from a building vary between 0.021 and 0.138 kg SO_2 eq/m^2/year (Thiers and Peuportier, 2012; Cuéllar--Franca and Azapagic, 2012; Estokova et al., 2016). An Australian study estimated an acidification impact of 0.147–0.148 kg SO_2 eq/m^2/year can result from a residential building (Carre and Crossin, 2015). Based on these reviews, the threshold value of acidification impact,**0.021 kg SO_2 eq/m^2/year** is considered achievable value for Australia and similar economies.

3.4. E−3.1: Eutrophication

Eutrophication impacts from buildings mainly result from the release of nitrogen and phosphorus during the manufacturing processes of building materials. An Australian study (Carre and Crossin, 2015), estimated the Eutrophication potential of 0.04 kg PO_4 eq/m^2/year for a residential 7-star energy performance rated building. In another study considering, a 5- star energy performance rated for 5 single-story residential buildings in three different locations in Australia (Melbourne, Sydney, and Brisbane), the impact was found to vary between 0.004 and 0.011 kg PO_4 eq/m^2/year (Carre, 2011). The study has thus considered the lowest value of **0.004 kg PO_4 eq/m^2/year** as the threshold value.

3.5. E−4.1: Land use

Two Australian studies showed that the amount of land use during the building life cycle varies from 0.000114 to 0.00638 Ha_a/m^2/year (Janjua et al., 2019b; Carre, 2011). The lowest value of 0.000114 Ha_a/m^2/year was found for a building made of the steel frame, brick wall, and concrete slab flooring while complying with a 5-star energy performance rating (Carre, 2011). The land use of **0.000114 Ha_a/m^2/year** is thus used as the threshold value for buildings.

3.6. E−4.2: Loss of biodiversity

The biodiversity integrity (BI) index by Majer and Beeston (1996), provides a degree on the intactness of original species richness over particular land use. The conservation of land i.e., the proportion of land that was not disturbed was used to determine the biodiversity index (Biswas and Cooling, 2013). Based on the threshold value of KPI- *Land use*, the **Biodiversity integrity (BI) index for land use of 0.000114 Ha_a/m^2/year** is used as a threshold value of loss of biodiversity.

3.7. E−5.1: Cumulative embodied water consumption

The cumulative embodied water consumption by residential buildings which was estimated by Australian studies (McCormack et al., 2007; Carre, 2011) varies from 0.15 to 0.5 kl/m^2/year for 5-star energy performance residential buildings. The highest embodied water consumption was found for the building made of timber frame, timber/-weatherboard cladding and elevated timber flooring, in Brisbane, Australia. Whereas, the lowest embodied water was calculated for steel-framed brick-cladded buildings with elevated flooring in Sydney, Australia (Carre, 2011). This study has thus considered the lowest value of cumulative embodied water consumption (**0.15 kl/m^2/year**) as the Threshold value.

3.8. E−6.1: Cumulative energy demand (CED)

The cumulative energy demand (CED) of Western Australian buildings varies from 0.488 to 0.588 GJ/m^2/year (Lawania and Biswas, 2018) and between 0.744 and 0.891 GJ/m^2/year for Melbourne, Australia (Rauf and Crawford, 2013). Another Western Australian study found that CED varies from 0.4 to 0.42 GJ/m^2/year for houses (Janjua et al., 2019b). The CED of a 5-star energy performance rated houses in Melbourne was found to vary from 0.174 to 0.192 GJ/m^2/year (Carre, 2011). Based on these studies, the threshold value was considered to be **0.174 GJ/m^2/year**, as the value is achievable using sustainable materials in Australia.

3.9. E−7.1: Cumulative fossil energy consumption

Fossil fuel consumption in Australia was 93.38% in 2015 as compared to 81.5% for the US (WBG, 2019). These fuels accounted for 82% of the cumulative energy demand (CED) of buildings (UNEP, 2018). Cumulative fossil energy consumption of 5-star energy performance rated houses was found to vary from 0.165 to 0.185 GJ/m^2/year in Melbourne, from 0.063 to 0.081 GJ/m^2/year in Sydney and from 0.065 to 0.084 GJ/m^2/year in Brisbane Australia (Carre, 2011). Hence, **0.063 GJ/m^2/year** was thus considered as a threshold value for cumulative fossil energy consumption.

3.10. E−8.1: C&D waste

C&D waste resulting from construction, replacements, repairing during active life (use stage) of building and demolition of building ranges from 0.0191 to 0.0238 tonnes/m^2/year for single-story detached houses (Janjua et al., 2019b; Lawania, 2016). The threshold value was thus considered as **0.0191 tonnes/m^2/year** for C &D waste generated for a residential building.

3.11. E−8.2: Recycling potential

The C&D waste recovery in Australia was 20.4 Mt in 2016–17 and the recycling rate was 66.67% (Pickin et al., 2018). Different building materials have different recycling potentials ranging from 0 to 100% (DOEE, 2012). A Western Australian study showed a recycling potential of C&D waste between 55 and 75% (Cullen, 2014). Western Australia is committed to exceeding C&D recycling by 75% by 2020 (Pickin et al., 2018). The threshold value for the recycling potential of C&D waste is thus considered greater than **75%/m^2/year** as it is achievable using standard demolishing techniques.

3.12. S-1.1: House affordability

Using Australian median gross household income (AUD 1616 a week in 2015–16) and house affordability threshold (30% of median gross household income, AUD1616 × 30% = AUD 485 per week), AUD 25,220 (AUD 485 × 52 = AUD 25,220) has been estimated to be the maximum value that can be spent annually on house cost without hurdle (ABS, 2017; Thomas, 2016). The value of **AUD 25,220/year (103.573 AUD/m^2/year)** has thus been considered as a threshold value for house affordability in this study.

3.13. S-1.2: Indoor living conditions

It is the share of household income to be paid for services including maintenance and repair bills during the active service life of the building. The factors that influence the annual house maintenance cost are age, weather, use conditions, and location of the house. The equalized household disposal income (net income after tax deduction and social contribution divided per family of 4 members) is 853 AUD per week (ABS, 2017). This study has considered an average value of 5% of Australian equalized disposable household income (853 × 52 × 5% = 2218 **AUD/year;** 9.11 **AUD/m^2/year**) as threshold value over the lifespan of the building (Pant, 2019; Tepper, 2018).

3.14. S-1.3: Thermal comfort

The thermal comfort of a house is attained by spending money on achieving a comfortable indoor environment. The average annual energy cost over the last five years for a household of four family members is 3475 AUD/year (Synergy, 2019; Alinta, 2019). The energy prices had a tendency to increase on a yearly basis from 2 to 6% in the last five years. Therefore, an average annual energy cost of **3475 AUD/year (14.27 AUD/m^2/year),** is considered as threshold value over the SL of building.

3.15. S-1.4: Noise

Airborne and structure noise can be reduced or blocked by using building materials of high sound transmission class (STC). Building codes of Australia (BCA) specify the minimum sound reduction index of 50 that is equivalent to STC of 50 (ABCB, 2018). Therefore, the study has considered **50 STC** as the threshold value for building sustainability.

3.16. S-1.5: Local material sourcing

As per the US green building council (LEED, 2016), the building material is categorized as regional material, if extracted, harvested or recovered within 800 km of the project site. Green building council of Australia credit materials procured within Australia as local materials (GBCA, 2019). Being a vast piece of land, for material sourcing, each Australian state has its own buy local policy. Western Australia's Buy local policy, divides the state into three zones in terms of sourcing regionally available materials (WA, 2002):

- Zone 1- Perth region (with no prescribed distance limit)
- Zone 2- up to 200 km distance from the project site
- Zone 3- within 400 km of the project

A distance of 200 km for material sourcing from the construction site has thus considered as a threshold value for local material sourcing in this study.

3.17. S-2.1: Energy conservation

A Western Australian study on 54 residential buildings of alternative envelope materials found that an energy reduction of 17% can be achieved by using sustainable materials (Lawania, 2016). A study calculated CED saving of 9%, 19% and 18% in Melbourne, Sydney, and Brisbane respectively for five buildings made of different building materials (Carre, 2011). Another Melbourne study found that 16% of CED can be reduced by using alternative building materials (Rauf and Crawford, 2013). An average of **20% per year** reduction in CED, has thus considered an achievable threshold value to conserve energy.

3.18. EC-1.1: Life cycle cost

The life cycle cost of a residential building in Brisbane very from 20.69 to 24.26 USD/m^2/year (30.41–35.66 AUD/m^2/year) (Islam et al., 2014) and from 15.88 to 19.14 USD/m^2/year (23.41–28.14 AUD/m^2/year) for a detached house with 20 envelope options (Lawania and Biswas, 2016) in Western Australia. This LCC was further reduced by 7–9% after applying CPS (solar photovoltaic cells and solar water heater). These studies did not include the maintenance cost for case study buildings that increases the LCC considerably. Therefore, the lower value of life cycle cost (i.e., **AUD 28.04/m^2/year)** that included maintenance cost (i.e. 20%)**,** has thus consdered as a threshold value as it is achievable in Australia.

3.19. EC-1.2: Potential savings

Sustainable building materials could potentially reduce the maintenance and energy costs during the active life of the building by 19% (Janjua et al., 2019b). A similar level of reduction (i.e., 19%) was achieved by another Australian study (Lawania, 2016). This study has considered a potential saving of **0.4% energy cost per year** (20% reduction in energy cost for a building life of 50 years), as a threshold for residential building, because it is achievable in Australia.

3.20. EC-1.3: Benefit-cost ratio (BCR)

If a buildings' BCR is greater than one, the building yields a positive net present value and if less than 1.0, the cost outweighs the benefits and thus it is not worthy to consider an investment for this building option. Therefore, this study has considered a BCR value of more than **1.0** as a threshold value.

3.21. EC-2.1: Net benefit

The net benefit for a detached house in Australia ranges between 3 and 7% of revenue for developers (MBWA, 2014). It is a difference in capital costs between conventional and alternative buildings during the pre-use stage (mining, process, transport, and construction) over the service life of a building. The study has taken a conservative approach, thus considered **0.14% /m^2/year** (or **7% of revenue for a building with a 50-year life span)** of revenue as an achievable threshold value for net benefit.

3.22. EC-2.2: Carbon tax saving

A Western Australian case study presented a reduction of 8% carbon footprint by replacing clay brick with the cast in situ sandwich wall panels (Lawania and Biswas, 2017). In another Western Australia's study, a 19% reduction in carbon footprint was calculated for 54 buildings with varying alternative envelope options (Lawania, 2016). Similar level of carbon footprint reduction of 12%, 23%, and 22% was calculated by Carre A. (2011), for five buildings made of different materials in Melbourne, Sydney, and Brisbane respectively. **Twenty percent** carbon footprint saving in residential buildings has thus considered achievable in Australia and hence it is regarded as a threshold value.

4. Testing of LCSA framework and TBL indicators using a hypothetical case study

Key performance indicators (KPIs) developed in this study were tested through a LCSA framework (Janjua et al., 2019c), using hypothetical values for a conventional single-story building made of timber frame roof, brick wall and concrete slab footing in steps below:

The service life of main structural components including wall, roof, and footing was estimated using factor method (Equation (2)). The least value of the estimated service life (ESL) of structural components was considered as the ESL of the building(Janjua et al., 2019b).

$$ESL = RSL*A*B*C*D*E*F*G \tag{2}$$

Where, ESL is estimated service life, RSL is reference service life and factors A, B, C, D, E, F, and G stand for the quality of building components, design quality, work execution level, indoor environment conditions, outdoor environment, in-use conditions, and maintenance level.

ESL of the building was calculated to be 57 years (Table A-4). The replacement of building components in the active life of the building was not considered for the case study.

The position value 'P' of each KPI on the 5-point Likert scale for the case study buildings was calculated using equations (3a) and (3b) (Janjua et al., 2019c).

$$p_{low} = \frac{\text{Threshold value}}{\text{Calculated value}} \times 5 \tag{3a}$$

$$p_{high} = \frac{\text{Calculated value}}{\text{Threshold value}} \times 5 \tag{3b}$$

where the calculated values are hypothtical values considered for test case study. These calculated values in fact reflect the TBL implications of the building on the stakeholders in its supply chain, including developers, suppliers, builders and end-users.

If a lower value is good for the KPI such as carbon footprint, land use, etc., equation (3a) was used to calculate position value on the 5-point Likert scale. Similarly, for KPIs where 'higher is better', such as net benefit, recycling potential, etc., then equation (3b) was used to find the position value P.

Gap G, is the difference between position value and the threshold value of each KPI (Table A-6). The gap was multiplied by the corresponding weight of the KPI (Table 4) to determine the performance gap (weighted gap) of KPI. The values of calculated Gap G of KPIs for the case study buildings are presented in Fig. 4. The highest gap for a KPI identifies the hotspot requiring improvement.

The performance gap of KPIs in each category were summed up to determine the performance gap of the impact category. The performance gap of each impact category was then integrated into the performance gap of sustainability objectives and finally aggregated to the performance gaps of sustainability of the building. The overall sustainability score of the building was obtained by subtracting the performance gap of building from the highest possible sustainability score 5. The performance gaps of KPIs, Impact categories and sustainability objective are presented in Fig. 5. The overall sustainability score of the building (i.e., 5 - performace gap of the building) indicates the best-integrated life cycle sustainability performance for a building.

The overall sustainability score of the case study building was 2.3195 (i.e., 5–2.6805 = 2.3195), showing the below-average sustainability performance. The performance gaps for environmental, social and economic objectives were 1.506, 0.455 and 0.720, respectively. Whilst environmental objective has the highest performance gap among all of the sustainability objectives, indicating lowest sustainability performance, some KPIs require improvemental measures (i.e., solar water heaters, solar photovoltaic panels, etc.). The hotspots of the environmental objectives are C*arbon footprint, Acidification,* E*utrophication,* C*umulative fossil energy consumption,* and *C&D waste,* which have sustainability gaps (G = 5 - P) of 3.31, 3.52, 3.89, 3.94 and 4.91, respectively. The economic objective of sustainability has the second-highest performance gap, where KPI- *Potential savings* (0.2415) and *KPI- Carbon tax saving* (0.21) were identified as hotspots, due to the use of energy-intensive conventional building materials in the case study building.

The sustainability performance of social objectives was best with a score of 0.455. In social objectives, the KPI- *Thermal comfort* was identified as the social hotspot with a gap of 2.02 and a performance gap of 0.1316. The KPI- *Energy conservation* had the highest gap (5.00) and performance gap (0.3205), indicating the lowest sustainability performance, due to the use of conventional building materials with high

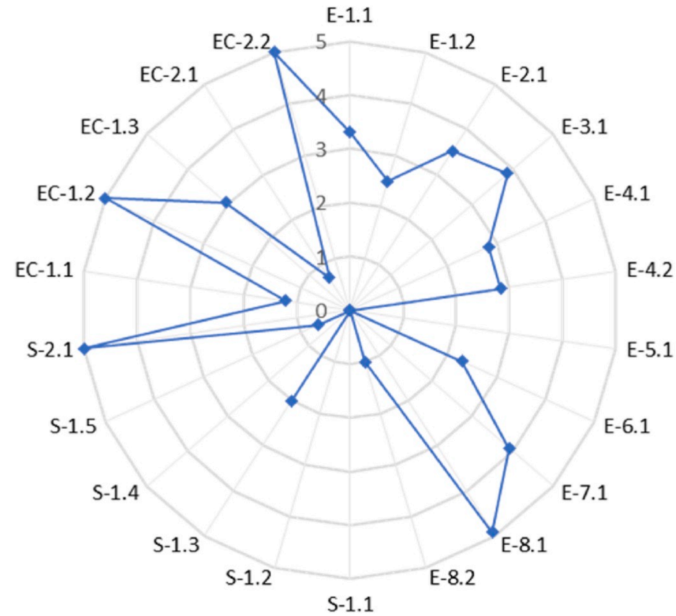

Fig. 4. Gap 'G' of KPIs on 5-point Likert Scale (E−1.1 Carbon footprint; E−1.2 Resilience and adaptation; E−2.1 Acidification; E−3.1 Eutrophication; E−4.1 Land use; E−4.2 Loss of biodiversity; E−5.1 Cumulative embodied water consumption; E−6.1 Cumulative energy demand; E−7.1 Cumulative fossil energy consumption; E−8.1 C&D waste; E−8.2 Recycling potential; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving).

energy demand. The KPIs- *House affordability, Indoor living conditions,* and *Noise* received the lowest performance gaps, presenting best sustainability performance, which has been due to;

- The lower interest rates on mortgage
- No replacement of building components were considered in hypothetical values
- Double brick wall building considered had high sound transmission class

5. Implication of LCSA framework

The calculation of performance gaps of KPIs, impact categories and sustainability objectives assists in the assessment of the sustainability performance of the building, by identifying the sustainability gap. The performance gaps of the building is calculated using weights of KPIs allocated by importance ranking of area experts with different background and therefore, enhance the credibility of this proposed LCSA framework. The feedback of the respondents in the development of TBL indicators strengthened the existing LCSA framework (Janjua et al., 2019c), by considering stakeholder involvement, region-specific weights for KPIs, segregation of sustainability performance into different levels i.e., KPI, impact categories and sustainability objectives. The overall performance gap of the building is the aggregation of all KPIs and no trade-off between TBL KPIs to represent strong sustainability is considered.

6. Limitation of LCSA framework

The initial selection of KPIs has been conceived from the literature review, however, the final list has been developed after conducting a census survey involving the area experts. The KPIs have been developed specifically for residential buildings of Australia. The relevance of these

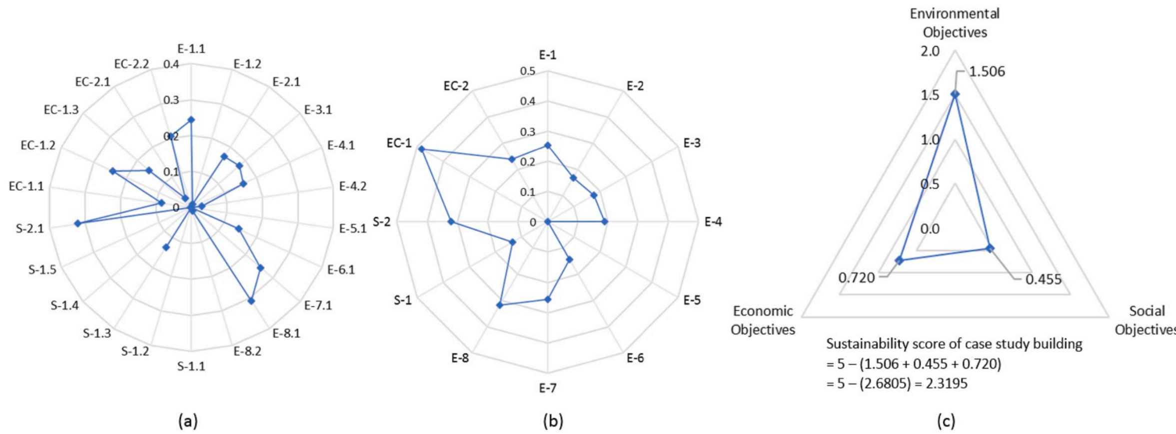

Fig. 5. (a) Performance gaps of KPIs = G × W; (b) Performance gaps of impact categories; (c) Performance gaps of sustainability objectives = ∑ G × W; (E−1 Climate change; E−2 Air quality; E−3 Water quality; E−4 Ecological footprint; E−5 Water scarcity; E−6 Energy; E−7 Abiotic resource depletion; E−8 Waste generation; S-1 Intra-generational equity; S-2 Inter-generational equity; EC-1 User perspective; EC-2 Developer perspective; E−1.1 Carbon footprint; E−1.2 Resilience and adaptation; E−2.1 Acidification; E−3.1 Eutrophication; E−4.1 Land use; E−4.2 Loss of biodiversity; E−5.1 Cumulative embodied water consumption; E−6.1 Cumulative energy demand; E−7.1 Cumulative fossil energy consumption; E−8.1 C&D waste; E−8.2 Recycling potential; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving).

KPIs may change over time as a result of potential changes in policies over time. The threshold values for KPIs are region-specific based on Australian legislation requirements, national statistics, international agreements, and published case studies. The same framework can be applied in other regions with revised weights of KPIs and revised threshold values. The threshold values are selected for the present scenario, however, the technological advancement in the future may change some of these threshold values especially for the environmental KPIs. The future aspect of the study could consider as to how the KPIs and threshold values will vary over time is beyond the scope of this research.

7. Conclusions

This paper presented the methodology to select and develop the KPIs for the TBL sustainability assessment of residential buildings applying a participatory approach. The survey involved the participation of experts from the building and construction industries of Australia in order to enhance the credibility and scientific acceptability of the selection of KPIs for the LCSA framework. The stakeholders directly or indirectly involved in the building sector were given a platform to provide their opinions through an online survey and to become a part of the selection process of KPIs as these stakeholders will ultimately be the beneficiaries of the proposed LCSA framework. The equal number of selected participants (10 out of 40) including Government and Engineers Australia, Academia, Practitioners, and Structural Engineers were involved in the selection of the TBL sustainability KPIs to assess the environmental, social and economic objectives of building sustainability performance in Australia's context. This paper is a follow-up work of the life cycle sustainability assessment framework to assess the residential buildings, initially developed by Janjua et al. (2019c), to develop TBL sustainability impact categories and key performance indicators list ascertained through a consensus survey.

Primarily 17 region-specific KPIs to assess the sustainability of building industries were selected through a rigorous literature review. Interestingly, more than 75% of the area experts/respondents, confirmed the relevance of these KPIs. Environmental KPIs were deemed important by more than 93% of respondents, while economic KPIs received the least importance (82%) in the building's sustainability. Five new KPIs, including recycling potential of C&D waste, loss of biodiversity, resilience, and adaptation of building to climate change, noise, and local material sourcing, as suggested by the participants, were included in the final list of the KPIs. In addition, the level of importance of these KPIs was ranked by area experts in order to calculate their weights. The KPIs found to have the highest and lowest weights are carbon footprint (88.1%) and noise (3.8%), respectively. Once these weights were used to convert the survey-based information to the numerical values of KPIs of a particular building, these values were compared with the corresponding threshold values of KPIs to find out the sustainability gaps. This paper explained in detail the basis of the threshold values of these KPIs. Using a hypothetical example, the applicability of this framework was tested using these KPIs. The immediate future study will consider the practical application of these indicators, their weights and threshold values in the sustainability assessment framework (Janjua et al. 2019a, b,c) to assess different types of buildings with varied service life.

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Declaration of competing interest

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Appendix A. Supplementary data

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Author contributions

Conceptualization and methodology, S.Y.J., P.K.S. and W.K.B.; Analysis, S.Y.J.; investigation, S.Y.J.; data curation, S.Y.J.; writing—original draft, S.Y.J.; visualization, S.Y.J.; writing—review and editing, S.Y.J., P.K.S., and W.K.B.; Supervision, P.K.S., and W.K.B.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

ABCB, 2018. Handbook. Sound Transmission and Insulation in Buildings, 2018, Australian Building Codes Board. Canberra, ACT, Australia. Accessed:14-16-2019. Retrieved from. https://www.abcb.gov.au/Resources/Publications/Education-Training/Sound-Insulation.

ABS, 2017. 6523.0 - Household Income and Wealth, Australia, 2015-16. Australian Bureau of Statistics, Canberra, Australia. Accessed: 24-1-2019. Retrieved from. https://www.abs.gov.au/ausstats/abs@.nsf/mf/6523.0.

ABS, Sep 2018. 8755.0 - Construction Work Done, Australia, Preliminary. Australian Bureau of Statistics, Canberra, Australia ausstats Accessed: 24-1-2019. Retrieved from. https://www.abs.gov.au, 8755, 2018.

ABS, 2019. 8782.0.65.001 - Construction Activity: Chain Volume Measures, Australia, Mar 2019. Australian Bureau of Statistics, Canberra, Australia. https://www.abs.gov.au. 〉 ausstats 〉 8782.0.65.001.

Ahmad, T., Thaheem, M.J., 2017. Developing a residential building-related social sustainability assessment framework and its implications for BIM. Sustain Cities Soc 28, 1–15. https://doi.org/10.1016/j.scs.2016.08.002.

AHURI, 2016. Understanding the 30:40 indicator of housing affordability stress. In: Comparing Household Income with Housing Costs. Australian Housing and Urban Research Institute, Melbourne, Australia. Accessed: 24-1-2019. Retrieved from: https://www.ahuri.edu.au/policy/ahuri-briefs/2016/3040-indicator.

Akadiri, P., Chinyio, E., Olomolaiye, P., 2012. Design of sustainable building: a conceptual framework implementing sustainability in the building sector. Buildings 2, 126–152. https://doi.org/10.3390/buildings2020126.

Alinta, 2019. Understanding Your Alinta Energy Bill. Alinta Energy. Perth Australia. Accessed: 17-6-2019. Retrieved from: https://www.alintaenergy.com.au/wa/natural-gas/your-gas-bill/understanding-your-bill.

Araújo, C., Almeida, M., Bragança, L., Barbosa, J.A., 2016. Cost-benefit analysis method for building solutions. Appl. Energy 173, 124–133. https://doi.org/10.1016/j.apenergy.2016.04.005.

Atmaca, A., 2016. Life-cycle assessment and cost analysis of residential buildings in southeast of Turkey: Part 2—Acase study. Int. J. Life Cycle Assess. 21, 925–942. https://doi.org/10.1007/s11367-016-1051-7.

CCC, 2013. Fourth Carbon Budget Review – Part 2 the Cost-Effective Path to the 2050 Target, Committee on Climate Change. London, UK. Accessed: 19-12-2018. Retrieved from: https://www.theccc.org.uk/publication/fourth-carbon-budget-review/.

Balasbaneh, A.T., Marsono, A.K., Khaleghi, S.J., 2018. Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: environmental, economic and social assessment. J. Build. Eng. 20, 235–247. https://doi.org/10.1016/j.jobe.2018.07.006.

Barthel, L., Wolf, M.A., Eyerer, P., 2005. Methodology of life cycle sustainability assessments. In: 11th Annual International Sustainable Development Research Conference (AISDRC). Helsinki, Finland.

BBC, 2004. Planet under pressure, British broadcasting corporation news. http://news.bbc.co.uk/2/hi/science/nature/3686106.stm.

Biswas, W.K., Cooling, D., 2013. Sustainability assessment of red sand as a substitute for virgin sand and crushed limestone. J. Ind. Ecol. 17, 756–762. https://doi.org/10.1111/jiec.12030.

Bragança, L., Mateus, R., Koukkari, H., 2010. Building sustainability assessment. Sustainability 2, 2001–2023. https://doi.org/10.3390/su2072010.

Brundtland, G.H., 1987. Our Common Future: Report of the World Commission on Environment and Developement. World Commission on Environment and Development, New York, NY, USA. http://www.un-documents.net/wced-ocf.htm.

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (lca) and life cycle energyanalysis (lcea) of buildings and the building sector: a review. Renew. Sustain. Energy Rev. 29, 394–416. https://doi.org/10.1016/j.rser.2013.08.037.

Carre, A., 2011. PNA147-0809. A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design. Forest & Wood Products Australia, Melbourne, Australia. Accessed: 19-12-2018. Retrieved from: https://www.fwpa.com.au/resources/market-access/204-comparative-life-cycle-assessment-of-alternative-constructions-of-a-typical-australian-house-design.html.

Carre, A., Crossin, E., 2015. PRA344-1415. A Comparative Life Cycle Assessment of Two Multistorey Residential Apartment Buildings. Forest & Wood Products Australia, Melbourne, Australia. Accessed: 19-12-2018. Retrieved from: http://www.fwpa.com.au/images/marketaccess/PRA344-1415-Australand.pdf.

COFA, 2011. Clean Energy Act 2011. Act No. 103.2013. Parliamentary Counsel, Commonwealth of Australia. Accessed: 10-18-2019, Retrieved from. https://www.legislation.gov.au/Details/C2013C00372/Download.

Cuéllar-Franca, R.M., 2012. Sustainability assessment framework for the residential construction sector in the UK. In: School of Chemical Engineering and Analytical Science. University of Manchester, Manchester UK.

Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: life cycle assessment of houses. Build. Environ. 54, 86–99. https://doi.org/10.1016/j.buildenv.2012.02.005.

Cullen, R., 2014. TW13022 - C&D Waste Recycling Resource Kit. Talis consultants Pty Ltd., Leederville, WA, Australia. Accessed: 10-18-2019, Retrieved from. https://www.wasteauthority.wa.gov.au/media/files/documents/East_Fremantle_CD_Recycling_Trial_and_Directory.pdf.

DOEE, 2012. Construction and Demolition Waste Guide- Recycling and Re-use across the Supply Chain. Department of sustainability, environment, Water, population and Communities, Canberra, Australia. Accessed: 7-7-2019, Retrieved from. https://www.environment.gov.au/system/files/resources/b0ac5ce4-4253-4d2b-b001-0becf84b52b8/files/case-studies.pdf.

DOEE, 2018. Australian Energy Statistics, Table O, April 2018. Department of Environment and Energy, Canberra, Australia. Accessed: 7-7-2019, Retrieved from. https://www.energy.gov.au/publications/australian-energy-statistics-table-o-electricity-generation-fuel-type-2017-18-and-2018.

DOEE, 2018. Australian Energy Update 2018. Department of Environment and Energy, Canberra, Australia. Accessed: 7-7-2019, Retrieved from. https://www.energy.gov.au/sites/default/files/australian_energy_update_2018.pdf.

DOEE, 2019. Quarterly Update of Australia's National Greenhouse Gas Inventory: December 2018. In: Australia's National Greenhouse Accounts. Department of Environment and Energy, Canberra, Australia. Accessed: 7-7-2019, Retrieved from: https://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/quarterly-update-australias-nggi-mar-2019.

DOEE, 2019. State and Territory Greenhouse Gas Inventories 2017. In: Australia's National Greenhouse Accounts. Department of Environment and Energy, Canberra, Australia. https://www.environment.gov.au. Accessed: 7-7-2019, Retrieved from 〉 system 〉 files 〉 resources 〉 files 〉state-territory-inventories-2017.

Dong, Y.H., Ng, S.T., 2016. A modeling framework to evaluate sustainability of building construction based on LCSA. Int. J. Life Cycle Assess. 21, 555–568. https://doi.org/10.1007/s11367-016-1044-6.

Dreyer, L.C., Hauschild, M.Z., Schierbeck, J., 2006. A framework for social life cycle impact assessment. Int. J. Life Cycle Assess. 11, 89–99. https://doi.org/10.1065/lca2005.08.223.

Ede, A.N., Adebayo, S.O., Ugwu, E.I., Emenike, C.P.G., 2014. Life cycle assessment of environmental impacts of using concrete or timber to construct a duplex residential building. J. Mech. Civ. Eng. 11, 62–72. http://eprints.covenantuniversity.edu.ng/id/eprint/9629.

Estokova, A., Vilcekova, S., Porhincak, M., 2016. Analyzing embodied energy, global warming and acidification potentials of materials in residential buildings. In: International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16). Elsevier, Procedia, Sydney, Australia. https://doi.org/10.1016/j.proeng.2017.04.330.

Fenton, G.G., Gerofi, J., 1981. Desalination in Australia- past and future. Desalination 39, 399–411.

Fernández-Membrive, V.J., Lastra-Bravo, X.B., Tolón-Becerra, A., 2015. Cost-benefit analysis of changes in energy in building technology in Southeast Spain. Energy Build. 103, 29–37. https://doi.org/10.1016/S0011-9164(00)86144-5.

Frischknecht, R., Wyss, F., Knöpfel, B.S., Lützkendorf, T., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. Int. J. Life Cycle Assess. 20, 957–969. https://doi.org/10.1007/s11367-015-0897-4.

GBCA, 2019. Local procurement. In: Innovation Challenges Handbook. Green Building Council of Australia, NSW, Australia. Accessed: 14-16-2019. Retrieved from. https://www.gbca.org.au/uploads/68/34884/Local%20Procurement.pdf.

Gluch, P., Baumann, H., 2004. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Build. Environ. 39, 571–580. https://doi.org/10.1016/j.buildenv.2003.10.008.

Greene, G., 1994. Caring for the earth: the world conservation union, the united nations environment programme, and the world wide fund for nature. Environ.Sci.Policy sutain.Dev. 36, 25–28. https://doi.org/10.1080/00139157.1994.9929182.

Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., Hewage, K., 2015. AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. J. Environ. Plann. Manag. 58, 1217–1241. https://doi.org/10.1080/09640568.2014.920704.

Huijbregts, M.A., Rombouts, L.J., Hellweg, S., Frischknecht, R., Hendriks, A.J., Van de Meent, D.V., Ragas, A.M., Reijnders, L., Struijs, J.A., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. 40, 641–648. https://doi.org/10.1021/es051689g.

Hunkeler, D., 2006. Societal LCA methodology and case study. Int. J. Life Cycle Assess. 11, 371–382. https://doi.org/10.1065/lca2006.08.261.

Islam, H., Jollands, M., Setunge, S., Ahmed, I., Haque, N., 2014. Life cycle assessment and life cycle cost implications of wall assemblages designs. Energy Build. 84, 33–45. https://doi.org/10.1016/j.enbuild.2014.07.041.

ISO/T, S 21929-1, 2006. Sustainability in building construction-Sustainability indicators. In: Part 1: Framework for the Developementvof Indicators for Buildings. International Standards Organisation. Switezerland.
Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019a. A review of residential buildings sustaianability performance using a life cycle assessment approach. J. Sustain. Res. 1, e190006 https://doi.org/10.20900/jsr20190006.
Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019b. Impact of service life on the environmental performance of buildings. Buidings 9, 9. https://doi.org/10.3390/buildings9010009.
Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019c. Sustainability assessment of a residential building using a lifecycle assessment approach. Chem. Eng. Trans. 72, 19–24. https://doi.org/10.3303/CET1972004.
Kamali, M., Hewage, K., Milani, A.S., 2018. Life cycle sustainability performance assessment framework for residential modular buildings: aggregated sustainability indices. Build. Environ. 138, 21–41. https://doi.org/10.1016/j.buildenv.2018.04.019.
Lawania, K.K., 2016. Improving the sustainability performance of western Australian house construction: a life cycle management approach. School of Civil and Mechanical Engineering. Curtin University, Perth, Australia.
Lawania, K.K., Biswas, W.K., 2017. Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia. Int. J. Life Cycle Assess. 23, 204–224. https://doi.org/10.1007/s11367-017-1314-y.
Lawania, K.K., Biswas, W.K., 2018. Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia. Int. J. Life Cycle Assess. 23, 204–224. https://doi.org/10.1007/s11367-017-1314-y.
Lawania, K.K., Biswas, W.K., 2016. Cost-effective GHG mitigation strategies for Western Australia's housing sector: a life cycle management approach. Clean Technol. Environ. Policy 18, 2419–2428. https://doi.org/10.1007/s10098-016-1217-9.
Lawn, P., 2006. Sustainable Development Indicators in Ecological Economics. Edward Elgar Publishing Limited, Cheltenham,UK.
LEED, 2016. Regional Materials, MRc 5; LEED BD+C: New Construction | V3-LEED 2009. Leadership in Energy and Environmental Design. Accessed: 14-16-2019. Retrieved from: https://www.usgbc.org/node/1731029?return=/credits/new-construction/v2009.
Lim, C.I., Biswas, W.K., 2018. Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry. Clean Technol. Environ. Policy 20, 539–560. https://doi.org/10.1007/s10098-017-1453-7.
Linstone, H.A., Turroff, M., 1975. The Delphi Method: Techniques and Applications. Addison -Wesley Pub. Co.
Maddox, B., Nunn, J., 2003. LCA Fact Sheet: Life Cycle Analysis of Clay Brick Housing – Based on a Typical Project Home 2003, the Centre for Sustainable Technology, the Unversity of Newcastle (Newcastle, Australia).
Majer, J.D., Beeston, G., 1996. The biodiversity integrity index: an illustration using ants in Western Australia. Conserv. Biol. 1, 65–73. https://doi.org/10.1046/j.1523-1739.1996.10010065.x.
MBWA, 2014. Profit Margins in Building. Master Builders Western Australia. Perth, Western Australia. Accessed: 14-16-2019. Retrieved from: https://www.mbawa.com/profit-margins-in-building/.
McCormack, M., Treloar, G.J., Palmowski, L., Crawford, R., 2007. Modelling direct and indirect water requirements of construction. Build. Res. Inf. 35, 156–162. https://doi.org/10.1080/09613210601125383.
Milman, O., 2014. Australia record biggest emissions drop in a decade as carbon tax kicks in. In: The Guardian. Australia. Accessed: 08-11-2018. Retrieved from:https://www.theguardian.com/environment/2014/dec/24/australia-records-biggest-emissions-drop-in-a-decade-as-carbon-tax-kicks-in.
Nance, A., 2013. Relative energy poverty in Australia. In: School of Energy and Resource. University College London (UCL Australia), Adelaide, Australia. https://www.sacoss.org.au. Accessed: 10-11-2018. Retrieved from: 〉 relative-energy-poverty-australia.
Ofori, G., 2001. Indicators for measuring construction industry development in developing countries. Build. Res. Inf. 29, 40–50. https://doi.org/10.1080/09613210150208787.
Ofori, G., 2006. Construction industry and economic growth in Singapore. Construct. Manag. Econ. 6, 57–70. https://doi.org/10.1080/01446198800000007.
Onat, N.C., Kucukar, M., Tatari, O., 2014. Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings. Int. J. Life Cycle Assess. 19, 1488–1505. https://doi.org/10.1007/s11367-014-0753-y.
Pant, P., 2019. How much you should budget for Home Maintenance. Accessed: 14-16-2019. Retrieved from: https://www.thebalance.com/home-maintenance-budget-453820.
Pickin, J., Randell, P., Trinh, J., Grant, B., 2018. National Waste Report 2018. Department of the Environment and Energy, Victoria, Australia. Accessed:10-11-2018. Retrieved from. http://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018.
Radcliffe, J.C., 2018. The water energy nexus in Australia - the outcome of two crises. WaterEnergy Nexus 1, 66–85. https://doi.org/10.1016/j.wen.2018.07.003.
Rashid, A.F.A., Idris, J., Yusoff, S., 2017. Environmental impact analysis on residential building in Malaysia using life cycle assessment. Sustainability 9, 329. https://doi.org/10.3390/su9030329.
Rauf, A., Crawford, R.H., 2013. The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. Architect. Sci. Rev. 56, 252–261. https://doi.org/10.1080/00038628.2013.810548.
Roosa, S.A., 2008. Sustainable Development Handbook. Fairment Press, Lilburn,GA, USA.
Sawe, B.E., 2018. The world's driest continent. Accessed. 15-19-2019. Available from: https://www.worldatlas.com/articles/which-is-the-world-s-driest-continent.html.
Sherif, Y.S., Kolarik, W.J., 1981. Life cycle costing: concept and practice. OMEGA: Int. J. Manag. Sci. 9, 287–291. https://doi.org/10.1016/0305-0483(81)90035-9.
Synergy, 2019. Standard electricity prices and charges. Synergy energy. https://www.synergy.net.au. Perth, Australia. Accessed: 14-16-2019. Retrieved from: 〉media〉Files〉PDF-Library〉Standard_Electricity_Prices_Charges_brochure.pdf.
Tepper, T., 2018. More than meets the mortgage: survey finds the hidden costs of home ownership. Accessed: 14-16-2019. Retrieved from: https://www.bankrate.com/mortgages/home-services-survey-0218/.
Thiers, S., Peuportier, B., 2012. Energy and environmental assessment of two high energy performance residential buildings. Build. Environ. 51, 276–284. https://doi.org/10.1016/j.buildenv.2011.11.018.
Thomas, M., 2016. Housing affordability in Australia: Australian society: parliamentary library briefing book- 45th parliament. Accessed: 14-6-2019. Retrieved from. https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/BriefingBook45p/HousingAffordability.
UN., 2015. A/RES/70/1 –Transforming Our World: the 2030 Agenda for Sustainable Development. United Nations, New York. USA. Accessed: 10-01-2019. Retrieved from: https://www.unfpa.org/resources/transforming-our-world-2030-agenda-sustainable-development.
UN., 2015. Paris agreement. United nations framework convention on climate change (UNFCCC). United nations. Le bourget, paris, France. https://unfccc.int. Accessed: 10-01-2019. Retrieved from: 〉 sites 〉 default 〉 files 〉 english_paris_agreement.
UNEP, 2006. Eco-Housing Guidelines for Tropical regions. Regional Resource Centre for Asia and the Pacific. United Nation Environment Programme, Bangkok, Thailand. www.rrcap.ait.ac.th. Accessed: 10-01-2019. Retrieved from: 〉 Publications 〉 eco-housing-unep.
UNEP, 2009. Guidlines for Social Life Cycle Assessment of Products. United Nation Environment Programme, Paris, France. Life Cycle Initiative. Accessed: 30-36-2018. Retrieved from. https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca.
UNEP, 2018. Towards zero-emission, efficient, and resilient buildings and construction sector. In: Global Status Report 2018. United Nation Environment Programme. Global Allience for Buildings and Construction (GABC), Paris, France. Accessed: 30-6-2018. Retrieved from: https://www.globalabc.org/uploads/media/default/0001/01/f64f6de67d55037cd9984cc29308f3609829797a.pdf.
Vale, M., Pentalone, M., Bragagnolo, M., 2017. Collaborative perspective in bio-economy development: a mixed method approach. IFIP Adv. Inf. Commun. Technol. 506, 553–563. https://doi.org/10.1007/978-3-319-65151-4_49.
WA, 2002. Buy Local Policy: A Western Australian Government Commitment to Supporting Local Business. Department of housing and works. Government of Western Australia. West perth, Western Australia. Accessed: 14-16-2019. Retrieved from. https://www.finance.wa.gov.au/cms/uploadedFiles/Building_Management_and_Works/Consultant_Information/Buy_Local_Policy_July_2002(1).pdf.
WBG, 2019. Fossil Fuel Energy Consumption (% of Total). World Bank Group. The International Energy Agency, Paris, France. Accessed: 08-01-2019. Retrieved from: https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS?locations=AU.
Wong, I.L., Perera, S., Eames, P.C., 2010. Goal directed life cycle costing as a method to evaluate the economic feasibility of office buildings with conventional and TI-facades. Constr.Manage. Econ. 28, 715–735. https://doi.org/10.1080/01446191003753867.
WWF, 2019. Environmental problems in Australia: issues with no end in sight. World wide fund for nature. Accessed: 18-7-2019. Retrieved from: http://wwf.panda.org/wwf_offices/australia/environmental_problems_in_australia/.
WWF, 2019. Impacts of global warming. World wide fund for nature. Accessed: 18-7-2019. Retrieved from: https://www.wwf.org.au/what-we-do/climate/impacts-of-global-warming#gs.4v3zax.

PAPER-3: ELECTRONIC SUPPLEMENTARY MATERIAL [1]

Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings

This supporting information consists of appendix- A, including tabular data of online survey responses, calculations of service life and sustainability scores of case study building.

APPENDIX A

Table A-1 Summary of KPIs' relevance to building sustainability

KPI Code	KPIs	Relevance response			Total
		No comments	Not relevant	Relevant	
E-1.1	Carbon Footprint	-	-	40	40
E-2.1	Acidification	2	2	36	40
E-3.1	Eutrophication	-	5	35	40
E-4.1	Land Use	-	3	37	40
E-5.1	Cumulative embodied Water Consumption	-	2	38	40
E-6.1	Cumulative Energy demand	-	6	34	40
E-7.1	Cumulative Fossil Energy consumption	-	2	38	40
E-8.1	C&D waste	-	2	38	40
S-1.1	House Affordability	4	3	33	40
S-1.2	Indoor Living Conditions	1	2	37	40
S-1.3	Thermal Comfort	1	1	38	40
S-2.1	Energy Conservation	1	4	35	40
EC-1.1	Life Cycle Cost	-	1	39	40
EC-1.2	Potential Savings	1	7	32	40
EC-1.3	Benefit Cost ratio	2	5	33	40
EC-2.1	Net benefit	3	7	30	40
EC-2.2	Carbon Tax Saving	3	7	30	40

[1] https://ars.els-cdn.com/content/image/1-s2.0-S0301479720304102-mmc1.docx

Table A-2 Summary of KPIs' importance level to building sustainability

KPI code	KPIs	Importance level response				Total
		Somewhat important	Moderately important	Important	very important	
E-1.1	Carbon footprint	-	2	15	23	40
E-2.1	Acidification	8	7	15	6	40
E-3.1	Eutrophication	7	12	9	7	40
E-4.1	Land use	5	6	14	12	40
E-5.1	Cumulative embodied Water Consumption	3	5	14	16	40
E-6.1	Cumulative energy demand	-	2	12	20	40
E-7.1	Cumulative fossil energy consumption	4	3	10	21	40
E-8.1	C&D waste	4	3	14	17	40
S-1.1	House affordability	3	5	13	12	40
S-1.2	Indoor living conditions	3	7	15	12	40
S-1.3	Thermal comfort	-	5	18	15	40
S-2.1	Energy conservation	-	4	10	21	40
EC-1.1	Life cycle cost	2	2	13	22	40
EC-1.2	Potential savings	4	6	12	10	40
EC-1.3	Benefit cost ratio	1	6	19	7	40
EC-2.1	Net benefit	4	4	19	3	40
EC-2.2	Carbon tax saving	5	8	10	7	40

Table A-3 *Brief analysis of additional KPIs proposed by respondents*

KPIs	Respondent feedback summary	Authors' response	Selection Yes/ No
1.Thermal mass	One respondent (government) proposed that thermal mass is an important environmental KPI, as it reduces the heating and cooling demand of the building.	Thermal mass has been considered in calculations of environmental KPIs, including GHG emissions and embodied energy in the environmental KPI- *carbon footprint*, and social KPI- *indoor living conditions.*	No
2. Recycling potential of C&D waste	Five respondents (government, practitioner, academia, structural engineer) suggested recycling and re-use potential of building material as important environmental KPI in addition to C&D waste generation. It helps to reduce carbon footprint and can be used to measure potential recovered cost at end of life of building.	In Australia, C&D waste accounts for significant portion (30.5%) of solid waste [1]. Regional waste authorities are trying desperately to divert wastes from landfill through recycling or reuse. Therefore, the proposed KPI is included for assessment under environmental impact category- Waste generation.	Yes
3. Sustainable building materials	One respondent from academia background suggested sustainable building materials as important indicator including the full range of issues e.g., being able to separate constituent materials for end-of-life materials recycling, use oil recycled content in manufacture, reduction in material quantity to achieve function.	The objective of this study is the assessment of sustainability implication of service life of buildings and building materials. The suggested KPI is aligned with the proposed objective and so it was not considered as a KPI.	No
4. Resilience and adaptation of buildings for climate change	Two respondents (academia and government) suggested, resilience and adaptation of building for climate change as an important environmental indicator.	Resilience and adaptation of buildings to climate change are related to durability of building materials and the compatibility of architectural and structural design of building to withstand the catastrophic circumstances like inundation, cyclones, bushfire, hailstorms, severe rains etc. The proposed KPI is worth to be considered in environmental objectives (impact category - Climate change), to measure durability of alternative building materials in buildings.	Yes

KPIs	Respondent feedback summary	Authors' response	Selection Yes/ No
5. Adaptability	Adaptability of buildings to alternative uses e.g., changing lifestyles, ages, disabilities, is proposed by three respondents (academia, government and practitioner) as an important social KPI arguing that it will reduce renovation cost impact on user.	The proposed indicator falls outside the scope of the research. This research does not involve human behavioural changes and health to assess the adaptability to the variation in building designs.	No
6. Aesthetics and colour selection	Three respondents with government and academic background, captured aesthetics and colour selection as important TBL indicator that affects mental health, thermal comfort, and reduce energy inputs and bills.	Like the previous one, this KPI is beyond the scope of this research. Firstly, the current project does not consider the interior design. Secondly, this research focused on building materials and service life for building performance. Colour was not considered as it does not affect the service life of the building.	No
7. Ecological impact	Five respondents (government, practitioner, and academia) suggested ecological impact due to land transformation is a very important environmental KPI that indicates the impacts (e.g., species loss, food insecurity, loss of natural environment) of transformation of agricultural land or bushland to development sites due to urban sprawl.	KPI- *Land use* has captured the impact as land transformation during building life cycle due to urban sprawl. However, a more direct KPI- *Loss of biodiversity* due to land use for building and construction activities is deemed necessary.	Yes
8. Service life	One respondent (practitioner) proposed service life of the building as an important factor in reducing aggregate impacts on a per annum basis as more durable buildings will last longer and can be re-purposed rather than demolished and rebuilt.	This is one of the key objectives of this research. The framework has already been designed to determine service life of buildings as service life helps determines buildings 'actual sustainability performance.	No
9. Indoor environment quality	Two respondents (government and academia) suggested to consider indoor environment quality as an important social KPI of health and well-being.	Indoor environment quality is a measure of indoor air quality, lighting, damp conditions, thermal and acoustic comfort, directly impacting the human health and wellbeing while indirectly impacting the operational costs. The indoor environment quality has already been directly and indirectly incorporated in two social KPIs i.e., *indoor living*	No

KPIs	Respondent feedback summary	Authors' response	Selection Yes/ No
		condition and *thermal comfort*, respectively.	
10. Social equity	Five respondents (government, practitioner, and academia) suggested social equity including modern slavery, gender, and race and age discrimination, human rights, as important social indicators in supply chain of buildings.	The existing social KPIs cover two impact categories, intra-generational and inter-generational equity, of social equity. *House affordability, indoor living conditions* and *thermal comfort* are the basic human rights irrespective of gender, age and race and has thus adequately captured in social KPIs for impact category in intra-generational equity.	No
11. Location accessible to services	Three respondents (government, practitioner, academia), captured building location accessible to services important environmental indicator that reduce commuting resulting in indirect low carbon footprint due to less use of transport.	The suggested indicator is an important local/urban planning strategy to reduce TBL sustainability impacts of the commuting, but it falls beyond the scope and system boundaries of study as it aimed to address the sustainability of buildings made of conventional and alternative materials. Alternatively, materials are considered as key variables here.	No
12. Shared amenity facilities	Two respondents (government, academia) suggested shared amenity facilities (open space, gardens, playgrounds) as important social indicator with the objectives of fostering community networks.	The suggested KPI is an important local/urban planning strategy to reduce TBL sustainability impacts of the urban planning but it falls beyond the scope of the study as it aimed to address the sustainability of buildings made of different building materials.	No
13. Life cycle water consumption	Two respondents (academia) proposed water consumption as environmental indicator for all life cycle stages. One respondent (practitioner) suggested that water efficiency rating can be considered as environmental indicator showing the overall water savings in a house from a combination of measures which can be converted to economic benefit.	This study has considered the embodied water consumption within the system boundary of the building (pre-use, use and post-use). So, this KPI has already been considered but in different terminology as *cumulative embodied water consumption*. Water efficiency rating is a strategy to reduce water consumption in return of economic benefits, thus falls beyond the scope of study.	No

KPIs	Respondent feedback summary	Authors’ response	Selection Yes/ No
14. Noise	Two respondents from government background suggested building construction noise to be considered as an important indicator specifically in urban areas and the noise insulation of finished buildings is an important factor in their habitability	Both airborne and structure borne noise causes mental fatigue, irritability and stress. The noise can be controlled to some extent using high rated STC (sound transmission class) materials. The STC value of building materials could be used to measure the KPI for the sound impact control in the building under intra-generational equity to ascertain the social sustainability of building.	Yes
15. Local material sourcing	Two respondents (government, academia) suggested life cycle economic impact as an important social indicator arguing that the use of local material can contribute to local community development by providing employment opportunities.	Local sourcing of materials and on-site construction practices could improve social sustainability performance of buildings by providing job opportunities to local communities, developing local business and reducing the carbon footprint and costs incurred as a result of transportation of building materials from remote areas/ countries. The environmental and economic aspects of the suggested KPIs are directly or indirectly considered in existing KPIs carbon footprint and life cycle costs. The local sourcing of the materials is worth considering under impact category of intra-generational equity of social objective and measured as distance (km) between construction site and location of extraction, processing or manufacturing of building materials/ components.	Yes
16. Community/ stakeholder input	One respondent (government) suggested community input as social indicator because community/stakeholder input into projects which will sit in the neighbourhood for years will result in more informed decision-making during planning and design, and hopefully more tolerance and understanding during use.	The development of this framework has already considered stakeholders’ input to the development of TBL indicators. Therefore, it has not been accepted as a KPI.	No

Table A-4 *Estimated service life of the case study building*

Structural components of building	ESL of building component	ESL of building
Timber frame Roof	57	57
Double brick wall	82	
Concrete slab footing	57	

Table A-5 Weight calculation of KPIs/ Impact categories/sustainability objectives

Respondents	E-1.1	E-1.2	E-2.1	E-3.1	E-4.1	E-4.2	E-5.1	E-6.1	E-7.1	E-8.1	E-8.2	S-1.1	S-1.2	S-1.3	S-1.4	S-1.5	S-2.1	EC-1.1	EC-1.2	EC-1.3	EC-2.1	EC-2.2	Total
r1	5	-	0	0	0	-	10	7.5	10	2.5	-	10	10	10	-	10	7.5	10	0	-	-	2.5	95
r2	10	7.5	7.5	10	10	10	7.5	10	10	7.5	-	5	10	7.5	7.5	7.5	10	7.5	5	10	0	5	165
r3	7.5	-	7.5	7.5	7.5	-	7.5	7.5	7.5	7.5	-	7.5	7.5	7.5	-	-	7.5	7.5	7.5	7.5	7.5	7.5	127.5
r4	10	-	10	7.5	10	-	10	10	10	10	-	7.5	7.5	5	-	-	10	10	10	10	7.5	10	155
r5	7.5	-	7.5	7.5	7.5	-	7.5	7.5	5	7.5	-	5	7.5	7.5	-	-	10	10	7.5	7.5	7.5	2.5	122.5
r6	7.5	-	7.5	0	7.5	-	7.5	10	7.5	5	-	10	7.5	10	-	-	7.5	10	7.5	7.5	5	5	122.5
r7	10	-	2.5	2.5	7.5	7.5	7.5	5	10	5	-	7.5	10	7.5	-	-	10	10	7.5	7.5	7.5	7.5	132.5
r8	10	-	2.5	2.5	10	10	5	0	5	2.5	-	-	-	5	-	-	0	0	0	0	0	0	52.5
r9	10	-	5	10	10	-	10	10	10	10	-	10	10	10	-	-	10	10	7.5	7.5	10	2.5	152.5
r10	10	-	7.5	5	2.5	-	2.5	7.5	2.5	2.5	-	-	2.5	7.5	-	-	7.5	7.5	2.5	7.5	2.5	5	82.5
r11	10	-	-	10	10	-	10	10	10	10	-	-	5	10	-	-	10	10	5	5	-	7.5	122.5
r12	7.5	-	2.5	5	7.5	-	7.5	7.5	7.5	7.5	-	7.5	7.5	7.5	-	-	7.5	7.5	7.5	7.5	7.5	0	112.5
r13	10	-	2.5	2.5	7.5	-	10	10	10	7.5	7.5	7.5	10	10	-	-	10	5	5	5	5	7.5	132.5
r14	10	-	7.5	5	5	-	5	0	10	10	-	0	0	10	-	-	5	7.5	2.5	0	0	2.5	80

Respondents	E-1.1	E-1.2	E-2.1	E-3.1	E-4.1	E-4.2	E-5.1	E-6.1	E-7.1	E-8.1	E-8.2	S-1.1	S-1.2	S-1.3	S-1.4	S-1.5	S-2.1	EC-1.1	EC-1.2	EC-1.3	EC-2.1	EC-2.2	Total
r15	10	-	7.5	5	7.5	10	5	7.5	10	10	-	10	5	7.5	-	-	7.5	7.5	7.5	7.5	7.5	7.5	140
r16	7.5	-	7.5	7.5	7.5	10	7.5	7.5	7.5	7.5	-	7.5	7.5	7.5	-	-	7.5	7.5	7.5	7.5	7.5	7.5	137.5
r17	10	-	10	10	10	-	10	10	10	10	10	2.5	2.5	7.5	-	-	10	10	10	7.5	0	10	150
r18	7.5	-	7.5	7.5	7.5	-	7.5	7.5	7.5	7.5	-	10	10	10	-	-	10	10	10	7.5	7.5	10	145
r19	10	10	10	10	10	-	10	10	10	10	-	10	10	10	-	-	10	10	10	7.5	7.5	7.5	172.5
r20	10	-	7.5	7.5	7.5	-	0	0	7.5	7.5	-	0	0	0	-	-	0	10	0	7.5	7.5	-	72.5
r21	7.5	-	2.5	2.5	2.5	-	5	10	7.5	5	-	5	5	7.5	-	-	10	10	10	10	7.5	5	112.5
r22	10	-	7.5	7.5	7.5	-	7.5	10	10	10	-	10	7.5	5	-	-	10	10	7.5	10	7.5	7.5	145
r23	7.5	-	7.5	2.5	2.5	-	2.5	10	10	2.5	-	7.5	2.5	7.5	-	-	10	7.5	10	10	7.5	10	117.5
r24	10	-	2.5	2.5	7.5	-	10	0	2.5	0	-	0	5	7.5	-	-	0	7.5	0	0	0	0	55
r25	5	-	5	5	5	-	10	7.5	2.5	10	-	5	7.5	7.5	-	-	10	5	2.5	5	2.5	2.5	97.5
r26	10	-	5	5	10	-	7.5	10	10	10	7.5	10	10	10	-	-	5	7.5	7.5	7.5	7.5	5	145
r27	10	-	2.5	0	0	-	10	10	10	10	-	7.5	7.5	10	-	-	10	10	0	0	0	0	67.5
r28	7.5	-	10	5	5	-	2.5	10	10	7.5	-	2.5	5	5	-	-	10	2.5	5	2.5	2.5	7.5	100
r29	10	-	10	10	10	-	10	10	10	10	-	10	10	10	-	-	10	10	10	10	10	10	170

Respondents	E-1.1	E-1.2	E-2.1	E-3.1	E-4.1	E-4.2	E-5.1	E-6.1	E-7.1	E-8.1	E-8.2	S-1.1	S-1.2	S-1.3	S-1.4	S-1.5	S-2.1	EC-1.1	EC-1.2	EC-1.3	EC-2.1	EC-2.2	Total
r30	7.5	-	5	5	5	-	10	10	10	10	-	5	7.5	5	-	-	5	10	0	7.5	7.5	5	115
r31	10	-	5	5	0	-	0	0	0	7.5	-	10	10	10	-	-	0	2.5	0	0	7.5	0	67.5
r32	7.5	-	5	5	2.5	-	10	10	7.5	10	-	10	10	7.5	-	-	7.5	10	7.5	5	5	5	125
r33	10	-	0	5	5	-	10	0	0	0	-	-	7.5	-	-	-	-	7.5	-	-	-	-	45
r34	7.5	-	5	2.5	5	-	7.5	7.5	2.5	7.5	-	7.5	7.5	7.5	-	-	7.5	10	2.5	5	2.5	5	100
r35	7.5	-	7.5	7.5	10	-	7.5	5	5	7.5	-	7.5	5	10	7.5	-	10	7.5	5	7.5	7.5	0	125
r36	7.5	-	-	0	7.5	-	5	10	10	10	10	7.5	10	7.5	-	-	7.5	7.5	10	7.5	7.5	0	125
r37	10	-	2.5	0	10	-	10	10	10	10	10	10	7.5	10	-	-	10	10	10	7.5	0	10	147.5
r38	10	-	10	10	10	-	10	10	10	10	-	2.5	7.5	10	-	-	10	10	10	10	10	10	160
r39	10	-	7.5	5	7.5	-	7.5	7.5	7.5	7.5	-	7.5	7.5	7.5	-	-	5	10	7.5	7.5	7.5	7.5	127.5
r40	7.5	-	7.5	7.5	2.5	-	7.5	7.5	7.5	7.5	-	7.5	5	7.5	-	-	10	10	5	5	5	-	110
Total Score	352.5	17.5	227.5	215	267.5	47.5	297.5	300	310	300	45	250	275	310	15	17.5	305	332.5	230	245	202.5	197.5	4760

Respondents	KPI Weight	Category Weight	Objective Weight
E-1.1	0.0741	0.0777	0.5000
E-1.2	0.0037		
E-2.1	0.0478	0.0478	
E-3.1	0.0452	0.0452	
E-4.1	0.0562	0.0662	
E-4.2	0.0100		
E-5.1	0.0625	0.0625	
E-6.1	0.0630	0.0630	
E-7.1	0.0651	0.0651	
E-8.1	0.0630	0.0725	
E-8.2	0.0095		
S-1.1	0.0525	0.1822	0.2463
S-1.2	0.0578		
S-1.3	0.0651		
S-1.4	0.0032		
S-1.5	0.0037		
S-2.1	0.0641	0.0641	
EC-1.1	0.0699	0.1696	0.2537
EC-1.2	0.0483		
EC-1.3	0.0515		
EC-2.1	0.0425	0.0840	
EC-2.2	0.0415		
Total	1.0000	1.0000	1.0000

Note. Scoring of response by each respondent was given as; Irrelevant= 0, somewhat important= 2.5, Moderately Important= 5, Important= 7.5 and very Important=10. New KPIs received only scoring given by the suggesting respondent. (E-1.1 Carbon footprint; E-1.2 Resilience and adaptation; E-2.1 Acidification; E-3.1 Eutrophication; E-4.1 Land use; E-4.2 Loss of biodiversity; E-5.1 Cumulative embodied water consumption; E-6.1 Cumulative energy demand; E-7.1 Cumulative fossil energy consumption; E-8.1 C&D waste; E-8.2 Recycling potential of C&D waste; S-1.1 House affordability; S-1.2 Indoor living conditions; S-1.3 Thermal comfort; S-1.4 Noise; S-1.5 Local material sourcing; S-2.1 Energy conservation; EC-1.1 Life cycle cost; EC-1.2 Potential savings; EC-1.3 Benefit-cost ratio; EC-2.1 Net benefit; EC-2.2 Carbon tax saving; r, respondent; KPI, key performance indicator)

Table A-6 *Score of KPIs/ Impact categories/sustainability objectives*

Sustainability objectives	Impact category code	Impact category	KPIs code	KPIs	KPIs position value P	KPIs gap G= 5-P	KPI score G x W	Impact category score	Sustainability objective score	Building score ∑ (G x W)	Building sustainability score = 5- ∑ (G x W)
Environmental Objectives	E-1	Climate change	E-1.1	Carbon Footprint	1.69	3.31	0.2450	0.2542	1.506	2.6805	2.3195
			E-1.2	Resilience and adaptation	2.50	2.50	0.0093				
	E-2	Air quality	E-2.1	Acidification	1.48	3.52	0.1683	0.1683			
	E-3	Water quality	E-3.1	Eutrophication	1.11	3.89	0.1758	0.1758			
	E-4	Ecological footprint	E-4.1	Land Use	2.16	2.84	0.1597	0.1881			
			E-4.2	Loss of Biodiversity	2.16	2.84	0.0284				
	E-5	Water scarcity	E-5.1	Cumulative Embodied Water Consumption	5.00	0.00	0.0000	0.0000			
	E-6	Energy scarcity	E-6.1	Cumulative Energy Demand (CED)	2.70	2.30	0.1448	0.1448			
	E-7	Abiotic resource depletion	E-7.1	Cumulative Fossil Energy consumption (CFEC)	1.07	3.93	0.2558	0.2558			
	E-8	Waste generation	E-8.1	C & D waste	0.09	4.91	0.3092	0.3187			
			E-8.2	Recycling potential of C & D waste	4.00	1.00	0.0095				

Sustainability objectives	Impact category code	Impact category	KPIs code	KPIs	KPIs position value P	KPIs gap G= 5-P	KPI score G x W	Impact category score	Sustainability objective score	Building score ∑ (G x W)	Building sustainability score = 5- ∑ (G x W)
Social Objectives	S-1	Intra-generational Equity	S-1.1	House Affordability	5.00	0.00	0.0000	0.1340	0.455		
			S-1.2	Indoor Living Conditions	5.00	0.00	0.0000				
			S-1.3	Thermal Comfort	2.98	2.02	0.1316				
			S-1.4	Noise	5.00	0.00	0.0000				
			S-1.5	Local material sourcing	4.35	0.65	0.0024				
	S-2	Inter-generational Equity	S-2.1	Energy Conservation	0.00	5.00	0.3205	0.3205			
Economic Objectives	EC-1	User Perspective	EC-1.1	Life Cycle Cost	3.80	1.20	0.0839	0.4824	0.720		
			EC-1.2	Potential Savings	0.00	5.00	0.2415				
			EC-1.3	Benefit Cost ratio	1.95	3.05	0.1571				
	EC-2	Developer Perspective	EC-2.1	Net benefit	4.29	0.71	0.0304	0.2379			
			EC-2.2	Carbon Tax Saving	0.00	5.00	0.21				

REFERENCE

1. Pickin, J., Randell, P., Trinh, J., Grant, B., 2018. National Waste Report 2018. Department of the Environment and Energy. Victoria, Australia. Accessed:10-11-2018. Retrieved from: http://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018.

APPENDIX-4: PAPER-4

Janjua SY, Janjua SY, Sarker PK, Biswas WK. Impact of Service Life on the Environmental Performance of Buildings. Buildings. 2019, 9:9. http://doi.org/10.3390/buildings9010009

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STATEMENT OF CONTRIBUTION

To Whom It May Concern,

I, Janjua SY, contributed to literature review, method formulation, result discussions, analysis and writing (80%) of the paper/publication entitled:

Janjua SY, Sarker PK, Biswas WK. Impact of Service Life on the Environmental Performance of Buildings. Buildings. 2019, 9:9. http://doi.org/10.3390/buildings9010009

The remaining 20% of this paper/ publication was contributed by A/Prof. Wahidul K. Biswas (10%) and A/Prof. Prabir K. Sarker (10%).

Signature: Date: 01 March 2021

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 01 March 2021

Co-author 2: A/Prof Prabir K. Sarker Date: 01 March 2021

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Impact of Service Life on the Environmental Performance of Buildings

Shahana Y. Janjua [1,*], Prabir K. Sarker [1] and Wahidul K. Biswas [2]

[1] School of Civil and Mechanical Engineering, Curtin University, Perth 6102, Australia; P.Sarker@curtin.edu.au
[2] Sustainable Engineering Group, Curtin University, Perth 6102, Australia; W.Biswas@curtin.edu.au
* Correspondence: s.janjua@postgrad.curtin.edu.au

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Abstract: The environmental performance assessment of the building and construction sector has been in discussion due to the increasing demand of facilities and its impact on the environment. The life cycle studies carried out over the last decade have mostly used an approximate life span of a building without considering the building component replacement requirements and their service life. This limitation results in unreliable outcomes and a huge volume of materials going to landfill. This study was performed to develop a relationship between the service life of a building and building components, and their impact on environmental performance. Twelve building combinations were modelled by considering two types of roof frames, two types of wall and three types of footings. A reference building of a 50-year service life was used in comparisons. Firstly, the service life of the building and building components and the replacement intervals of building components during active service life were estimated. The environmental life cycle assessment (ELCA) was carried out for all the buildings and results are presented on a yearly basis in order to study the impact of service life. The region-specific impact categories of cumulative energy demand, greenhouse gas emissions, water consumption and land use are used to assess the environmental performance of buildings. The analysis shows that the environmental performance of buildings is affected by the service life of a building and the replacement intervals of building components.

Keywords: building; environmental life cycle assessment; service life; environmental performance

1. Introduction

A building is a complex product of different components of variable materials, structural importance, functional life, exposure constraints, and damage mechanisms. Each component of a building has a typical functional requirement and it should perform as per the prescribed function in its service life. Life cycle assessment (LCA) studies that have been conducted, to date, consider the service life of building and building components between 30 and 70 years with a most commonly used value of 50 years (Table 1). However, the real picture is quite contradictory to these assumptions as the service life of buildings varies with materials, operation and maintenance and the surrounding environment [1,2]. This discrepancy may lead to inaccuracy of LCA analyses, and material and energy balance. Any building needs regular maintenance and replacement of its non-structural components to keep the building in performing conditions. In second half of the 20th century, a considerable number of buildings were constructed that need annual inspections and maintenance, influencing the national economy and competitive position of the construction industry [3]. The maintenance and replacement intervals of existing buildings need to be optimized to achieve environmental, social and economic benefits. For new constructions, the estimated intervals of maintenance and replacements should be planned as concisely and wisely as possible. The integration of knowledge of building component durability and its structural and functional performance into building LCA could help conduct a realistic assessment of the environmental performance of building components [4]. Due to the uncertainty associated with the use of assumed service life of a building, as well as the unavailability of service life data of building components, LCA studies have not frequently addressed the real energy consumed during maintenance and replacement activities. However, this energy (hereafter, named replacement energy) may be as much as 7% to 110% of the initial embodied energy, if the service life of building materials is not properly implemented in the design phase of a building [4–7]. The building life span, whether short or long, has discretionary effects on a building's environmental performance. Short service life of buildings results in excessive solid waste, embodied energy and subsequent greenhouse gas (GHG) emissions during pre-use stage (extraction of material to construction). Long service life of buildings increases replacement of building components, resulting in an increase of replacement energy and prolonged use stage, increasing operational energy and GHG emissions [1]. These two constraints need to be taken into account during material selection by considering the service life of the whole building, as well as its components, and is essential to achieve environmental performance while fulfilling social and economic objectives.

Table 1. Existing case studies.

Author	Life Span (Years)	Impact Indicators
Ramesh et al. [8]	75	Life cycle energy demand
Allacker K. [9]	60	External costs
Audenaert A. [10]	50	Waste generation
Carre A. [11]	60	Global warming potential (GWP), Cumulative energy demand (CED), water use, solid waste, photochemical oxidation, eutrophication, land use, and resource depletion
Iyer-Raniga U. [12]	100	Carbon emission, energy, photochemical oxidation, eutrophication, land use and water use
Rouwette R. [13]	50	GHG, CED
Cuellar-Franca R.M. [14]	50	GWP, acidification, eutrophication, abiotic depletion, ozone depletion, photochemical ozone creation, human toxicity
Nemry F. [15]	40	GWP, primary energy, acidification, eutrophication, ozone depletion, photochemical, ozone creation
Ortiz O. [16]	50	GWP, acidification, human toxicity, abiotic depletion, ozone depletion
Crawford et al. [6]	50	Embodied energy, cost, operational energy
Cabeza et al. [17]	30 to 100 mostly 50	Life cycle energy
Biswas W.K. [18]	50	GHG emissions, Embodied energy (EE)
Islam H. [19]	50	Life cycle energy, life cycle cost (LCC)
Atmaca A. [20]	30 to 100 mostly 50	GHG emissions
Lawania K.K. [21]	50	GHG emissions, life cycle energy
Grant A. [1]	Estimated	GWP, atmospheric ecotoxicity, atmospheric acidification
Dixit M.K. [22]	50	Embodied energy
Vitale P. [23]	50	GWP, respiratory inorganics potential, non-renewable energy potential, waste framework directive
Vitale P. [24]	50	Respiratory inorganics, GWP, non-renewable energy
Balasbaneh A.T. [25]	50	GWP, human toxicity, acidification, eutrophication, LCC, labor wage rate, job creation

According to ISO 15686-1, "Service life is the period of time after construction, in which a building and its parts meet or exceed the acceptable minimum requirements of performance established" [26]. The service life of building components largely depends on the materials' properties, damage mechanisms, environment and quality of design, and work execution. This study aims to estimate the service life of buildings and building components and expected replacement intervals of non-structural components, and to assess the impact of this service life on life cycle environmental performance of buildings.

1.1. Service Life Estimation

Service life (SL) estimation of buildings is quite a complicated process that involves intensive data analysis as there is no proto-type in buildings. Each building is unique in its composition, material specification and architectural and structural design. Therefore, the SL estimation cannot be generalized and needs to be carried out on a component to component basis. Construction materials have different properties and damage mechanisms and behave differently in different climates. User requirements, degradation agents, and building performance against these agents are important factors to consider for service life planning [27]. The state-of-the-art report on performance-based methods on service life prediction states that "Prediction of durability is subject to many variables and cannot be an exact science" [28]. Therefore, efforts should be made to achieve the most likely estimate by considering the most reliable data sources.

SL prediction methods should be generalized, easy to apply to a variety of materials, user friendly and give clear boundary limitations [29]. SL was first studied by Legget and Hutcheon in 1958. However, SL estimation has been under the limelight since the 1990s by different standard institutes. The Guidelines for Service Life Planning were first published by the Architectural Institute of Japan (AIJ) in 1989 followed by British Standard Institute (BSI) in 1992 and Canadian Standards Association (CSA) in 1995. International standard organizations (ISO) published ISO 15686-1, Building and constructed assets—Service Life Planning—Part 1 in 2000 [30]. A series of publications on ISO 15686 were published afterwards, covering different aspects and procedures of service life predictions.

Service life can be estimated by deterministic, engineering and probabilistic methods. The probabilistic method is the research approach considering degradation probability of a building during a prescribed time. The deterministic method is a simple approach utilizing factors influencing the degradation of a building under certain conditions. The factor method, described in standard, ISO 15686-2 [31], is the well-known deterministic approach. Engineering methods lie somewhere in between deterministic and probabilistic methods. Engineering methods are easy, and use the time-based degradation mechanism for interpretation [32]. SL estimation needs a wide range of data from different sources and under different conditions. These information resources may be existing building data, information collected by surveys, manufacturer data, service life modelling, insurance companies and real estate data, and expert opinion [33]. The engineering approach depends on structural properties of materials, loading conditions, chemical composition, and damage mechanisms in a buildings' life time. However, there is a huge variety of chemical compositions in materials, degradation in different environments, and variable human influences, to treat all materials just the same. Accelerated life tests carried out on building components to predict SL give reasonably accurate results. It is still a big challenge to depict the realistic conditions for life tests. In addition, the accelerated tests are quite expensive. There are also some other approaches to predict SL by considering service life models and obsolescence factors [1,34]. This method can be used for existing buildings or to be built buildings with the same material. This method requires empirical data that cannot be collected for innovative materials. Acquiring data for service life models and time constraint can pose a challenge for the SL prediction approach.

The factor method is the deterministic method that uses seven factors to predict the service life behavior of the building in different climatic conditions and geographic locations. The factor method uses reference service life (RSL) of a building component as a baseline and seven factors to modify the RSL to estimated service life (ESL). The service life estimation is different from service life prediction in the sense that the first is meant for particular conditions, and the second is recorded performance over a prescribed time or referenced SL [30,35]. The factor method helps to estimate service life of building and building components using Equation (1) [30].

$$\text{ESL} = \text{RSL} \times \text{A} \times \text{B} \times \text{C} \times \text{D} \times \text{E} \times \text{F} \times \text{G}, \tag{1}$$

where,

ESL = Estimated service life of building components

RSL = Reference service life of building components

Factor A = Quality of components including manufacturing, storage, transport and protective coating etc.

Factor B = Design level including incorporation, sheltering by rest of structure and surrounding buildings

Factor C = Work execution level, site management, workmanship level, weather condition during work

Factor D = Indoor environment conditions, humidity, ventilation, and condensation etc.
Factor E = Outdoor environment, microenvironmental conditions, weathering factors, building elevation etc.
Factor F = In-use conditions, mechanical impact, wear and tear, category user etc.
Factor G = Maintenance level, quality and frequency.

The method incorporates the material behavior, human involvement and degradation mechanism to interpret the ESL. The factor method is flexible, and it considers the combined effect of different deteriorating factors. The method needs judgement of factors as protective or deteriorating and requires fair and definite limitations on factors to avoid complexity [36]. Reliable data is required for the RSL and factors for each building component. The availability of data and reliability of data sources play an important role in SL estimation. The data sources may be manufacturers of building products, test laboratories, government agencies reports, existing studies etc., [37]. The most challenging issue in SL estimation is how to use effectively the available data to predict the SL of a structure that is to be built. In this study, the service life was estimated for most likely values (±5 years) using the factor method.

1.2. Environmental Life Cycle Assessment

The environmental life cycle assessment (ELCA), frequently known as life cycle assessment is a comprehensive tool to assess the environmental impacts of a product or system or service, in pre-use, use, and post-use stages [38]. The ELCA was studied for the first time in the 1960s and up until the 1970s, it was used only to compare the packaging options of consumer goods. In 1969, the Midwest Research Institute conducted a study on LCA for a Coca Cola Company for different types of beverage containers [39]. The studies in this period revolved around policy making and enterprises with a focus on solid wastes, energy consumption, and air pollutant impacts. In the 1990s, SETAC, conducted various workshops and published the first code of practice for life cycle assessment in 1993 [40]. Afterwards, the international standards organization (ISO), was involved actively and published generalized procedures and methods for LCA in ISO 14040-44 in 1997–2000 [38].

In the construction sector, ELCA was first applied in 1980s by Bekker to study the environmental implications of the use of renewable resources in buildings [41]. ELCA was used in buildings to assess the environmental impacts of construction materials and is a credible solution to compare material sustainability [42–45]. Now, the ELCA covers a wide range of areas from building materials (i.e., bricks, cement etc.) to urban planning [46]. The life cycle stages that are usually considered from life cycle assessment of buildings and building components include pre-construction, construction, use and end of life stages. Environmental product declarations (EPDs) involved the use of LCA to estimate environmental impacts for environmental declaration purposes for certification purposes [47]. ELCA helps to improve the performance of building in its entire life span by first identifying hotspots and then by applying mitigation strategies [47,48]. However, the system boundaries, functional units and scope definition are unique for each building LCA study, resulting in variation in results among studies [49–51].

Environmental performance of buildings is also defined as a quantified relationship between occupant's comfort level and environmental impacts [52–54]. Embodied and operational impacts are usually two main categories of environmental impacts. Embodied impacts are static and further divided into pre-use embodied impacts and replacement embodied impacts [6]. Pre-use embodied impacts are the impacts due to extraction, manufacturing and construction of buildings and replacement embodied impacts are a result of renovations, replacements and maintenance in the active service life of buildings. The operational or use stage impacts are dynamic in nature and occur in the service life of building [55,56]. Better building performance can be achieved by considering factors including material selection, construction techniques, cost factors, and cleaner production strategies (CPS).

Whilst Australia accounts for only 0.32% of the world's population, its per capita GHG emission is extremely high compared to countries with similar economies (UK, Mexico, South Korea) i.e., 26 tonnes GHG emissions per capita per year as opposed to 13 tonnes per capita GHG emissions for South Korea, 10 tonnes per capita GHG emissions for UK and 20.3 tonnes per capita GHG emissions for Canada [57]. Australia is the second driest continent after Antarctica [58]. The annual rainfall is highly variable and central Australia is mostly arid with only 6% arable land in coastal areas [59]. Water is the most precious commodity and its scarcity is covered by desalination of sea water [60–62]. Water mapping in the construction industry helped to identify need for reducing the life cycle water demand/footprint of buildings by using renewable resources. In addition, Australia's per capita waste generation is 2.6 tonnes per year as compared to 0.706 tonne per capita per year for US, out of which 0.8 tonnes per capita per year is construction and demolition waste [63]. Therefore, these two issues are inevitable for assessment of the environmental impacts of building and construction industry at the planning stage of buildings using an ELCA to discern strategies to avoid these environmental consequences. This study thus considered these impact categories, including cumulative energy demand, GHG emissions, water consumption and land use to assess the environmental performance of buildings.

2. Method

This study focuses on the impact of service life on environmental performance of buildings. The methodology consists of four main steps (Figure 1). Step 1: Twelve residential buildings were selected. All specifications of the buildings including the architectural design, covered area, orientation, and utility were the same except for the difference in building materials. The residential buildings were modelled using three main systems of roof, wall and footing.

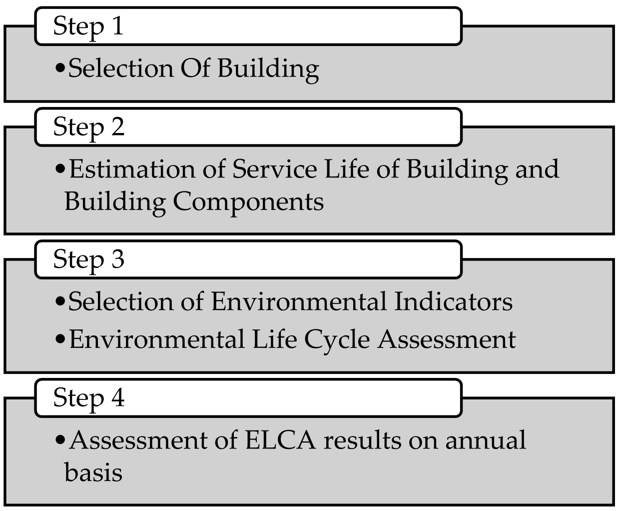

Figure 1. Building environmental performance assessment procedure.

The roof system comprised of roof cladding, roof frame, and suspended ceiling. The wall system comprised of exterior render, wall frame and interior plaster and the footing system comprised of footing slab and flooring. The variation in buildings was created only in materials of structural components. The materials for non-structural components were unchanged as replacements for these components are considered easy and does not affect the service life of the whole building. Two types of roof frames, two wall frames and three types of slab footings, resulted in 12 combinations of buildings (Table 2) and a conventional building named Building-50 composed of a timber roof frame, double brick walls and conventional concrete was considered as a reference case for comparison with the aforementioned 12 buildings.

Table 2. Building components of building combinations and the reference building.

Building	Building Specifications	Building Components		
		Roof Frames	Wall Frames	Slab Footing
Building-50	TF-DB-CC	Timber frame	Double Brick	Conventional concrete
1	TF-CB-CC	Timber frame	Concrete Block	Conventional concrete
2	TF-CB-FAGC	Timber frame	Concrete Block	30% FA Green concrete
3	TF-CB-GGBFS	Timber frame	Concrete Block	30% GGBFS Green concrete
4	TF-DB-CC	Timber frame	Double Brick	Conventional concrete
5	TF-DB-FAGC	Timber frame	Double Brick	30% FA Green concrete
6	TF-DB-GGBFS	Timber frame	Double Brick	30% GGBFS Green concrete
7	SF-CB-CC	Steel Frame	Concrete Block	Conventional concrete
8	SF-CB-FAGC	Steel Frame	Concrete Block	30% FA Green concrete
9	SF-CB-GGBFS	Steel Frame	Concrete Block	30% GGBFS Green concrete
10	SF-DB-CC	Steel Frame	Double Brick	Conventional concrete
11	SF-DB-FAGC	Steel Frame	Double Brick	30% FA Green concrete
12	SF-DB-GGBFS	Steel Frame	Double Brick	30% GGBFS Green concrete

Step 2: The service life of each building component was estimated using the factor method [37]. The service life of a system was taken as the service life of structural components i.e., ESL of the roof system was the value of service life for the roof frame. The least value of service life among building systems i.e., roof system, wall system and footing system, was taken as the estimated service life of the building [3]. The service life estimation of components was required, not only to determine the service life of the whole building, but also, to find the replacement intervals of non-structural components during the service life of a building. The service life of a reference building, Building-50 was assumed 50 years based on a literature review (Table 1).

Step 3: The indicators for environmental objective were selected by consulting existing studies. ELCA of the building was carried out as per ISO 14040-44 [38]. A quantitative life cycle inventory for building materials and transportation was compiled for construction, the subsequent replacements and demolishing activities. The ELCA considered a cradle to grave approach including pre-use (mining to material, transport of material to site and construction), use, post-use (demolition and disposal) and replacement (replacement of building components throughout the active service life of building) stages. ELCA software, SimaPro 8.4 [64], was used to determine the environmental indicators for impact categories of energy, GHG emissions, water consumption and land use.

Step 4: The impact values were presented on an annual basis for a service life of a building as estimated in the second step in order to investigate the impact of SL on environmental performance of buildings.

3. Case Studies

A typical house of four bedrooms and two bathrooms, with a covered area of 245.5 m^2 located in Perth WA, was selected for the case study. Twelve building combinations were created based on the roof, wall and footing systems, keeping architectural design, orientation, location and covered area constant (Table 2).

Table 3. Criteria and Coefficients of service life estimation

Factor Description		Roof System				Wall System				Footing System			
Factor	**Criteria**	**Timber Truss**	**Steel Truss**	**Terracotta Tiles**	**Gypsum board**	**Concrete Block**	**Double Brick**	**Plaster**	**Render**	**CC**	**30% FAGC**	**30% GGBFS**	**Ceramic Tiles**
A	A = 1.1, Best Available Material; A = 1.05, Good Material; A = 1.0, N/A-No effects; A = 0.95, Slightly low Standard material; A = 0.90, Low Standard Material	1.10	1.10	1.10	1.10	1.10	1.10	1.05	1.05	1.05	1.05	1.10	1.10
B	B = 1.1, Best Design with special considerations to strengthen the structure; B = 1.05, Good Design, (as per standards approach); B = 1.0, N/A-No effects; B = 0.95, low Standard design; B = 0.90, poor design	1.05	1.05	1.00	1.00	1.10	1.10	1.05	1.05	1.05	1.05	1.05	1.00
C	C = 1.1, Satisfaction Level $\geq$ 90%; C = 1.05, 80% < Satisfaction Level > 90%; C = 1.0, N/A-No effect; C = 0.95, 70% < Satisfaction Level > 80%; C = 0.9, Satisfaction Level $\leq$ 70%	0.90	0.90	0.90	1.05	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90
D	NOT CONSIDERED	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E	E = 1.1, Supportive; E = 1.05, mild; E = 1.0, N/A-No effect; E = 0.95, Harsh; E = 0.9, Reactive	1.05	1.05	0.95	1.00	1.00	1.00	1.00	0.90	0.90	1.05	1.05	1.00
F	NOT CONSIDERED	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
G	G = 1.1, Best quality and interval as specified by manufacturer/designer; G = 1.05, good quality and interval as per requirement; G = 1.0, N/A-NO EFFECT; G = 0.95, low quality and as per required; G = 0.9, poor quality	1.05	1.05	1.05	1.05	1.00	1.00	1.05	1.05	1.00	1.00	1.00	1.05
RSL	Primary source [80% reliability] = manufacturers technical sheets, EPDs	50	75	50	25	60	75	25	15	60	60	60	50
ESL	Secondary source [60% reliability] = Databases like NAHB, BOMA; literature; experimental studies; codes and practices;	57	86	49	30	65	82	26	15	57	66	69	52

Each of the roof, wall and footing systems was modelled using structural and non-structural building components. Only the non-structural components were selected, that resulted in costly replacements and provided a thermal envelope to the building. However, this aspect of the building enveloping components will be assessed in future study. The roof system included two types of roof assemblies: TF—timber roof frame, terracotta tiles and gypsum board ceiling; and SF—steel roof frame, terracotta tiles and gypsum board ceiling. The wall system consisted of two types of wall assemblies: DB—double brick wall and interior plaster; and CB—concrete block wall, exterior render and interior plaster.

The footing system comprised of on-grade slab footing and ceramic tile flooring with three types of concrete mixes: CC—conventional concrete; 30% FA—Green concrete with 30% replacement of Ordinary Portland Cement (OPC) by class F fly ash; 30% GGBFS—Green concrete with 30% replacement of OPC by ground granulated blast furnace slag (GGBFS). The building systems were developed based on the most commonly used materials, in Western Australia with a design life of 50 years as proposed by National Building Codes. A conventional residential building with a timber roof, double brick walls and conventional concrete slab footing and 50-year service life was used as the reference building, Building-50.

A thorough study was conducted to collect the service life data of the building components used in the case study. Based on the gathered information, ranking criteria were set for each factor, to get most likely values (ESL $\pm$ 5 years) of ESL (Table 3). Factor A, B, C, E, G were assigned ranking values from 1.1 to 0.9 [37], and Factor D, F were not considered in the study as these are dependent on occupant behavior and vary greatly. These factors were assigned a value of 1.0 in service life estimation equation. The factor values were reduced to increase the confidence level as compared to previously used values to test the sustainability framework for Building 1 and 2 [65].

The manufacturer data, life expectancy databases of building components and existing case studies were used as data sources for RSL. The manufacturer's technical data sheets were consulted to set the component quality. The factor B values were assigned by considering commonly used practices in building design in Western Australia. Building commission WA annual reports were consulted to estimate the construction works execution level. The climatic conditions, reports of Bureau of Meteorology Western Australia, and inspection reports of residential buildings were considered for weighting outdoor climatic conditions and subsequent effect on the building components.

The life cycle assessment software SimaPro 8.4 was used to assess the environmental impacts of buildings with a grave to cradle approach. Materials required for each building were estimated for building construction and successive replacements. The transportation distances were calculated for nearest available materials retailers and manufacturers. The energy consumption during the use stage was estimated for thermal comfort, hot water, lighting and home appliances. AccuRate sustainability software [66] was used to estimate the annual cooling, heating, and hot water demand. The life cycle inventories for materials, energy consumption and transportation distances were compiled to incorporate in the SimaPro (Tables A1–A5). Table 4 shows the environmental impact categories, impact indicators and methods used to assess the environmental impacts. These impact indicators were selected based on literature review and relevance to the scope of the study.

Table 4. Environmental Impact indicators

Impact Category	Impact Indicators	Impact Assessment Methods
Energy	Cumulative energy demand	Cumulative Energy Demand V1.09
GHG emissions	Life cycle GHG emissions	IPCC 2013 GWP 100a V1.02
Land use	Land use	Ecological footprints Australian V1.00
Water consumption	Resource depletion	Pfister et al. 2009 (Eco-indicator 99) V1.02

4. Results and Discussion

4.1. Estimated Service Life

The ESL of buildings and building components are presented in Table 5. The service life estimation shows that due to the large variation in service life of building components, enough life of building components is compromised. Approximately, 20% to 35% of ESL of structural components of 12 buildings, studied in this paper, is wasted. In buildings 4–7, the wall system has 82 years ESL that is 30.5% more than the ESL of the building. In buildings 10–12, the wall and roof systems both have higher ESL values than the footing system. In buildings 7–9, the roof system has a high ESL value compared to the wall and footing systems.

Table 5. Estimated service life of building systems and buildings.

Service Life (Years)	TF-CB-CC	TF-CB-FAGC	TF-CB-GGBFS	TF-DB-CC	TF-DB-FAGC	TF-DB-GGBFS	SF-CB-CC	SF-CB-FAGC	SF-CB -GGBFS	SF-DB-CC	SF-DB-FAGC	SF-DB-GGBFS
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Roof System	57	57	57	57	57	57	86	86	86	86	86	86
Wall System	65	65	65	82	82	82	65	65	65	82	82	82
Footing System	57	66	69	57	66	69	57	66	69	57	66	69
Building	57	57	57	57	57	57	57	65	65	57	66	69

In building combinations 1–3, all the three systems have comparable ESLs that makes these the combinations with less material wastage at the post-use stage.

Based on the ESL of building components, the replacements of each building component in the ESL of buildings are specified. These ESLs are calculated conservatively considering that the components maintenance is carried out, strictly on schedule as described by the manufacturer or designer. No replacement is considered in the study for the building components within a range of ±5 years of the ESL of buildings [37]. This difference is assumed to be covered by maintenance. The ceramic floor tiles have an ESL of 52 years. As the ESL of ceramic tiles is within a range of ±5 years of the ESL of buildings 1–7 and 10, therefore, no replacement for ceramic tiles is suggested in the study. However, in buildings 8–9 and 11–12, one replacement of the ceramic floor tiles is considered. One replacement for terracotta tiles is considered for all buildings. The ESL of gypsum board ceiling needs to be replaced once in the ESL of buildings 1–7, 10 and twice in buildings 8–9, and 11–12. However, exterior rendering and interior plaster of walls need regular replacements after 15 and 26 years respectively, to maintain the aesthetic looks of buildings and to strengthen the concrete block wall against its inherent porous structure. Figure 2 shows the total ESL of building components at post-use stage including replacements. The red line shows the ESL of building and above this line is the remaining ESL of building components at the post-use stage. The remaining ESL is the duration for which a component is still in serviceable condition at the time of demolition of the building. The remaining life for structural components is the ESL of the component, however, the remaining life for non-structural components is calculated by multiplying the ESL of building components with number of replacements and subtracting from the ESL of building. The estimated number of replacements and remaining service life of building components is presented in Tables A6 and A7 in Appendix A section. The study has shown that the lowest remaining life of building components at post-use stage (end of life of building), results in better environmental performance of building, due to reduced material wastage to landfill.

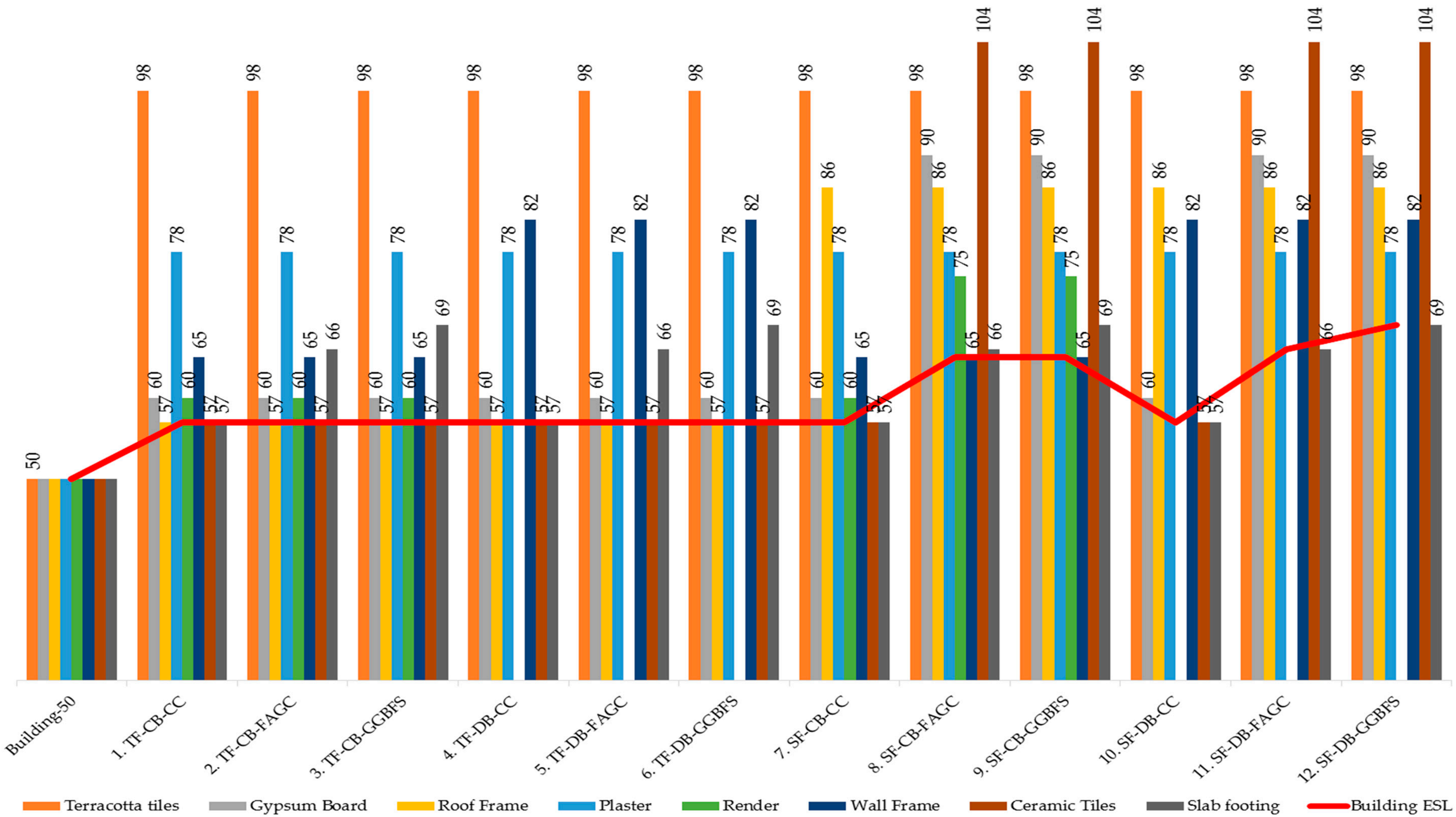

Figure 2. Remaining service life of building components at Post-Use Stage.

4.2. Cumulative Energy Demand

The cumulative energy demand (CED) is calculated on an annual basis to study the impact of service life on the environmental performance of buildings. The CED ranges from 97.799 to 101.813 GJ/year for 12 buildings. The CED is the highest in use stage with a value of 82.634 GJ/year and uniform in each case as no CPS is applied to buildings. The pre-use CED values are highest after the use stage due to energy consumed in extraction of raw materials, manufacturing of materials, transportation to site and construction activities. The replacement stage is the third main contributor to the CED of buildings (range from 2.02 to 3.73 GJ/year for 12 buildings), due to constant addition of embodied energy of replaced building components, at regular intervals (Table A6) during building service life. The post-use CED is negligible, as demolition and disposal of demolition waste to landfill ranges from 0.98 to 1.27 GJ/year for 12 buildings (1% of total energy demand) [4,67].

Figure 3 shows that CED is the lowest for building 8 (SF-CB-FAGC) with an ESL of 65 years i.e., 4.23% lower than the conventional Building-50 (TF-DB-CC) due to its longer ESL and the use of green concrete (OPC replaced by 30% FA). Similarly, the CED of building 9 (SF-CB-GGBFS) is 4.08% lower than Building-50, also mainly due to longer ESL. Buildings 4 (TF-DB-CC), 5 (TF-DB-FAGC), 6 (TF-DB-GGBFS) and building 10 (SF-DB-CC) have almost the same CED as Building-50 (102.118 GJ/year) with negligible differences between 0.37% and 0.63% owing to relatively shorter ESL than buildings 8–9, 11–12, and also because of the use of energy intensive structural material (e.g., double brick wall).

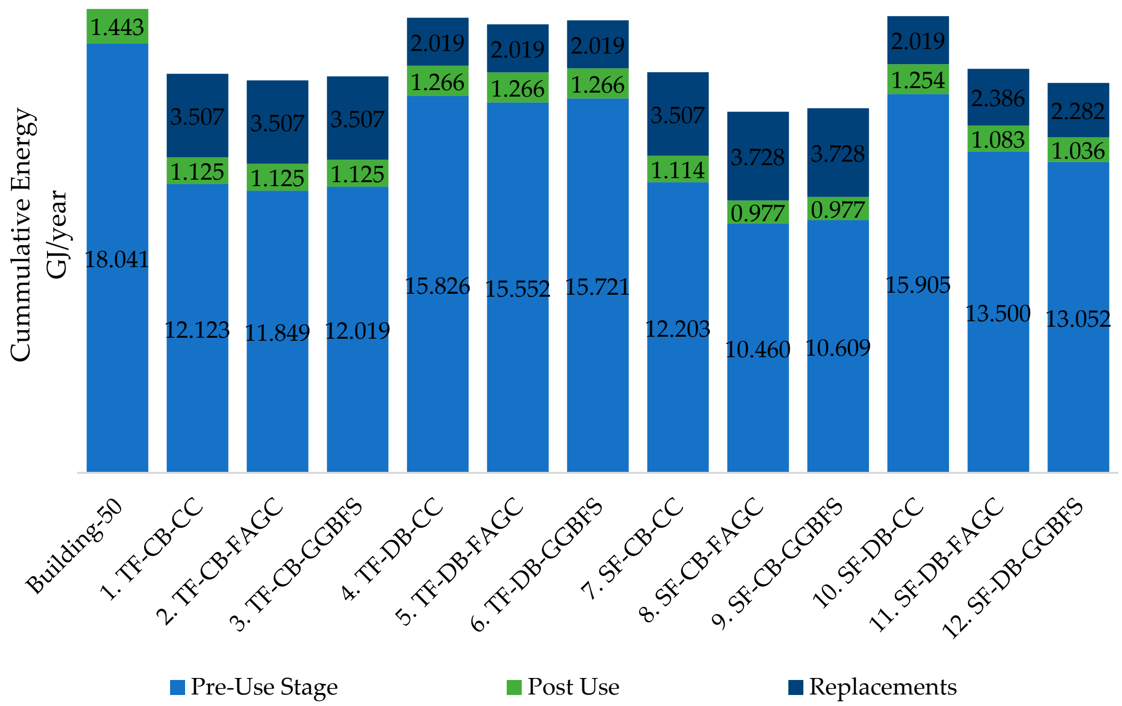

Figure 3. Cumulative Energy Demand per year per building, for 12 buildings and Building-50. (Use stage is omitted in the graph as the use-stage CED value 82.634 GJ/year is uniform in all cases and if plotted on same scale, other stages due to low values cannot be presented properly).

The longer ESL of building 12 (SF-DB-FAGC) and 11 (SF-DB-GGBFS) with ESL of 69 and 66 years, has reduced the share of pre-use energy consumption in comparison to buildings 4–6 and 10 that are composed of energy intensive brick walls and have an ESL of 57 years. Building 9 has the lowest energy demand in pre-use and post-use stage due to having low energy intensive concrete block wall and ESL of 65 years reducing per year share of CED of the building.

In the replacement stage, buildings with concrete block wall (1–3, 7–9) have high replacement embodied energy due to frequent replacements of energy intensive rendering and plastering. In buildings 8–9, the replacement embodied energies are highest due to ceramic tiles replacement in addition to rendering and plastering (Figure 2). Similarly, buildings 4–6, 10 with double brick walls have low replacement embodied energy as only interior plastering is replaced at a regular interval of 26 years (Table A6). Buildings 11 and 12, with longer ESL, have slightly higher replacement stage embodied energy due to replacement of ceramic tiles.

Although replacement embodied energy is higher in some buildings, the longer ESL of buildings reduces the impact of replacement embodied energy, as in buildings 8–9. In some cases, the use of energy intensive structural building components in fact reduced the overall CED of buildings. The steel frame roof is an energy intensive material, but its use had indirectly reduced the annual CED by increasing ESL of building combinations 8–9 and 11–12.

The results of this study were compared with similar studies in WA. Lawania and Biswas [68], estimated the annual CED for residential buildings across Western Australia showed slightly higher CED (138 GJ/year), which this value varies between 97.8 and 101.81 GJ/year under this current study. This variation happened due to the fact that Lawania and Biswas had used 18 different climatic locations and also one service life of 50 years was considered. In other studies of residential buildings that considered the embodied energy of building components replaced during ESL, embodied energy was found to increase by 20% to 40% due to increase of service life from 50 to 100 years [4,69,70]. Similar results were found for some buildings (buildings 8–9, 11–12) in the current study, where longer ESL had in fact increased the CED by 17% to 33% due to replacement of building components during ESL.

4.3. GHG Emissions

The GHG emissions in 12 buildings vary from 11.383 to 11.49 t CO_2 eq. The GHG emissions are highest in use stage with a value of 9.918 t CO_2 eq/year and uniform for all buildings like CED assessment due to use of electricity that is predominantly generated from fossil fuels (49% black coal and 36% gas) in WA [71]. The pre-use GHG emissions are highest after the use stage due to fossil fuel consumptions in extraction and manufacturing of materials, transportation of materials to site and construction equipment. The replacement stage is the third main contributor to the GHG emissions of buildings, due to the addition of the materials to building during ESL. The post-use CED is negligible as the demolition and disposal of demolition waste to landfill consumes only 1% of the total energy [4,67].

Building-50 (reference building) with a 50-year ESL, has annual GHG emissions of 11.455 t CO_2 eq/year, despite the absence of the replacement stage. Annual GHG emissions for building 2 (TF-CB-FAGC) with an ESL of 57-years, are the lowest among all the building combinations (i.e., 0.626% less than Building-50) due to use of low carbon intensive materials (timber, concrete blocks), less replacements of non-structural components (rendering, plastering) and most importantly due to having a similar ESL of building components as the whole building. These design specifications result in lower wastage of material or embodied energy at the post-use stage. Building 10 (SF-DB-CC) with an ESL of 57 years has the highest GHG emissions per year of 11.49 t CO_2 eq/year (i.e., 0.308% higher than Building 50) due to shorter ESL and use of energy intensive structural components (double brick wall, steel frame roof) with ESL longer than building ESL. It is worth mentioning that the building components with longer ESL than the whole building remains unused after the end of life demolition and disposal stage and are being considered as wastes.

Figure 4 shows that the double brick buildings 4 (TF-DB-CC), 5 (TF-DB-FAGC), 6 (TF-DB-GGBFS), and 10 (SF-DB-CC) have high pre-use stage annual GHG emissions of 1.265, 1.218, 1.230, and 1.279 t CO_2 eq/year, than Building-50, with 1.443 t CO_2 eq/year annual GHG emissions due to relatively longer ESL of 57 years and also due to use of energy intensive structural components i.e., brick walls (buildings 4–6, 10) and steel frame roof (building 10) with longer ESL (Figure 2) that is wasted to landfill at the post-use stage.

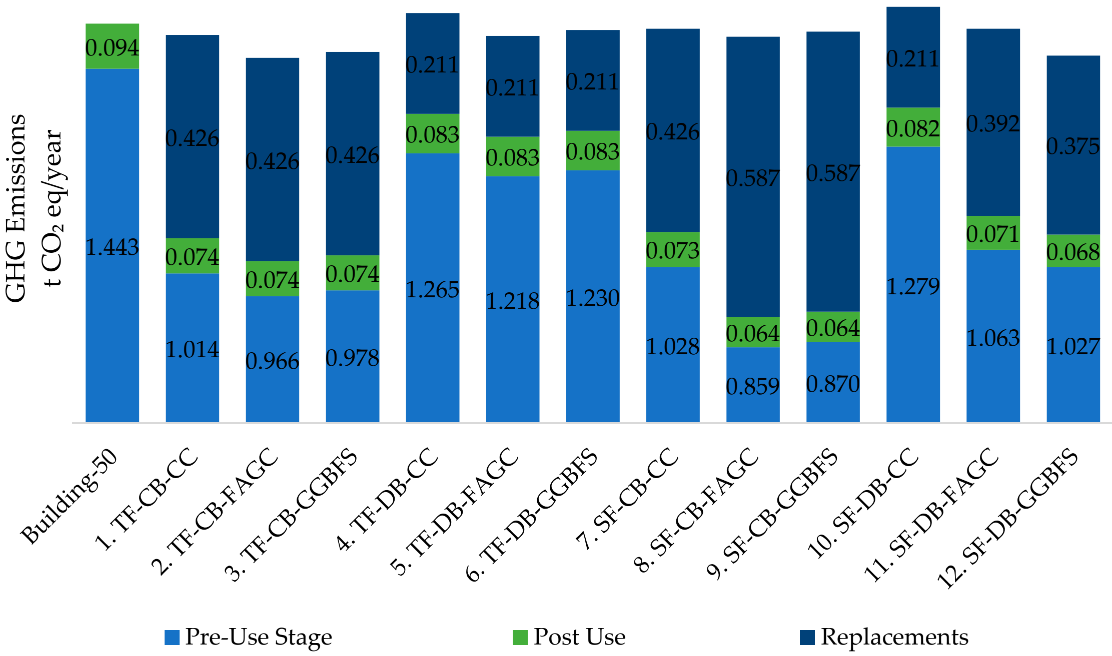

Figure 4. Life cycle greenhouse gas (GHG) emissions per year per building for 12 buildings and Building-50. (Use stage is omitted in the graph as the use-stage GHG value 9.918 t CO_2 eq/year is uniform in all cases and if plotted on same scale, other stages due to low values cannot be presented properly).

The GHG emissions associated with the replacement of components during the active service life are highest for building 8 (SF-CB-FAGC) and 9 (SF-CB-GGBFS) with a value of 0.587 t CO_2 eq/year. The reason for high replacement GHG emissions in these buildings is the use of carbon intensive ceramic tiles (13.07 t CO_2 eq) and rendering processes (10.56 t CO_2 eq). Additionally, the replaced ceramic tiles were not fully utilized as the ESL of buildings 8 and 9 expired at the 33% ESL of ceramic tile and therefore this valuable material was disposed along with other building materials into the landfill. The recovery of this carbon intensive material thus needs to be considered for use in similar applications during its remaining life (i.e., 67% of ESL). In addition, the rendering used large amounts of carbon intensive OPC (Ordinary Portland Cement). Nonetheless, due to the porous nature of concrete blocks, rendering or an alternative process is required to provide coverage to concrete blocks, which in fact increased the overall energy consumption as well as the GHG emissions.

Annual GHG emissions for case study buildings in the current study vary between 10.957 and 11.49 t CO_2 eq/year and is slightly higher than Lawania and Biswas [68,72] (9.4 t CO_2 eq/year). This is mainly due to differences in parameters like service life and climatic conditions affecting use stage GHG emissions. In a study by Carre A. [11] for Australian houses with a 50-year service life, pre-use GHG emissions (0.908 t CO_2 eq/year) are similar to current study (0.859 to 1.279 t CO_2 eq/year).

4.4. Land Use

Land use impact is the highest in the use stage (1.353 Ha_a/year) as standard energy input is used for all buildings without considering any greener choices such as wind mills, solar panels etc. The land use in the pre-use stage is the highest after the use stage as it is the summation of all land utilized during the extraction of raw materials, manufacturing of materials, transportation to site and construction equipment, followed by the replacement stage. The post-use stage land utilization is negligible as only energy consumption for the demolition and disposal of demolition waste to landfill is assessed for the study.

Figure 5 shows that the building 4 (TF-DB-CC) has the highest land use impact of 1.583 Ha_a (actual hectare) per year due to the timber frame roof (material acquired by plants) and shorter ESL.

Building 12 (SF-DB-GGBFS) has the lowest impact with a value of 1.558 Ha_a/year. The longer ESL of building 12 and use of industrial by-products like GGBFS [11] has contributed to the lower land use impact.

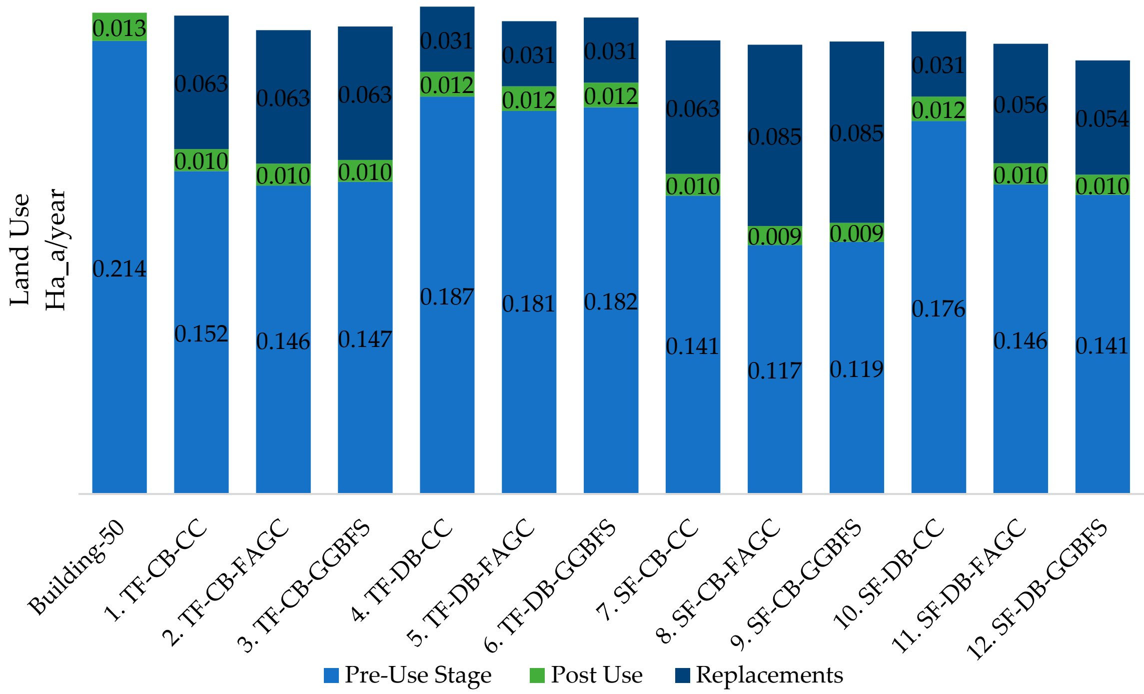

Figure 5. Life cycle land use per year per building for 12 buildings and Building-50. (Use stage is omitted in the graph as the use-stage Land use value 1.353 Ha_a/year is uniform in all cases and if plotted on same scale, other stages due to low values cannot be presented properly).

Building 4 (TF-DB-CC), 5 (TF-DB-FAGC), and 6 (TF-DB-GGBFS) have the highest land use in the pre-use and post-use stages among 12 buildings, due to the increased amount of land requirement associated with the production of a timber frame roof, and also because these materials have short ESL meaning that more land is required to make these materials to meet the demand for replacement. The land use impact for replacement stage is higher for buildings 8 and 9 with 65-year ESL, as more energy and carbon intensive materials (e.g., ceramic tiles, rendering, plastering) requiring more space for mining, processing and manufacturing are replaced during this long ESL (Figure 2). Replaced building components in buildings 8 and 9 have about 33% to 60% of the remaining life at the end of the building service life (Figure 2).

The building with components with similar ESLs to the whole building ESL generate less waste which means the diversion of waste from landfill or residue area, thus conserving land or reducing the land footprint. From the ecological footprint point of view, the buildings with a timber roof and double brick wall frame have higher impacts than building with building components of industrial material on an annual basis, which is consistent with the existing study of Allacker et al. [73]. In the post-use stage, ceramic tiles and rendering have the highest impacts as these materials are disposed of before their ESL was finished.

4.5. Water Consumption

Life time water consumption by case study buildings is calculated in terms of damage to resources. The resource depletion is the minimum time step to assess the water resource depletion in areas like Western Australia with fixed annual precipitation cycle [60].

Resource depletion is the highest in the use stage due to high water consumption in electricity generation [74]. The resource depletion in the pre-use stage is the second highest in buildings due to water consumption mainly in the extraction of materials and manufacturing processes. In the pre-use stage, onsite water consumption (construction works) is negligible (0.1%) as compared to upstream processing of materials. The replacement stage is contributing as the third major stage due to building component replacements. Like CED, GHG emissions and land use, the post-use stage has the least water footprint due to consideration of only demolition of buildings and transportation energy consumption to dispose of these wastes to landfill.

Figure 6 shows that the annual resource depletion is the highest for building 8 (SF-CB-GGBFS) due to use of industrial materials (steel frame, concrete block, rendering and interior plaster). The resource depletion is lowest for Building-50 as no replacement is considered for Building-50 and it has a brick wall and timber frame roof that are less water consuming materials. In the case study buildings, building 5 (TF-DB-FAGC) has slightly higher water demand as compared to the reference building (Building-50) mainly because of replacements and an ESL of 57 years.

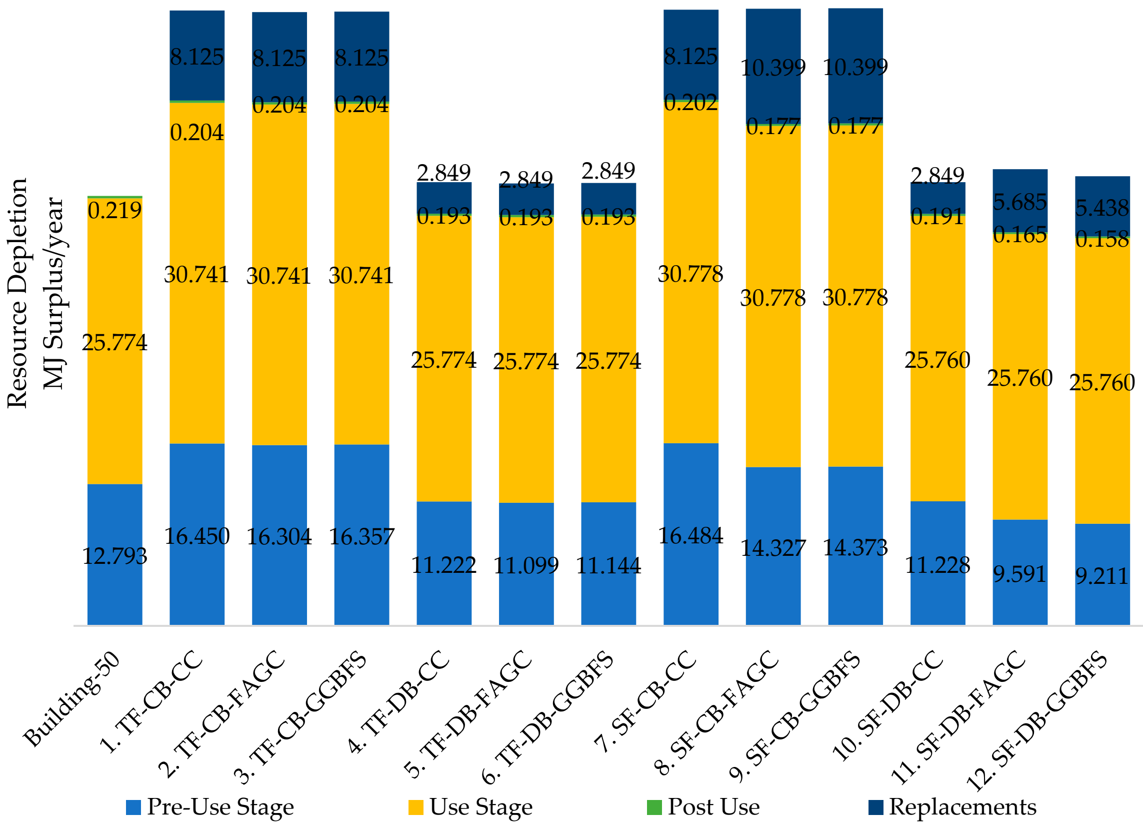

Figure 6. Life cycle resource depletion per year per building for 12 buildings and Building-50.

For pre-use stages, building 7 has the highest water footprint of 16.484 MJ surplus/year due to a shorter ESL and use of building components of industrial materials. The lowest water footprint in pre-use stage is for building 12 (SF-DB-GGBFS) with longer ESL and structural components like brick, green concrete, that have lower water demand and decreased overall water consumption by building [75,76]. In concrete block wall buildings (building 1 (TF-CB-CC), 2 (TF-CB-FAGC), 3 (TF-CB-GGBFS)), water consumption in concrete block and plaster production, as well as the rendering process and their shorter ESL, are the main contributing factors for water footprint [75]. In the replacement stage, the concrete block wall and steel frame roof in buildings 8 (SF-CB-FAGC) and 9 (SF-CB-GGBFS) with 65-year ESL have the highest mineral resource depletion due to frequent replacements of rendering, interior plaster and water intensive ceramic tiles.

5. Conclusions

This study used the life cycle assessment procedure (ISO 14040-44) [38] and factor method (ISO 15686-2) [31,37], to determine the impact of service life on the environmental performance of buildings. The service life of a building and building components have a direct relationship with environmental performance of building. Estimation of replacements intervals is important in the environmental life cycle assessment of buildings, as these are the third main contributing stage to environmental impacts, after use and pre-use stage. The cumulative energy demand for building 8 (SF-CB-FAGC) is 97.779 GJ/year, 4.23% lower than the reference building, due to the ESL of 65 years. The GHG emissions for building 2 (TF-CB-FAGC) is 11.383 t CO_2 eq/year, the lowest among the case study buildings, due to use of structural components with a comparatively similar service life as ESL of buildings. The land use for building 12 (SF-DB-GGBFS) is 1.558 Ha_a, the lowest among case study buildings (0.96% lower than reference building), due to longer ESL and the use of industrial by-products which reduces land use for residue storage. Building 5 (TF-DB-FAGC) has the lowest water footprint (39.915 MJ Surplus/year) amongst case study buildings (2.827% higher than the reference building), due to use of timber and brick.

This study showed that buildings 1–12 have better performance than Building-50 for CED, and buildings 1–3, 5–9 and 11–12 have lower GHG emissions than Building-50. In the land use impact category, buildings 1–3 and 5–12 have lower land use. However, the water footprint results are slightly different than CED, GHG and land use. Building-50 has the lowest water demand as compared to the 12 case study buildings.

Current research shows that building environmental performance is dependent on building component's materials and ESL, and the way these components are modeled into building. The use of industrial byproducts (concrete blocks, steel) could enhance performance for land use, while building materials like timber and brick have a better water footprint. Industrial byproducts (FA) have lower environmental impact for all indicators considered in this research. The service life of buildings and building components affect the environmental performance of buildings. The use of alternative, eco-friendly strategies in buildings like grey water, green concrete, renewable resources are effective only if these are aligned with building service life. Longevity of the service life of buildings can produce sustainable outcomes, if all of the building component's service life is nearest to the building's service life, which causes fewer replacements, as well as the GHG emissions from the transportation of waste during the post-use stage.

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Appendix A

Table A1. Life cycle inventory of materials for the construction stage of case study buildings.

Material (tonnes)	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS
1. Excavation of foundation	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83
2. Sand: Sub-base	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01
3. On grade slab (including water proofing membrane, mesh reinforcement, ready mix concrete-N20)	79.56	79.56	79.56	79.56	79.56	79.56	79.56	79.56	79.56	79.56	79.56	79.56	79.56
4. Floor Tiles (Ceramic)	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
5. Concrete Blocks wall (including mortar, steel rebar, metal lintels)		75.78	75.78	75.78				75.78	75.78	75.78			
6. Bricks (including mortar, metal lintels)	107.4				107.4	107.4	107.4				107.4	107.4	107.4
7. Plaster	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54
8. Rendering		13.86	13.86	13.86				13.86	13.86	13.86			
9. Gypsum board ceiling	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19
10. Roof Timber (including bat insulation)	4.61	4.61	4.61	4.61	4.61	4.61	4.61						
11. Roof Steel (including bat insulation)	x	x	x	x	x	x	x	2.33	2.33	2.33	2.33	2.33	2.33
12. Terracotta roof tiles	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55
13. Metal door frames: 12 no.	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Door shutters: 12 no.	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
14. Aluminum windows: Single glazed	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Total material transported to construction site	254.3	236.5	236.5	236.5	254.3	254.3	254.3	234.3	234.3	234.3	252	252	252
Total material transported to landfill	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83

Table A2. Life cycle inventory of materials for the replacement stage of case study buildings.

Material (tonnes)	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS
Terracotta tiles		16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55
Gypsum board		2.19	2.19	2.19	2.19	2.19	2.19	2.19	4.38	4.38	2.19	4.38	4.38
Plaster		21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08
Render		41.58	41.58	41.58	n/a	n/a	n/a	41.58	55.44	55.44	n/a	n/a	n/a
Ceramic tiles		0	0	0	0	0	0	0	5.47	5.47	0	5.47	5.47
Total material transported to site for replacement works		81.4	81.4	81.4	39.8	39.8	39.8	81.4	102.9	102.9	39.8	47.5	47.5
Total material transported to landfill		81.4	81.4	81.4	39.8	39.8	39.8	81.4	102.9	102.9	39.8	47.5	47.5

Table A3. Life cycle inventory of material transportation for the construction stage of case study buildings.

Carriage (tkm)	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS
Sand for levelling	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5
Material to site	6848.4	6316.2	6316.2	6316.2	6848.4	6848.4	6848.4	6247.8	6247.8	6247.8	6780	6780	6780
Construction waste	342.42	315.81	315.81	315.81	342.42	342.42	342.42	312.39	312.39	312.39	339	339	339
Dirt to landfill	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5
Material to landfill	1683.92	1657.31	1657.31	1657.31	1683.92	1683.92	1683.92	1653.89	1653.89	1653.89	1680.5	1680.5	1680.5

Table A4. Life cycle inventory of material transportation for the replacement stage of case study buildings.

Carriage (tkm)	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS
Material to site		2442.0	2442.0	2442.0	1194.6	1194.6	1194.6	2442.0	3087.6	3087.6	1194.6	1424.4	1424.4
Construction waste		122.1	122.1	122.1	59.7	59.7	59.7	122.1	154.4	154.4	59.7	71.2	71.2
Material to landfill		4070.0	1341.5	1341.5	1991.0	1991.0	1991.0	4070.0	5146.0	5146.0	1991.0	2374.0	2374.0
Total material to landfill		4192.1	1463.6	1463.6	2050.7	2050.7	2050.7	4192.1	5300.4	5300.4	2050.7	2445.2	2445.2

Table A5. Life cycle inventory of energy for the use stage of case study buildings.

Energy	Energy Consumption GJ/year
Non-thermal energy (home appliances, lighting)	18.834
Thermal energy (heating/cooling)	10.430
Natural gas consumption (hot water)	22.610
Total energy (use stage)	51.874

Table A6. Estimated number of replacements of building components in active service life of buildings.

Replacements of Building Components	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS
Building	50	57	57	57	57	57	57	57	65	65	57	66	69
Terracotta tiles	0	1	1	1	1	1	1	1	1	1	1	1	1
Gypsum board	0	1	1	1	1	1	1	1	2	2	1	2	2
Plaster	0	2	2	2	2	2	2	2	2	2	2	2	2
Render	0	3	3	3	n/a	n/a	n/a	3	4	4	n/a	n/a	n/a
Ceramic tiles	0	0	0	0	0	0	0	0	1	1	0	1	1

Table A7. Estimated Remaining life of building components at post-use stage of buildings.

Remaining Life (years)	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB -GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS
Building	50	57	57	57	57	57	57	57	65	65	57	66	69
Terracotta tiles		41	41	41	41	41	41	41	32	29	41	32	29
Gypsum board		3	3	3	3	3	3	3	25	25	3	24	21
Roof frame		0	0	0	0	0	0	29	21	21	29	20	17
Plaster		21	21	21	21	21	21	21	13	13	21	12	9
Render		3	3	3	n/a	n/a	n/a	3	10	10	n/a	n/a	n/a
Wall frame		8	8	8	25	25	25	8	0	0	25	16	13
Ceramic tiles		0	0	0	0	0	0	0	39	39	0	38	35
Slab footing		0	9	12	0	9	12	0	9	12	0	9	12

References

1. Grant, A.; Ries, R.; Kibert, C. Life cycle assessment and service life prediction: A case study of building envelope materials. *J. Ind. Ecol.* **2014**, *18*, 187–200. [CrossRef]
2. Nunen, H.V. Assessment of the Sustainability of Flexible Building: The Improved Factor Method: Service Life Prediction of Buildings in The Netherlands, Applied to Life Cycle Assessment. Ph.D. Thesis, Universiteit Eindhoven, Eindhoven, The Netherlands, 2010.
3. Leticia, O.M.; Begoña, S.L. Proposed method of estimating the service life of building envelopes. *J. Constr.* **2015**, *14*, 60–88.
4. Rauf, A.; Crawford, R.H. The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. *Artich. Sci. Rev.* **2013**, *56*, 252–261. [CrossRef]
5. Robert, H.; Crawford, R.J.F. Energy and greenhouse gas emissions implications of alternative housing types for Australia. In Proceedings of the State of Australian Cities National Conference Australian Sustainable Cities and Regions Network (ASCRN), Melbourne, VIC, Australia, 29 November–2 December 2011; pp. 1–12.
6. Robert, H.; Crawford, I.C.; Robert, J.F. A comprehensive framework for assessing the life-cycle energy of building construction assemblies. *Archit. Sci. Rev.* **2010**, *53*, 288.
7. Silvestre, J.D.; Silva, A.; de Brito, J. Uncertainty modelling of service life and environmental performance to reduce risk in building design decisions. *J. Civ. Eng. Manag.* **2015**, *21*, 308–322. [CrossRef]
8. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of a residential building with different envelopes and climates in Indian context. *Appl. Energy* **2012**, *89*, 193–202. [CrossRef]
9. Allacker, K. Sustainable Building: The Developement of an Evaluation Method. Ph.D. Thesis, Katholieke Universiteit Leuven, Leuven, Belgium, 2010.
10. Audenaert, A.; de Cleyn, S.H.; Buyle, M. Lca of low energy flats using the eco-indicator 99 method: Impact of insulation materials. *Energy Build.* **2012**, *47*, 68–73. [CrossRef]
11. Carre, A. *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*; PNA147-0809; Forest & Wood Products Australia: Melbourne, Australia, 2011.
12. Iyer-Raniga, U.; ChewWong, J.P. Evaluation of whole life cycle assessment for heritage buildings in australia. *Build. Environ.* **2012**, *47*, 138–149. [CrossRef]
13. Rouwette, R. *Lca of Brick Products*; Think Brick Australia: Melbourne, Australia, 2010.
14. Cuellar-Franca, R.M.; Azapagic, A. Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Build. Environ.* **2012**, *54*, 86–99. [CrossRef]
15. Nemry, F.; Uihlein, A.; Colodel, C.M.; Wetzel, C.; Braune, A.; Wittstock, B.; Hasan, I.; Kreißig, J.; Gallon, N.; Niemeier, S.; et al. Options to reduce the environmental impacts of residential buildings in the european union-potential and costs. *Energy Build.* **2010**, *42*, 976–984. [CrossRef]
16. Ortiz-Rodríguez, O.; Castells, F.; Sonnemann, G. Life cycle assessment of two dwellings: One in spain, a developed country, and one in colombia, a country under development. *Sci. Total Environ.* **2010**, *408*, 2435–2443. [CrossRef] [PubMed]
17. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (lca) and life cycle energy analysis (lcea) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
18. Biswas, W.K. Carbon footprint and embodied energy assessment of a civil works program in a residential estate of western australia. *Int. J. Life Cycle Assess.* **2014**, *19*, 732–744. [CrossRef]
19. Islam, H.; Jollands, M.; Setunge, S. Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 129–140. [CrossRef]
20. Atmaca, A. Life-cycle assessment and cost analysis of residential buildings in south east of turkey: Part 2—A case study. *Int. J. Life Cycle Assess.* **2016**, *21*, 925–942. [CrossRef]
21. Lawania, K.K.; Biswas, W.K. Achieving environmentally friendly building envelope for western australia's housing sector: A life cycle assessment approach. *Int. J. Sustain. Built Environ.* **2016**, *5*, 210–224. [CrossRef]
22. Manish, K.; Dixit, J.L.F.; Lavy, S.; Charles, H.C. Need for an embodied energy measurement protocol for buildings: A review paper. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3730–3743.
23. Vitale Pierluca, A.N.; Fabrizio, D.G.; Umberto, A. Life cycle assessment of the end of life phase of a residential building. *Waste Manag.* **2017**, *60*, 311–321. [CrossRef]

24. Pierluca Vitale, U.A. An attributional life cycle assessment for an italian residential multifamily building. *Environ. Technol.* **2018**, *39*, 3033–3045. [CrossRef]
25. Balasbaneh, A.T.; Marsono, A.K.B.; Khaleghi, S.J. Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment. *J. Build. Eng.* **2018**, *20*, 235–247. [CrossRef]
26. Buildings and constructed assets—Service life planning. *Part-1: General Principles and Framework*; ISO 15686-1; International Standards Organisation: Geneva, Switzerland, 2011.
27. Hed, G. Service life planning of building components. *Durab. Build. Mater. Compnt.* **1999**, *8*, 1543–1551.
28. Hovde, P.J.; Moser, K. *Performance Based Methods for Service Life Prediction*; In-House Publishing: Rotterdam, The Netherlands, 2004.
29. Masters, L.W.; Brandt, E. Prediction of service life of building materials and components. *Mater. Struct.* **1987**, *20*, 55–77. [CrossRef]
30. Building and constructed assets—Service planning. *Part 1: General Principals and Framework*; ISO 15686-1:2000; International Standards Organisation: Geneva, Switzerland, 2000.
31. Buildings and constructed assets—Service life planning. *Part-2: Service Life Prediction Procedures*; ISO 15686-2; International Standards Organisation: Geneva, Switzerland, 2012.
32. Cecconi, F. Performance lead the way to service life prediction. In Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 17–20 March 2002.
33. Ivan Cole, P.C. Predicting the service life of buildings and components. *Constr. Mater.* **2011**, *164*, 305–314. [CrossRef]
34. Chen, C.-J.; Juan, Y.-K.; Hsu, Y.-H. Developing a systematic approach to evaluate and predict building service life. *J. Civ. Eng. Manag.* **2017**, *23*, 890–901. [CrossRef]
35. Hovde, P.J. Performance Based Methods for Service Life Prediction, Part A: Factor Methods for Service Life Prediction. Available online: http://site.cibworld.nl/dl/publications/Pub294.pdf (accessed on 1 January 2019).
36. Hovde, P.J. *Evaluation of the Factor Method to Estimate the Service Life of Building Components*; Department of Building and Construction Engineering, The Norwegian University of Science and Technology: Trondheim, Norway, 1998.
37. Buildings and constructed assets—Service-life planning. *Part 8: Reference Service Life and Service-Life Estimation*; ISO 15686-8; International Standards Organisation: Geneva, Switzerland, 2008.
38. *Environmental Management—Life Cycle Assessment, Principles and Framework*; ISO 14040; International Standards Organization: Geneva, Switzerland, 2006.
39. Guinee, J.B.; Udo de Haes, H.A.; Huppes, G. Quantitative life cycle assessment of products: 1: Goal definition and inventory. *J. Clean. Prod.* **1993**, *1*, 3–13. [CrossRef]
40. Consoli, F.A.; Boustead, I.; Fava, J.; Franklin, W.; Jensen, A.; Oude, N.; Parrish, R.; Perriman, R.; Postlethwaite, D.; Quay, B.; et al. *Guide Lines for Life-Cycle Assessment: A Code of Practice*; Society of Environmental Toxicology and Chemistry: Pensacola, FL, USA, 1993.
41. Bekker, P.C.F. A life cycle approach in building. *Build. Environ.* **1982**, *17*, 3–13. [CrossRef]
42. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on lca. *Constr. Build. Mater.* **2009**, *23*, 28–39. [CrossRef]
43. Lotteau, M.; Loubet, P.; Pousse, M.; Dufrasnes, E.; Sonnemann, G. Critical review of life cycle assessment (lca) for the built environment at the neighborhood scale. *Build. Environ.* **2015**, *93*, 165–178. [CrossRef]
44. Anderson, J.E.; Wulfhorst, G.; Lang, W. Expanding the use of life-cycle assessment to capture induced impacts in the built environment. *Build. Environ.* **2015**, *94*, 403–416. [CrossRef]
45. Passer, A.; Ouellet-Plamondon, C.; Keneally, P.; John, V.; Habert, G. Impact of future scenarios on building renovation strategies towards plus energy buildings. *SBE16 Zurich* **2016**, *124*, 2.
46. Norman, J.; MacLean, H.; Kennedy, C.A. Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. *J. Urban Plan. Dev.* **2006**, *132*, 10–21. [CrossRef]
47. Wahidul, K.; Biswasa, Y.A.; Krishna, K.L.; Prabir, K.S.; Elsarrag, E. Life cycle assessment for environmental product declaration of concrete in the gulf states. *Sustain. Cities Soc.* **2017**, *35*, 36–46.
48. Lawania, K.K.; Biswas, W.K. Cost-effective ghg mitigation strategies for western australia's housing sector: A life cycle management approach. *Clean Technol. Environ. Policy* **2016**, *18*, 2419–2428. [CrossRef]

49. Werner, F.; Richter, K. Wooden building products in comparative lca. *Int. J. Life Cycle Assess.* **2007**, *12*, 470–479.
50. Wahidul, K.; Biswas, L.B.; Carter, D. Global warming potential of wheat production western australia: A life cycle assessment. *Water Environ. J.* **2008**, *22*, 206–216.
51. Mirabella, N.; Röck, M.; Saade, M.R.M.; Spirinckx, C.; Bosmans, M.; Allacker, K.; Passer, A. Strategies to improve the energy performance of buildings: A review of their life cycle impact. *Buildings* **2018**, *8*, 105. [CrossRef]
52. Vincenzo Franzitta, M.L.; Gennusa, G.P.; Rizzo, G.; Scaccianoce, G. Toward a european eco-label brand for residential buildings: Holistic or by-components approaches? *Energy* **2011**, *36*, 1884–1892. [CrossRef]
53. Francesco Barreca, P.P. Post-occupancy evaluation of buildings for sustainable agri-food production—A method applied to an olive oil mill. *Buidings* **2018**, *8*, 83. [CrossRef]
54. Samaratunga, M.; Ding, L.; Bishop, K.; Prasad, D.; Yee, K.W.K. Modelling and Analysis of Post-Occupancy Behaviour in Residential Buildings to Inform Basix Sustainability Assessments in Nsw. *Procedia Eng.* **2017**, *180*, 343–355. [CrossRef]
55. Aneurin Grant, R.R. Impact of building service life models on life cycle assessment. *Build. Res. Inf.* **2013**, *41*, 168–186. [CrossRef]
56. Galle, W.; de Temmerman, N.; de Meyer, R. Integrating scenarios into life cycle assessment: Understanding the value and financial feasibility of a demountable building. *Buidings* **2017**, *7*, 64. [CrossRef]
57. TCI. *Australia's Emissions: What Do the Numbers Really Mean?* The Climate Institute: Sydney Australia, 2015.
58. Argent, R.M. *Australia State of the Environment 2016: Inland Water*; Australian Government Department of the Environment and Energy: Canberra, Australia, 2017.
59. BOM. *Average Anual, Seasonal and Monthly Rainfall*; BOM: Melbourne, Australia, 2018.
60. Pfister, S.; Koehler, A.; Hellweg, S. Assessing the environmental impacts of freshwater consumption in lca. *Environ. Sci. Technol.* **2009**, *43*, 4098–4104. [CrossRef] [PubMed]
61. Fenton, G.G. Desalination in australia-past and future. *Desalination* **1981**, *39*, 399–411. [CrossRef]
62. Radcliffe, J.C. The water energy nexus in australia-the outcome of two crises. *Water-Energy Nexus* **2018**, *1*, 66–85. [CrossRef]
63. Joe Pickin, P.R. *Australian National Waste Report 2016*; Department of the Environment and Energy & Blue Environment Pty Ltd.: Docklands, Australia, 2017.
64. PRe'-Consultants. *Simapro 8.4 Lca Software*; Pre' Consultants: Amersfoort, The Netherlands, 2016.
65. Shahana, Y.; Janjua, P.K.S.; Wahidul, K.B. Sustainability implication of a residential building using a lifecycle assessment approach. In Proceedings of the 4th International Conference on Low Carbon Asia and Beyond (ICLCA), Johor Bahru, Malaysia, 24–26 October 2018; Chemical Engineering Transactions: Johor Bahru, Malaysia, 2018; Volume 73, pp. 1–6.
66. AccuRate. *Accurate Sustainability Tool Version 2.3.3.13 sp3*; CSIRO Land & Water Flagship and Distributed by Energy Inspection Pty Ltd.: Canberra, Austrailia, 2015.
67. Crowther, P. Design for disassembly to recover embodied energy. In Proceedings of the 16th International conference on Passive and Low Energy Architecture, Melbourne/Brisbane/Cairns, Australia, 22–24 September 1999.
68. Lawania, K.K. *Improving the Sustainability Performance of Western Australian House Construction: A Life Cycle Management Approach*; Curtin University: Perth, Australia, 2016.
69. Treloar, G.; Fay, R.; Love, P.E.D.; Iyer-Raniga, U. Analysing the life-cycle energy of an australian residential building and its householders. *Build. Res. Inf.* **2000**, *28*, 184–195. [CrossRef]
70. Fay, R.; Treloar, G.; Iyer-Raniga, U. Life-cycle energy analysis of buildings: A case study. *Build. Res. Inf.* **2000**, *28*, 31–41. [CrossRef]
71. Vass, N. Western Australia Energy Fact Sheet. Available online: http://www.australianpowerproject.com.au/western-australia-energy-fact-sheet/ (accessed on 19 December 2018).
72. Lawania, K.; Biswas, W.K. Application of life cycle assessment approach to deliver low carbon houses at regional level in western australia. *Int. J. Life Cycle Assess.* **2018**, *23*, 204–224. [CrossRef]
73. Allacker, K.; Maia de Souza, D.; Sala, S. Land use impact assessment in the construction sector: An analysis of lcia models and case study application. *Int. J. Life Cycle Assess.* **2014**, *19*, 1799–1809. [CrossRef]
74. Spang, E.S.; Moomaw, W.R.; Gallagher, K.S.; Kirshen, P.H.; Marks, D.H. The water consumption of energy production: An international comparison. *Environ. Res. Lett.* **2014**, *9*, 1–14. [CrossRef]

75. Bardhan, S. Assessment of water resource consumption in building construction in India. *WIT Trans. Ecol. Environ.* **2011**, *144*, 93–101.
76. Robert, H.G.; Treloar, J.T. An assessment of the energy and water embodied in commercial building construction. In Proceedings of the 4th Australian Life Cycle Assessment Conference, Sydney, NSW, Australia, 23–25 February 2005; pp. 1–10.

APPENDIX-5: PAPER-5 +ESM

Janjua SY, Sarker PK, Biswas WK. Sustainability Implications of the service life of residential buildings- An application of life cycle sustainability assessment framework.

This is a peer reviewed paper published in indexed journal "Environmental and Sustainability Indicators" and currently in press.

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STATEMENT OF CONTRIBUTION

To Whom It May Concern,

I, Janjua SY, contributed to literature review, method formulation, data collection, result discussions, analysis and writing (80%) of the paper/publication entitled:

Janjua SY, Sarker PK, Biswas WK. Sustainability Implications of the service life of residential buildings- A life cycle sustainability assessment approach. 2021. Environmental and Sustainability Indicators. 2021. 10, 100109, http://doi.org/10.1016/j.indic.2021.100109

The remaining 20% of this paper/ publication was contributed by A/Prof. Wahidul K. Biswas (10%) and A/Prof. Prabir K. Sarker (10%).

Signature: Date: 01 March 2021

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 01 March 2021

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Sustainability implications of service life on residential buildings – An application of life cycle sustainability assessment framework

Shahana Y. Janjua [a], Prabir K. Sarker [a], Wahidul K. Biswas [b,*]

[a] School of Civil and Mechanical Engineering, Curtin University, Perth, 6102, Australia
[b] Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Perth, 6102, Australia

A R T I C L E I N F O

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A B S T R A C T

Sustainable building design should consider durability, affordability, resource conservation, intra and intergenerational social equity aspects, and stakeholder's perspective throughout its service life. This research has applied life cycle sustainability assessment (LCSA) framework to estimate the sustainability performance in terms of a single score, and to identify avenues for sustainability improvement strategies of buildings. These case study buildings were modeled by taking into account the variation in building materials while maintaining architectural designs, covered area and location constant. The paper demonstrate the flexibility of this LCSA framework as all indicators are interlinked and any change or improvement in one or some indicators affects others positively and negatively. The sustainability objectives were assessed on an annual basis to capture the implications of the variation in the service life of buildings. Buildings made of recycled steel-framed roof, brick walls, and green concrete used in slab footing, showed higher sustainability performance among case study buildings. The use stage energy consumption and maintenance activities have been identified as the main hotspot. The cleaner production strategies (CPS) including product modification (double glazed window) and technology modification (rooftop solar photovoltaic panels, solar water heaters) were thus deemed appropriate to further reduce the use stage triple bottom line (TBL) impacts. These CPS have improved the sustainability performance of the case study buildings by 30–49%. The LCSA analysis confirms that the service life of buildings and their components have a significant bearing on the overall sustainability performance of residential buildings. However, the material selection at the design phase is crucial to building sustainability performance due to its durability and thermal properties. The longer service life of the building could result in more sustainable buildings only if service life of the non-structural components is aligned with service life of building to mitigate the maintenance activities.

1. Introduction

Sustainability issues have peaked recently due to environmental degradation, economic concerns, and social partiality world-wide. Alongside other industries, the growing construction industry is stiving to address environmental, social, and economic challenges. The international commitments and legislative changes are pressurizing the construction and building industry to make sustainable buildings with reduced social, economic, and environmental impacts (APH 2018; DOEE 2019; LEED 2016; UN 2015). The residential buildings constitute a major element of the construction industry contributing significantly to environmental deterioration directly or indirectly (UNEP 2018). The Australian building industry is growing at a high rate due to urbanization (NHSC 2011) with residential buildings being 65% of the total buildings constructed annually (ABS 2019), which is enhancing social prosperity and economic uplift by increasing resource utilization, energy consumption, and waste production (UNEP 2018).

Sustainable development caters to the aggregated environmental,

Abbreviations: AUD, Australian dollar; BI Index, Biodiversity Integrity index; CB, concrete block; CC, conventional concrete; C&D, construction and demolition; CPS, cleaner production strategies; CO_2 eq, Carbon dioxide equivalent; DB, double brick; E, environmental; EC, economic; ESL, estimated service life; ESM, electronic supplementary material; FAGC, fly ash green concrete; G, Gap; GGBFS, ground granulated blast furnace slag; GHG, greenhouse gases; GJ, gigajoules; Ha_a, annual hectare; ISO, International standards organization; kl, kilolitre; km, kilometer; KPI, key performance indicator; LCC, life cycle cost; LCI, life cycle inventory; LCSA, life cycle sustainability assessment; OPC, ordinary portland cement; P, position value; PO_4 eq, phosphate equivalent; RA, recycled aggregate; S, social; SF, steel frame; SO_2 eq, sulfur dioxide equivalent; STC, sound transmission class; TBL, triple bottom line; TF, timber frame; W, weight.

* Corresponding author.
E-mail address: W.Biswas@curtin.edu.au (W.K. Biswas).

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social, and economic sustainability of residential buildings rather than a trade-off among these factors (Janjua et al., 2019). Significant research has been carried out to address environmental, social and economic challenges of the building sector using environmental life cycle assessemnt (ELCA), life cycle costing (LCC) and social life cycle assessment (SLCA). The environmental objective of building sustainability was mainly assessed by considering either a single impact category like carbon footprint and/or energy consumption or both of these indicators (Geng et al., 2017). In the case of economic objective, LCC of residential buildings has been considered widely (Vale et al., 2017), however, the economic impacts from stakeholders' perspective i.e., developers and end-users have not been discussed explicitly. Similarly, SLCA studies of residential buildings could have incorporated two key ingredients of sustainability including intra-generational and inter-generational social equity unanimously (Biswas and Cooling 2013). Though these sustainability tools (ELCA, SLCA and LCA) are fair enough to deal with the single sustainability objective over the life span of the buildings, an integration of these tools to determine the overal sustainability score of the building would be very useful (Klöppfer 2008). LCSA uses ELCA, LCC and SLCA tools to integrate social, economic and environmental objectives of sustainability. This framework focuses on broader impacts by carefully selecting indicators from different perspectives, which avoids double-counting, aligns social indicators to a functional unit, involves the stakeholders in the weighting of indicators to avoid uncertainties in assessment, considers both positive (e.g., benefit) and negative indicators (e.g., carbon footprint), and applies on practical examples (Guinée 2015).

The LCSA for assessing environmental, social, and economic aspects of sustainability of the building industry is still at the preliminary stage (Dong and Ng 2016; Janjua et al., 2019). Though a limited number of LCSA studies of residential buildings was carried out, authors' review confirmed that these studies did not take into account the regional variation in the selection of sustainability indicators, participation of supply chain stakeholders, integration of TBL objectives and service life of all building components and building itself, to develop a comprehensive LCSA framework (Janjua et al., 2019). The TBL sustainability objectives (environmental, social and economic objectives) and key performance indicators (KPIs) of the buildings vary with locations due to climatic, regional and socio-economic differences (e.g., child labor, temperate zone, water scarcity, etc.). Similarly, the selection of supply chain stakeholders and their participation in the development of KPIs are crucially important in establishing the acceptability of KPIs (Mathur et al., 2008).

Considering a fixed service life of buildings either overestimates or underestimates the sustainability performance of buildings (Janjua et al., 2019a). For example, Australian building code suggests a service life of 50 years, while existing literature on sustainability performance has used a service life between 30 and 100 years for residential buildings, with the most commonly used value of 50 years, disregarding the actual service life of building for different design aspects (Grant and Ries 2013; Grant et al., 2014). However, one of authors' recent studies found that taking into account the variation of the actual service life of a building due to the variation in durability of its components influences the environmental LCA results/outcomes of buildings (Janjua et al., 2019a). The absence of the integration of service life into sustainability assessment creates a discrepancy in the accuracy of results due to having an early end of life of a building, and also the exclusion of repair activities during the active life of the building ignores the impact of the durability of various building materials (Janjua et al., 2019a).

Thus, a holistic LCSA framework that integrates TBL objectives is inevitable to assess the life cycle sustainability performance of residential buildings, considering estimated service life (ESL) of building components and the overall building, region-specific sustainability indicators with different possible perspectives (developers, user, societal and generational), quantitative social KPIs related to functional unit, and the involvement of the stakeholders in the selection of KPIs (Janjua et al. 2019b, 2020). The consideration of the aforementioned factors will evolve an LCSA framework to diagnose the reasons for sustainability performance gaps using KPIs to suggest relevant improvement strategies. The authors have thus developed a life cycle sustainability assessment framework to assess as well as to improve the TBL sustainability performance of residential buildings (Janjua et al., 2019, 2019a, 2019b, 2020). Table 1 presents as to how the LCSA framework by Janjua et al. (2019b, 2020) has overcome the weaknesses of the existing sustainability frameworks of building and construction industries. Unlike other frameworks (Balasbaneh et al., 2018; Cuéllar-Franca 2012; Hossaini et al., 2015; Dong and Ng 2016; Onat et al., 2014), the authors have adopted a scientific methodology for the selection and weighting of the KPIs, to achieve a transparent, fair and unbiased assessment (Janjua et al., 2020).

Whilst this framework has been preliminarily tested using hypothetical values, nonetheless, the practical application of authors' LCSA framework using real-world data needs to be carried out in order to establish novelty and wide-scale applicability of the framework. Therefore, this paper aims to execute the practical application of the authors' LCSA framework (Janjua et al. 2019, 2019a, 2019b, 2020) to assess the sustainability performance of residential buildings using Western Australia as a case study to determine suitable improvement strategies to further improve the sustainability performance of building.

2. Method

This section discusses how the LCSA framework developed by the authors (Janjua et al. 2019b, 2020) can be practically tested on the ground, by conducting the sensitivity analysis of the developed method and by determining the impact of the use of alternative materials such as by-products and recycled materials in the construction of residential buildings. This LCSA framework uses ELCA, LCC and SCLA tools to caculate environmental, eocnomic and social performce of buildings of different service life and specifications, respectfully. The steps adopted in the LCSA framework to assess the sustainability performance of residential buildings (Fig. 1) is as follows;

1 Service life: The first step was to estimate the service life of the buildings which is considered an important baseline parameter to compare the sustainability performance of buildings made of different construction materials.

2 KPIs: The KPIs for TBL sustainability objectives were developed through an online consensus survey. The sustainability performance of the building has been measured using a sustainability score ranging from 0 to 5, with 5 as the most sustainable residential building. The overall sustainability score of a building was scientifically segregated into TBL sustainability objectives. Each of the sustainability objectives was further segregated into impact categories and each impact category was further segregated into key performance indicators (KPIs). Janjua et al. (2020), selected KPIs as well as allocated weights to these KPIs, based on responses obtained through online census survey of area experts at the national level. The threshold values of KPIs were selected after an intensive literature review of Australian case studies, international treaties, government statistics, and authentic reports. When the values of KPIs are the same as their threshold values, sustainability performance will be considered achieved. These threshold values were finally published in the journal of environmental management through a peer reviewed process (Janjua 2020) in order to enhance the acceptability of this LCSA framework.

3 Performance gap: The qualitative and quantitative data was collected to compile the life cycle inventory (LCI) of energy, material and transportation for each case study building. The LCI was then used to calculate the values of TBL sustainability KPIs (*Calculated values*) through ELCA, SLCA, and LCC. Equation (1a) and equation (1b) were then used to rank the position of the calculated values on a 5-point Likert scale (*Position values 'P'*) (Janjua et al., 2019b).

Table 1
Comparative analysis of proposed LCSA framework and existing LCSA frameworks of buildings.

Challenges of LCSA frameworks	Balasbaneh et al. (2018)	Cuéllar-Franca (2012)	Hossaini et al. (2015)	Dong and Ng (2016)	Onat et al. (2014)	Kamali et al. (2018)	Janjua et al., (2021) (Current Paper)
Integration of three objectives of sustainability (economic, social and environmental) using a strong sustainability approach (Ecologically focused development)	×	×	×	×	×	×	✓
Incorporation of ESL of residential buildings in order to determine TBL sustainability performance on annual basis,	×	×	×	×	×	×	✓
Inclusion of major repairs as per ESL of building components	×	×	×	×	×	×	✓
Aligning social KPIs to the functional unit and adjusting both negative and positive TBL sustainability impacts	×	✓	×	×	×	×	✓
Incorporating supply chain stakeholders' perspectives (i.e., developers, users and society) into LCSA	×	✓	×	✓	×	×	✓
Application of structured survey method by involving area experts, for the selection of region-specific TBL KPIs	×	×	×	×	×	×	✓
Application participatory approach involving area experts, for weighting of KPIs	×	×	×	✓	×	✓	✓
Identification of TBL hotspots in life cycle sustainability assessment of buildings	✓	✓	×	✓	✓	✓	✓
Proposing cleaner production strategies (CPS) to reduce sustainability gaps	×	✓	×	×	×	×	✓
Enabling further sustainability improvement through an iterative process	×	×	×	×	×	×	✓
Communicating the LCSA (economic, social and environmental) results in a single sustainability score for easy comparison	×	×	✓	×	×	×	✓

$$P_{\text{low}} = \frac{\text{Threshold value}}{\text{Calculated value}} \times 5 \tag{1a}$$

$$P_{\text{high}} = \frac{\text{Calculated value}}{\text{Threshold value}} \times 5 \tag{1b}$$

The threshold values have been allocated a position of 5 on the 5-point Likert scale. The Gap 'G' of the KPIs was determined by subtracting the position value 'P' from the threshold value of each KPI. Each KPI has been assigned a weight 'W' provided by the participants in the online survey (Janjua et al., 2020). The gap 'G' of each KPI was multiplied by the weight 'W' of the respective KPI to calculate the score, hereafter named performance gap, of each KPI.

4 Hotspots analysis: The calculated performance gaps were used to identify the TBL hotspots of KPIs. The cleaner production strategies (CPS) recommended by the United Nations Environment The Program (e.g., product modification, technology modification, good housekeeping, input substitution, and on-site recycling) were then applied to treat the hotspots (UNEP 2015).

4 Sustainability improvement: A follow-up TBL sustainability assessment was carried out after updating the life cycle inventories with improvement strategies to observe the changes in performance gaps of KPIs. The performance gaps of KPIs, under each impact category, were subsequentially aggregated to performance gaps of impact categories. Likewise, performance gaps of impact categories were aggregated to determine performance gaps of sustainability objectives. The performance gaps of TBL objectives were finally aggregated to obtain an overall performance gap of sustainability of the building. The difference between the overall performance gap of the building and threshold value (i.e., 5) determines the sustainability score of the building.

3. Case study

Western Australia has been taken as a case study for LCSA framework implementation as the authors' research organization is situated in this state. Detached houses of 4 bedrooms and 2 bathrooms are usually preferred by two-third of Western Australians (idcommunity 2019; ABS 2010). Accordingly, the sustainability performance of fourteen alternative detached residential buildings was compared with a typical Western Australian building. The service life of the 14 alternative buildings will vary with the type of materials used, while the service life of the conventional building is 50 years. The size, location, orientation, and architectural design were considered the same for all these buildings. Fenestrations for case study buildings included single glazed windows and wooden doors with metal frames.

3.1. Building systems

The difference between the case study buildings was created by using different building materials for structural components including walls, roof frame, and footing slab (Table 2). Each building was subdivided into three systems i.e., wall system, footing system, and roof system. Each system has been further categorized based on the materials used for manufacturing the system components. Whilst the thermal performance, durability, embodied energy, affordability, and applicability in the local building construction industry were the key variables of building materials, it was assured that the structural soundness of the building was not compromised, and the structural design had followed the building codes of Australia.

3.1.1. Roof system

Two types of roof systems were used in the case study i.e., timber truss frame and steel truss frame. The timber truss frame roof has been used by 64% of dwellings in Australia (ABS 2000). Steel roof framing is not as common in Western Australia as in the Eastern states (DOCWA 2016b). The timber roof framing is generally cost-effective at the construction stage. However, it has high maintenance costs during the use stage, and also it is less durable and suspected to rot and insect infestation as compared to steel frame roof (Reardon et al., 2013). Steel is an energy-intensive material, but is highly durable and has 100% recycling capability (Reardon et al., 2013; Gloria 2016; NASH 2018).

3.1.2. Wall system

The wall systems used in this case study are concrete blocks and brick masonry. In Western Australia, brick masonry is used in more than 87%

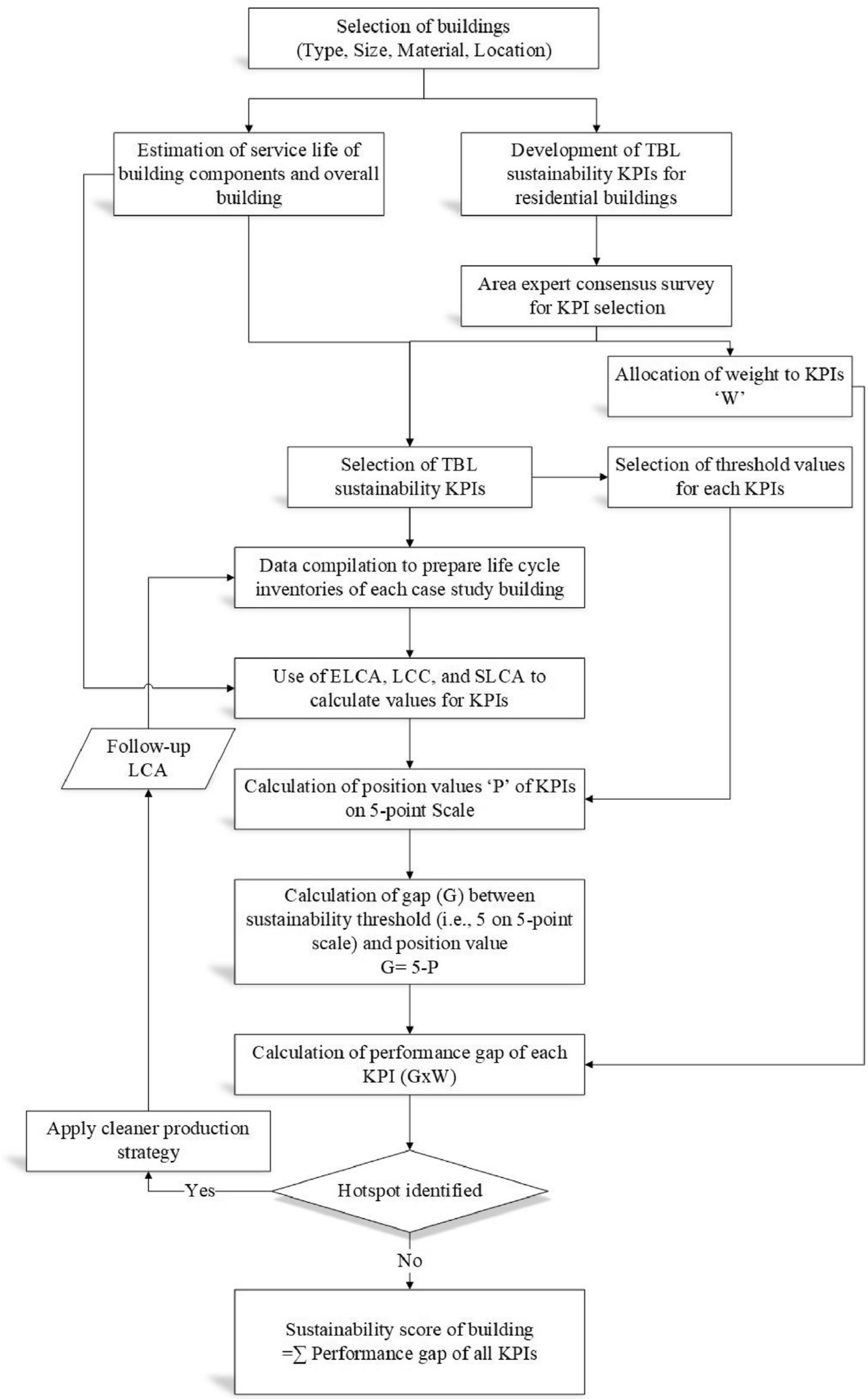


Fig. 1. LCSA implementation framework.

of residential buildings (ABS 1995). However, concrete blocks are replacing brick masonry due to ease of laying, resilience to catastrophic circumstances, and modern architectural designs (Inglis and Downton 2013). Both concrete blocks and clay bricks have high compressive strength, durability, fire, and noise and vermin resistance (AS 2018). Unlike bricks, concrete blocks are porous and require surface treatment like rendering to avoid moisture wicking. A reinforced concrete block wall provides very good resistance against horizontal impacts and cracking due to partial movements in sandy soils (AS 2018; Inglis and Downton 2013; CMAA 2019).

3.1.3. Footing system

On grade slab is a recommended footing system for unreactive or slightly reactive soils (soil class A/S) (AS 2011; ASRIS 2019; CCAA

Table 2
Building specifications of a case study based on building systems.

Building #	Building Code	Roof System	Wall System	Footing System
Building 50	TF-DB-CC	Gypsum Ceiling; Timber Truss	Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
1	TF-CB-CC	Gypsum Ceiling; Timber Truss Frame; Terracotta tile	Rendering, Concrete blocks; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
2	TF-CB-FAGC			On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
3	TF-CB-GGBFS			On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
4	TF-DB-CC		Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
5	TF-DB-FAGC			On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
6	TF-DB- GGBFS			On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
7	SF-CB-CC	Gypsum Ceiling; Steel Truss Frame; Terracotta tile	Rendering, Concrete blocks; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
8	SF-CB-FAGC			On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
9	SF-CB-GGBFS			On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
10	SF-DB-CC		Double brick with 50mm air gap; white set + Plaster	On grade concrete slab with 100% OPC; Ceramic tiles
11	SF-DB-FAGC			On grade concrete slab with 30% OPC replacement by fly ash; Ceramic tiles
12	SF-DB- GGBFS			On grade concrete slab with 30% OPC replacement by GGBFS; Ceramic tiles
13	SF-DB-50% GGBFS+50% RA			On grade concrete slab with 50% OPC replacement by GGBFS + 50% recycled aggregate; Ceramic tiles
14	SF-DB-50% GGBFS+100% RA			On grade concrete slab with 50% OPC replacement by GGBFS + 50% recycled aggregate; Ceramic tiles

Note: TF = timber frame; SF = steel frame; CB = concrete block; DB = double brick; CC = conventional concrete; FAGC= Fly ash green concrete; GGBFS = ground granulated blast furnace slag; RA = recycled aggregates.

2003). It reduces partial settlement of buildings and provides good resistance against termite and noise. The on-grade slab also helps to maintain the stable temperatures of a well-insulated house (Clarke et al., 2013). The cracking in conventional concrete slab (100% OPC and natural aggregates) may lead to the initiation of chemical damage including carbonation, chlorides, and sulphates, reducing the life of the footing system. Therefore, industrial byproducts including fly ash and GGBFS enhance the durability of concrete by reducing the porosity (Nath et al., 2018). Moreover, a slab footing of conventional concrete is an energy-intensive component of building and if cement and aggregates are partially replaced by by-products and recycled materials, it leads to a reduction in the environmental impacts and demand for scarce virgin materials. This case study has considered five types of concretes used for slab footing to compare the sustainability performance of the buildings. The cut-off approach is used for the environmental assessment of the by-products and recycled materials (i.e., collection and transportation) used in modeling the case study buildings. These concrete types include conventional concrete, green concrete with 30% replacement of OPC with Fly ash, green concrete with 30% replacement of OPC with GGBFS, green concrete with 50% replacement of OPC with GGBFS and 50% natural aggregate replacement with recycled aggregate, green concrete with 50% replacement of OPC with GGBFS and 100% natural aggregate replacement with recycled aggregates.

3.2. Estimation of service life of case study building components and overall buildings

Service life is the period, after construction, a building and its components remain functional and meet the minimum acceptable performance requirements (ISO 2000). The service life estimation of a building depends on the material properties of the building components, damage mechanism, and work execution level and exposure conditions. Being unique in material composition, architectural and structural design, and region-specific climatic conditions, service life estimation of buildings can not be generalized. Damage mechanisms associated with construction materials vary in intensity with geographic locations and exposure conditions and need to be addressed on component basis. “Prediction of durability is subject to many variables and cannot be an exact science” (Hovde and Moser 2004). Therefore, uncertainty is always present in service life predictions (Silva et al., 2016). However, efforts should be made to reduce uncertainty by considering reliable data sources. The service life is predicted through probabilistic, deterministic and engineering methods. The probabilistic approach considers the deterioration of building during a prescribed period of time. The method works well to predict the potential service life of buildings using existing building models made of same building materials. The deterministic method is an easy to use approach by utilizing different factors influencing the deterioration of building components under certain circumstances. The probabilistic approach has a benefit as it depends on manufacturer data and can be easily applied to buildings made of innovative materials. Whereas, the engineering method lies somewhat between probabilistic and deterministic methods and is expensive and time-consuming.

Following Janjua et al. (2019a), this paper has used the deterministic approach, the factor method, ISO 15686-8 (ISO 2008), to estimate the service life of case study buildings made of virgin materials, recycled materials and industrial by-products. The factor method integrates seven factors to the reference service life, to estimate the service life of building under certain conditions using Equation (2). It involves material quality, workmanship standards, deterioration of material in response to climatic conditions specific to the building location, and human behavior. Reliable data for reference service life and factors A to G are required to calculate the estimated service life (ESL) (ISO 2008).

$$ESL = RSL \times Factor\ A \times Factor\ B \times Factor\ C \times Factor\ D \times Factor\ E \times Factor\ F \times Factor\ G \quad (2)$$

where.

ESL – estimated service life, RSL – referenced service life, Factor A– quality of building components, Factor B – design level, Factor C – quality of work execution, Factor D – indoor environment conditions, Factor E – outdoor exposure conditions, Factor F – in use conditions, Factor G – maintenance quality and frequency.

Service life estimation of the case study building included ESL of components of wall system, roof system, and footing system; ESL of wall system, roof system, and footing system; ESL of case study buildings and estimation of major repairs (non-structural component of buildings) in ESL of building. The case study has used manufacturer's technical sheets, environmental product declaration sheets, material databases including the National Association of home builders' database US (NAHB), Building Owners and Managers Association US (BOMA), existing literature and experimental reports, government institution reports and building codes and practices to assign the reference service life to each building component. The seven Factors A to G have been ranked from 0.9 to 1.1 (ISO 2008) with 1.0 as neutral or not applicable. The ranking of factors for ESL is summarized in ESM_Table A1 for each building component. The manufacturer information sheets were considered to rank the material quality and common building design practices and Australian standards were used to rank the design level of the building component (ABCB 2019). The workmanship quality for each building component was assessed based on prevailing inspection reports by the department of commerce, building commission Western Australia (DOCWA 2016a; 2016b; 2017a; 2017b; 2019). Existing literature, climatic condition reports by the Bureau of Meteorology Western Australia (BOM 2018), and inspection reports were consulted to rank indoor and outdoor environmental impact on building components. Routine maintenance was considered for exposed building components. Factor F—in-use conditions— was not considered in this study as it is mainly dependent on user behavior.

The service life estimation of the case study included ESL of 14 building combinations. Following Janjua et al. (2019), the ESL of building components was estimated by multiplying the factors tabulated in Electronic supplementary material (ESM) ESM_Table A1. The ESL of the main structural component of a system was selected as ESL of the respective system i.e., ESL of block wall or brick wall as ESL of wall system; ESL of roof frame as ESL of the roof system and ESL of the slab as ESL of footing system (Janjua et al., 2019a). To estimate the service life of overall building, the minimum ESL of a system in the building (i.e., roof, wall, footing systems) was taken as the ESL of the building, as the end of life of one of the structural component could lead to the end of life of the whole building (Fig. 2). The estimated service life of study buildings, building systems, and building components are presented in ESM_Table A2-A6.

The estimated service life for case study buildings has been calculated using the condition typical to Western Australia, however, the effect of material quality on ESL is inavoidable. To capture the uncertainty in estimated service life of overall buildings due to the variation in material properties from best (1.1) to worst (0.9), the service life of each case study building was calculated using Factor A as 1.1(best quality material) and 0.9 (worst quality material). Table 3 shows that the ESL of the case study buildings varied from 19 % to 20 % for best to worst quality building materials. The maximum percentage variation in ESL was observed in Buildings 7–14 due to the variation in material quality for roof system and wall system. In Buildings 1–6, the roof system made of timber frame with minimum ESL, determined the ESL of the buildings among building systems (Fig. 2). In Buildings 7–14, the wall system made of concrete blocks has the lowest ESL among the building systems (roof system, wall system and footing system) for both best and worst-case scenarios. Therefore, the wall system determined the ESL for Buildings 7–14, and the confidence level of the estimated service life has been considered as ± 20%.

To maintain the building in serviceable conditions, in addition to routine maintenance, major repairs including replacement of the non-structural components (i.e., plaster, roof covering, floor tiles) are unavoidable at specific intervals. This interval of the major repairs has been calculated considering ESL of the building components. The number of replacements of each non-structural building component in the active life of the building has been estimated considering the end of ESL of respective building components and included in the life cycle inventory of the buildings (ESM_Table A7).

3.3. Life cycle sustainability assessment

LCSA is a comprehensive tool to assess the socio-economic and environmental impacts of a building throughout its life cycle (SETAC 2012). LCSA of a building involves the flow of natural resources (Water, energy, fuel, and material), labor, and money through all life stages

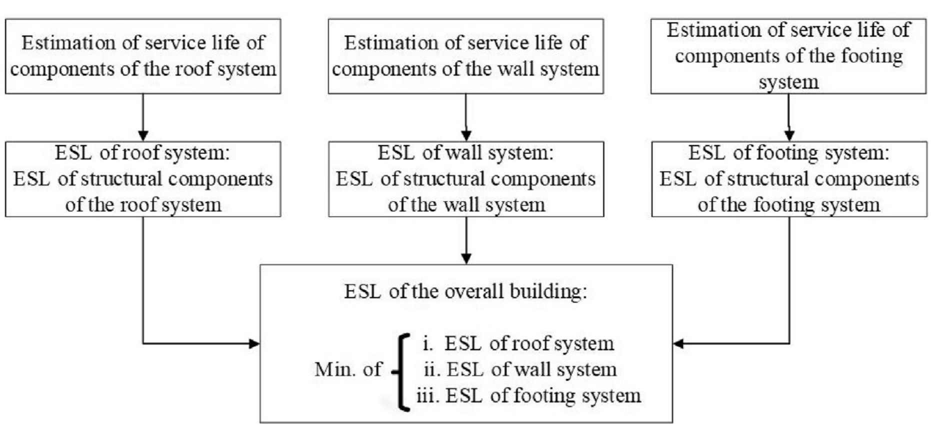


Fig. 2. Flow chart for service life estimation of the overall Building.

Table 3
Uncertainty in service life estimation based on material properties in overall Building.

Buildings	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS+50%RA	14. SF-DB-50%GGBFS+100%RA
Max. ESL	57	57	57	57	57	57	65	65	65	66	66	66	66	66
Calculated ESL	57	57	57	57	57	57	57	65	65	57	66	66	60	63
Min. ESL	47	47	47	47	47	47	53	53	53	54	54	54	54	54
Average difference (%)	19	19	19	19	19	19	20	20	20	20	20	20	20	20

(pre-use, use, and post-use stages) within the system boundary of buildings resulting in emissions, waste, revenue, and social implications of stakeholders within the supply chain. The life cycle assessment techniques including environmental life cycle assessment (ELCA), life cycle costing (LCC), and social life cycle assessment (SLCA) are used to assess the potential TBL sustainability performance of buildings. ISO-14040-14044 (ISO 2006) guidelines are the globally accepted standards to apply the LCA techniques. The life cycle sustainability assessment involves four steps; 1) Goal and scope definition, 2) Inventory compilation, 3) Impact assessment, and 4) interpretation (ISO 2006; SETAC 2012).

3.3.1. Goals and scope of the study

The goals of the life cycle sustainability assessment of residential buildings are;

5. To estimate the sustainability score of buildings made of different construction materials
6. To determine the effect of service life on the sustainability performance of the respective building
7. To determine the effect of major repairing and maintenance works on the sustainability performance of buildings during the operation stage of the building.
8. To identify the sustainability (social, economic and environmental) hotspots in the supply chain for developing improvement strategies

3.3.2. Functional unit of the study

The functional unit of LCSA of buildings is usually considered as 'per building' and compared with other buildings for the same floor area of case study buildings (Carre 2011). Since floor area for the case study houses in this LCSA is same, instead of using 'per building', the 'per square meter' of gross floor area was used for comparing the sustainability performance results with case study buildings and results from other studies. In addition, this study incorporated the service life of these buildings into LCSA to capture its impact on the overall sustainability performance of these buildings. Therefore functional unit for the LCSA of the case study buildings was finally used as *'per square meter per year'* (/m^2/year).

3.3.3. System boundary of the study

The system boundary of the assessment follows a cradle to grave approach (Fig. 3);

The life cycle stages of the building are distributed into three stages based on EN 15978 life cycle modules (EN 2011);

9. The pre-use stage includes extraction of the raw materials, forestry (e.g., special types of timber growth for commercial use), manufacturing of building materials (A1-A3 modules of building life cycle– EN 15978:2011) and transportation to the construction site, and construction work at the construction site (A4-A5 modules of building life cycle– EN 15978:2011).
10. Use stage, including building operation i.e., heating and cooling, appliances, and building maintenance (B1–B6 module of building life cycle– EN 15978:2011), use stage water consumption (i.e., B7 module of building life cycle– EN 15978:2011) has not been considered in the study as these processes were dependent on user behavior and were not related to building construction and materials.

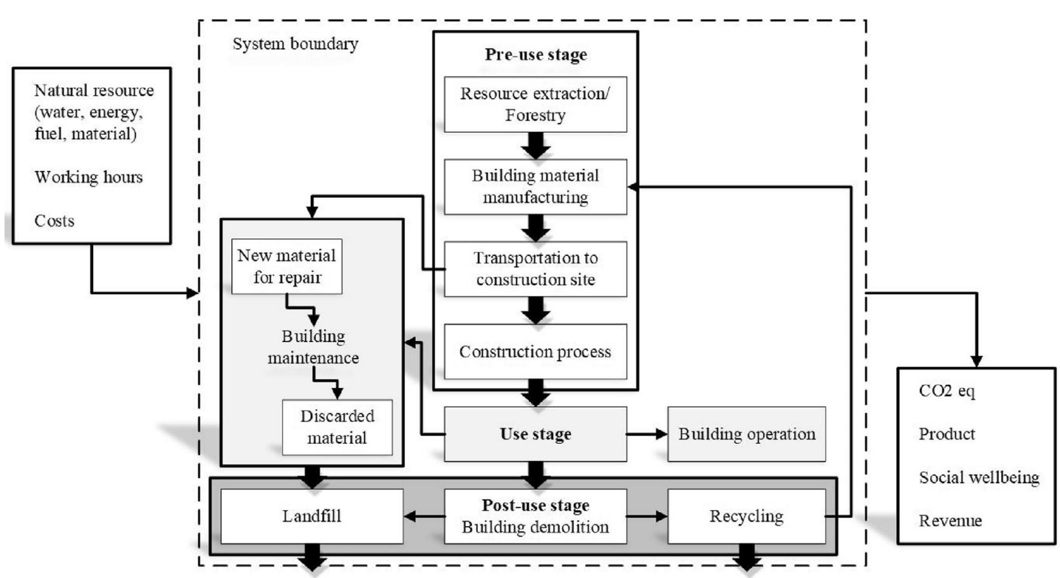


Fig. 3. System boundary of LCSA framework (Shade colors present processes included in one stage). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

11. Post-use stage, including building demolition and disposal of these wastes to landfill or recycling (C1–C4 module of building life cycle– EN 15978:2011).

3.3.4. Life cycle inventory for LCSA of the case study buildings

The development of a life cycle inventory is a pre-requisite to estimate the KPIs using the LCSA framework. Janjua et al. (2020), developed a list of 22 KPIs for sustainability assessment of residential buildings through an online survey by area experts. The KPIs were aggregated into 12 impact categories, and then these impacts were aggregated into 3 sustainability objectives. The TBL sustainability KPIs for residential buildings have been used as the smallest unit for sustainability assessment of the buildings. The threshold values ascertained by Janjua et al. (2020), have been assigned a maximum position value of 5 on a 5- point Likert scale.

Calculation of KPI values required the compilation of the life cycle inventory of each case study building. The material quantities were calculated for the case study buildings to compile the life cycle inventory of materials, energy, and costs (ESM_Table B1). The qualitative and quantitative data were collected using online and published resources from Alinta energy Australia, Synergy Australia, Rawlinson Western Australia, Commonwealth Bank of Australia, Australian Bureau of Statistics, construction material manufacturers and suppliers, and Australian building codes. The building specifications, material, and orientation were considered to assess the operational energy (cooling and heating) using the AccuRate sustainability software (Chen and CSIRO 2019). The software has limited input material options for roof and footing, therefore, the energy requirement was mainly calculated for 1) brick wall buildings (i.e., Building 50, Buildings 4–6 and Buildings 10–14) and 2) concrete block wall buildings (i.e., Building 1–3, and Building 7–9).

3.3.5. Calculation of TBL sustainability KPIs

Table 4 presents the LCA stages and inputs used to calculate the TBL sustainability KPIs. The material, energy, and transportation distance inputs in the LCI were incorporated into the life cycle assessment software SimaPro 8.4 to calculate the environmental KPIs (E-1.1, E-2.1, E-3.1, E-4.1, E-5.1, E-6.1, E-7.1, E-8.1) using Australian indicator set V2.01 (PRe'-Consultants 2016). The materials, energy, and carriage inputs from LCI were used to determine the life cycle calculated values of social KPI (S-2.1) and economic KPI (EC-2.2). Using the same LCI, that was used for determining environmental impacts, the life cycle cost (LCC) of each building was calculated by adding the present values of construction materials, operational cost, replacement cost and end of life cost (Pelzeter 2007). Only labor cost was the item that had been included in the LCI for the LCC calculation.

The calculation of a few indicators did not require the use of LCA, as they deal with the stage-specific issue (i.e., these KPIs are related to a specific stage like recycling potential is related to end of life waste production; resilience and adaptation is dependent on durability of building components). The Biodiversity index for KPI–E-4.2 (loss of biodiversity) was calculated by the equation of BI index (Majer and Beeston 1996; Biswas and Cooling 2013) using the proportion of undisturbed land. The recycling potential was calculated by aggregating the percentage of volumes of building components from LCI material that can be recycled. KPI–E-1.2 (Resilience and adaptation) was calculated using design, workmanship, exposure conditions, and inherent material properties of building components of each building from material inventory. Both cost and energy inputs from LCI were used to calculate the KPIs of social and economic sustainability objectives including S-1.2, S-1.3, S-2.1, EC-1.2, EC-1.3, EC-2.1. The capital cost of each building, based on the LCI for materials, was used to calculate the KPI–S-1.1 (House affordability) using the current interest rate of 3.32% over a mortgage period of 30 years for a 10% initial deposit (CBA 2019). The STC value for KPI–S-1.4 was calculated by integrating the STC values for the building system of each building. However, the KPI–S-1.5 was taken as the maximum transportation distance for the building materials from factory to construction site for pre-use (transportation) stage and material transportation for maintenance activities in use-stage.

Table 4
System boundaries including input and LCA stages for TBL sustainability KPIs.

Code	KPIs	Stages of LCA	Input
E-1.1	Carbon Footprint	Pre-use, use, post-use	Materials, Energy, Carriage
E-1.2	Resilience and adaptation	Pre-use, use	Materials
E-2.1	Acidification	Pre-use, use, post-use	Materials, Energy, Carriage
E-3.1	Eutrophication	Pre-use, use, post-use	Materials, Energy, Carriage
E-4.1	Land Use	Pre-use, use, post-use	Materials, Energy, Carriage
E-4.2	Loss of Biodiversity	Pre-use, use, post-use	Materials, Energy, Carriage
E-5.1	Cumulative Embodied Water Consumption	Pre-use, use, post-use	Materials, Energy, Carriage
E-6.1	Cumulative Energy Demand	Pre-use, use, post-use	Materials, Energy, Carriage
E-7.1	Cumulative Fossil Energy Consumption	Pre-use, use, post-use	Materials, Energy, Carriage
E-8.1	C & D waste	Post-use	Materials
E-8.2	Recycling potential	Post-use	Materials
S-1.1	House Affordability	Pre-use	Materials, Costs
S-1.2	Indoor Living Conditions	Use stage (maintenance)	Materials, Costs
S-1.3	Thermal Comfort	Use stage (operational energy)	Energy, Costs
S-1.4	Noise	Pre-use stage (construction), Use stage	Materials
S-1.5	Local material sourcing	Pre-use stage (transportation), Use stage (Maintenance)	Materials, Carriage
S-2.1	Energy Conservation	Pre-use, use, post-use	Materials, Energy, Carriage
EC-1.1	Life Cycle Cost	Pre-use, use, post-use	Costs, Energy, Materials
EC-1.2	Potential Savings	Use stage (operational energy)	Energy, Costs
EC-1.3	Benefit-Cost ratio	Pre-use, use, post-use	Costs
EC-2.1	Net benefit	Pre-use stage	Costs
EC-2.2	Carbon Tax Saving	Pre-use, use, post-use	Materials, Energy, Carriage

All values for the aforementioned KPIs were calculated for 1m^2 of building gross floor area and then they were divided by ESL of alternative buildings to estimate the impact per m^2 per year basis.

4. Interpretation of life cycle sustainability performance

The calculated values for KPIs (ESM_Table B2), were used to determine the position of the KPIs on a 5-point Likert scale for each case study building (ESM_Table B3) using equations (1a) and (1b). Acceptable sustainability criteria for Australian buildings are presented as threshold values (i.e., 5) and the Gap is the difference between the position values and threshold values for each KPI of alternative buildings. The performance gap was calculated by multiplying the Gap of each KPI (ESM_Table B4) with the corresponding weight of the KPI of the alternative building (Table 5).

Table 5 presents the position of TBL sustainability KPIs for the case study buildings on a 5-point Likert scale. The performance gap of the case study buildings showed that all buildings had met the threshold values (i.e. performace Gap = 0) for three KPIs S-1.1 (House affordability), S-1.5 (Local material sourcing), and EC-2.1 (Net benefit). The KPIs for social objective performed the best with an average performance gap of 23.2%, KPIs for economic objective has an average performance gap of 34.8%, whereas KPIs for environmental objectives have the highest performance gap with an average value of 42% among TBL sustainability objectives.

4.1. KPIs for environmental sustainability objective

The KPIs for environmental objectives are much lower than the threshold values in most of the cases with few exceptions i.e., only KPI – E-5.1 (Cumulative embodied water consumption) met the threshold values for eight buildings and KPI – E-8.2 (Recycling potential of C&D) met the threshold values for four buildings.

4.1.1. Carbon footprint (KPI– E-1.1)

There exists larger gaps for KPI– E-1.1 for buildings with concrete block wall system (Building 1–3, 6–9) as compared to double brick wall buildings (Building 50, 4–6, 9–14) (Table 5). The performance gap of KPI –E-1.1 in case study buildings and the reference building varied from 0.191 (Building 13) to 0.211 (Building 7), mainly due to the variations in building operation and maintenance during the use stage.

The annual carbon footprint for building operation was about 10% higher for case study buildings with concrete block wall system as compared to case study buildings with brick wall system mainly due to higher energy consumption (U-value = 2.71 W/m^{2}K) and quite a few replacements of energy-intensive materials (terracotta tiles, rendering, ceramic tiles) for concrete block wall buildings (ESM_Table A7) during the use stage of buildings (Janjua et al., 2019a). Building 13 (SF-DB-50% GGBFS + 50% RA) has the lowest performance gap of 0.191 among case study buildings mainly due to longer ESL (63 years), lower energy consumption during the use stage (U-value = 1.58 W/m^{2}K), and also due to the use of recycled aggregates and GGBFS in concrete (Carre 2011). Building 7 (SF-CB-CC) has the highest carbon footprint (0.211) among case study buildings due to the use of carbon-intensive materials (i.e. concrete blocks, rendering, plastering), higher energy consumption in use stage due to having lower thermal efficiency (U-value = 2.71 W/m^{2}K), and also due to the replacements of necessary building components with relatively shorter ESL including terracotta tiles, rendering, ceramic tiles (Janjua et al., 2019a).

4.1.2. Resilience and adaptation (KPI– E-1.2)

The performance gap for KPI– E-1.2 of the case study buildings varies between 0.006 and 0.009 (Table 5). Building 11 (SF-DB-FAGC) and Building 12 (SF-DB-GGBFS) have the lowest performance gap for KPI– E-1.2 among all the case study buildings and 38% lower than the reference building due to the use of durable materials (i.e., steel, green concrete, brick) for structural components in building design, requiring fewer replacements of building components during ESL of the building.

4.1.3. Acidification (KPI– E-2.1)

The case study buildings with concrete block walls have higher acidification potential with a performance gap between 0.196 - 0.195 as compared to the case study buildings with double brick walls (0.192 - 0.190) (Table 5). Building 7 (SF-CB-CC) has the highest performance gap of 0.196 (i.e., 1.85% higher than Building 50 with a performance gap of 0.192), mainly due to the replacement of energy-intensive components (i.e., terracotta tiles, ceramic tiles). Building 13 (SF-DB-50% GGBFS + 50% RA) has the lowest performance gap (i.e., 0.190), due to longer ESL and the use of industrial by-products and recycled materials in building components (Carre 2011).

4.1.4. Eutrophification (KPI– E-3.1)

The concrete block wall buildings (Building 1–3, 6–9) have a higher performance gap for KPI –E-3.1 than the brick wall buildings (Building 50, 4–6, 9–14) due to higher operational energy requirements (i.e. releasing higher NOx in the air due to burning of coal and natural gas for electricity generation) (Table 5). Secondly, the building components made of concrete (rendering, plastering, concrete block wall, concrete footing) contribute to the eutrophication which could be due to the release of NOx, COD, NH_3, NH_4+, NO_3-, and PO_4- from the concrete manufacturing process (Kim and Chae 2016). The eutrophication impact of the concrete block wall buildings reduced in Building 2 (TF-CB-FAGC) and Building 8 (SF-CB-FAGC) due to the use of industrial byproducts or the avoidance of emissions associated with the production of virgin cementitious materials. Building 13 (SF-DB-50% GGBFS + 50% RA), has the lowest performance gap (0.190) among all the case study buildings, not only due to the use of industrial by-products and recycled materials but also for having a longer ESL of 66 years.

4.1.5. Land use and loss of biodiversity (KPI– E-4.1; E-4.2)

The buildings using plant-based materials (Building 50, Building 1–6) have a higher performance gap for KPI– E-4.1 (Land use) and KPI– E-4.2 (Loss of biodiversity) (Table 5) than buildings using mineral-based materials (Building 7–14) due to higher land transformation in commercial forestry operations (Carre 2011). The increased use stage energy consumption (12.1%) has contributed to a higher performance gap for the concrete block buildings (Building 1–3, 7–9) as compared to the brick wall buildings (Building 4–6, 10–14). Land use for mining and power generation increased with higher energy demand (Trainor et al., 2016; Fthenakis and Kim 2009). Building 1 (TF-CB-CC) has the highest performance gap for E-4.1 and E-4.2, due to the use of timber frame roof and necessary replacements of energy-intensive non-structural components. Building 11 (SF-DB-FAGC) has the lowest performance gap for both KPIs mainly due to lower energy consumption of the double brick wall building, with ESL and also due to the use of industrial by-products (e.g., fly ash and GGBFS) which altogether result in lower annual impacts.

4.1.6. Cumulative embodied water consumption (KPI– E-5.1)

KPI–E-5.1 met the threshold values for the brick wall buildings (Building 4–6, 10–14) mainly due to lower energy consumption during the use stage (Table 5). The brick wall has relatively lower coefficient of heat transmission (U-value of 1.58 W/m^{2}K) (Clark et al., 2013; Miglietta et al., 2018) and so lower embodied water consumption during upstream processes as compared to concrete blocks (McMormack et al., 2007; Hosseinian and Nezamoleslami 2018). Building 1 (TF-CB-CC) has the highest performance gap for KPI–E-5.1 due to the use of forestry-based materials with high water consumption (Carre 2011) and also due to the use of water-intensive concrete blocks with comparatively shorter ESL of 57 years, thus resulting in higher annual impact.

4.1.7. Cumulative energy demand (KPI– E-6.1)

The performance gap for KPI–E-6.1 varied from 0.197 to 0.208 for the case study buildings (Table 5). Building 7 (SF-CB-CC) with an ESL of 57 years, has the highest performance gap of 0.208 (2.64% higher than reference building), due to use of energy-intensive structural component materials (steel, concrete, concrete blocks), and the need for replacements of non-structural components (render, ceramic tiles, terracotta tiles, etc.). The performance gap for cumulative energy demand for Building 13 (SF-DB-50% GGBFS+50% RA) was the lowest among case study buildings and 2.94% lower than the reference building, due to its longer ESL (i.e., 63 years) that is actually reducing impacts per year basis, and also due to the use of green concrete using GGBFS and recycled aggregates (Shaikh et al., 2019), and also due to the lower energy consumption during use stage (12.1%) of the brick wall buildings.

Table 5
Performance gap of KPI for Case study Buildings.

Code	KPIs	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	0.197	0.211	0.210	0.210	0.196	0.194	0.195	0.211	0.209	0.211	0.196	0.192	0.193	0.191	0.191
E-1.2	Resilience and adaptation	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.006	0.006	0.008	0.006	0.006	0.007	0.007
E-2.1	Acidification	0.192	0.196	0.195	0.196	0.192	0.191	0.192	0.196	0.195	0.196	0.192	0.191	0.191	0.190	0.191
E-3.1	Eutrophication	0.192	0.195	0.195	0.195	0.192	0.191	0.191	0.195	0.194	0.195	0.192	0.191	0.191	0.190	0.190
E-4.1	Land Use	0.197	0.201	0.200	0.200	0.195	0.194	0.195	0.187	0.186	0.187	0.179	0.177	0.177	0.180	0.177
E-4.2	Loss of Biodiversity	2.71E-07	2.89E-07	2.88E-07	2.89E-07	2.62E-07	2.61E-07	2.61E-07	2.31E-07	2.26E-07	2.30E-07	2.04E-07	1.97E-07	1.98E-07	2.06E-07	1.98E-07
E-5.1	Cumulative Embodied Water Consumption	0.000	0.025	0.024	0.024	0.000	0.000	0.000	0.025	0.013	0.015	0.000	0.000	0.000	0.000	0.000
E-6.1	Cumulative Energy Demand	0.203	0.208	0.208	0.208	0.200	0.199	0.200	0.208	0.207	0.208	0.200	0.197	0.198	0.197	0.198
E-7.1	Cumulative Fossil Energy Consumption	0.280	0.282	0.282	0.282	0.279	0.279	0.279	0.282	0.282	0.282	0.279	0.278	0.278	0.278	0.278
E-8.1	C & D waste	0.094	0.069	0.069	0.069	0.081	0.081	0.081	0.067	0.051	0.051	0.079	0.057	0.057	0.069	0.081
E-8.2	Recycling potential	0.001	0.004	0.003	0.003	0.000	0.000	0.000	0.002	0.005	0.005	0.000	0.001	0.001	0.001	0.001
S-1.1	House Affordability	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.2	Indoor Living Conditions	0.000	0.062	0.062	0.062	0.000	0.000	0.000	0.062	0.068	0.068	0.000	0.002	0.002	0.015	0.028
S-1.3	Thermal Comfort	0.081	0.107	0.107	0.107	0.081	0.081	0.081	0.107	0.107	0.107	0.081	0.081	0.081	0.081	0.081
S-1.4	Noise	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.5	Local material sourcing	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-2.1	Energy Conservation	0.321	0.321	0.321	0.321	0.279	0.270	0.275	0.321	0.321	0.321	0.280	0.246	0.251	0.241	0.254
EC-1.1	Life Cycle Cost	0.083	0.104	0.103	0.103	0.069	0.068	0.068	0.108	0.088	0.088	0.074	0.049	0.048	0.061	0.073
EC-1.2	Potential Savings	0.242	0.242	0.242	0.242	0.137	0.137	0.137	0.242	0.151	0.151	0.137	0.022	0.022	0.058	0.096
EC-1.3	Benefit Cost ratio	0.258	0.192	0.190	0.189	0.000	0.000	0.000	0.220	0.116	0.116	0.000	0.000	0.000	0.000	0.000
EC-2.1	Net benefit	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-2.2	Carbon Tax Saving	0.208	0.208	0.208	0.208	0.201	0.193	0.195	0.208	0.208	0.208	0.202	0.182	0.184	0.172	0.177

4.1.8. Cumulative fossil energy consumption (KPI– E-7.1)

The performance gap for case study and refernce buildings for KPI–E-7.1 varied between 0.277 and 0.282 (Table 5). Building 7 (SF-CB-CC) has the highest performance gap of 0.282 (0.86% higher than reference building) due to relatively shorter ESL, use of energy-intensive structural component materials (steel, concrete, concrete blocks), and also there is frequent replacement of non-structural components (rendering, ceramic tiles, terracotta tiles). Building 13 (SF-DB-50% GGBFS+50% RA) with an ESL of 63 years has the lowest performance gap of 0.277 mainly due to the use of green concrete made with GGFBFS and recycled aggregates, and due to the lower energy consumption during use stage (12.1%) for brick wall buildings.

4.1.9. Construction and demolition waste (KPI– E-8.1)

Construction and demolition waste is the amount of waste generated during the end of life of buildings. This waste could either go to landfills or recycling facilities. Table 5 shows that the reference building (Building 50) with a service life of 50 years has the highest annual impact of C&D waste with a performance gap of 0.094 due to shorter service life resulting in the higher annual impact of the KPI. Building 11 (SF-CB-FAGC) has a lower gap of 0.051, due to longer ESL of 66 years, resulting in lower yearly waste for the building.

4.1.10. Recycling potential (KPI– E-2.1)

KPI– E-8.2 met the threshold value of three-quarters of the Buildings (4–6, 10) due to use of higher quantities of recyclable materials (timber, brick) in building construction (Table 5). Building 9 (SF-CB-GGBFS) has the highest performance gap of 0.005 for this KPI mainly due to the use of lower volume of recyclable materials (i.e., steel- 55% lesser in weight as compared to timber, concrete blocks- 32% lesser weight as compared to bricks) with a longer ESL which altogether resulting in even lower annual quantities of recyclable materials.

4.2. KPIs for social sustainability objective

The social sustainability gaps for all buildings are much lower than Environmental sustainability gaps (Table 5). All the case study buildings have met threshold value for KPI–S-1.1 (House affordability) and KPI–S-1.5 (Local material sourcing). This is because the economic backdrop has lowered the interest rates in Australia (during the time of this life cycle assessment work), making the houses affordable to low-income people (RBA 2019). Secondly, the house affordability was consistent with the Australian real estate market and was aligned with the remarks made by the participants during the KPI development survey (Janjua et al., 2020). Thirdly, the construction materials for the case study buildings were obtained within 200 km vicinity of the construction site, which is within the sustainable distance limit for all buildings.

4.2.1. Indoor living conditions (KPI– S-1.2)

The reference building and four case study buildings (Building 4–6, 10) have no gap for KPI–S-1.2 due to shorter ESL requiring the reduced number of replacements of building components (Table 5). Building 8 (SF-CB-FAGC) and Building 9 (SF-CB-GGBFS) have the highest performance gap of 0.068 compared to other social KPIs, mainly due to longer ESL and the requirement for more replacements of costly building components (render, ceiling, plaster, windows, etc.).

4.2.2. Thermal comfort (KPI– S-1.3)

The performance gap of KPI– S-1.3 varied from 0.081 to 0.107 (Table 5). Buildings made of concrete block wall (Buildings 1–3, 7–9) with a higher U-value of 2.71W/m2K, have 12.1% higher annual operational energy requirement in the use stage than brick wall buildings (Building 4–6, 10–14) with a lower U-value of 1.58W/m2K due to. As a result, concrete block wall buildings have a 27 % higher performance gap than the brick wall buildings.

4.2.3. Noise (KPI– S-1.4)

KPI– S-1.4 ranges from 0 to 0.0016 for the case study buildings (Table 5). Buildings 7–14 have met the threshold value for KPI– S-1.4 due to the high noise resistance of building materials (i.e. STC-53 for steel truss roof, STC-50 for the double brick wall) (BIA 2000; SFIA 2013). Building 50 and Buildings 4–6 have a very small performance gap of 0.0012 as compared to concrete block buildings (Building 1–3) with a performance gap of 0.0016 due to having a double brick wall that has slightly higher noise resistance capacity (BIA 2000).

4.2.4. Energy conservation (KPI– S-2.1)

The concrete block wall buildings (Building 1–3, 7–9) have the highest gap for KPI–S-2.1 (Table 5). This is due to the fact that no remediation strategy is applied to the case study buildings at this stage of assessment. Among the double brick wall buildings, Building 13 (SF-DB-50%GGBFS+50%RA) with a longer ESL, showed the lowest gap for KPI – S-2.1 due to the use of industrial by-products and recycled aggregate. The use of by-products and waste replaced energy-intensive construction materials without affecting the structural performance of the buildings (Shaikh et al., 2019).

4.3. KPIs for economic sustainability objective

Only one of the five KPIs for economic sustainability objective, KPI–EC-2.1 (Net Benefit) met the threshold value for all case study buildings (Table 5). The KPI –EC-2.1 for residential buildings has been calculated

Table 6
Percentage variation of sustainability score due to ESL uncertainty for case study buildings.

Buildings	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
Sustainability score for calculated ESL (current case)	2.366	2.374	2.373	2.892	2.912	2.903	2.352	2.594	2.586	2.903	3.128	3.120	3.070	2.976
Sustainability score for best case ESL	2.366	2.374	2.373	2.892	2.912	2.903	2.678	2.594	2.586	3.189	3.128	3.120	3.246	3.068
Sustainability score for worst case ESL	1.813	1.823	1.821	2.449	2.474	2.463	2.140	2.040	2.103	2.777	2.716	2.707	3.244	3.077
% variation in Sustainability score due ESL uncertainty	26%	26%	26%	17%	16%	16%	22%	24%	21%	14%	14%	14%	0%	0%

Table 7
TBL hotspots of case study buildings.

Code	KPIs	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA	Max. Performance gap %	Hotspot
E-1.1	Carbon Footprint	0.211	0.210	0.210	0.196	0.194	0.195	0.211	0.209	0.211	0.196	0.192	0.193	0.191	0.191	**57%**	1
E-1.2	Resilience and adaptation	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.006	0.006	0.008	0.006	0.006	0.007	0.007	43%	
E-2.1	Acidification	0.196	0.195	0.196	0.192	0.191	0.192	0.196	0.195	0.196	0.192	0.191	0.191	0.190	0.191	**82%**	2
E-3.1	Eutrophication	0.195	0.195	0.195	0.192	0.191	0.191	0.195	0.194	0.195	0.192	0.191	0.191	0.190	0.190	**86%**	3
E-4.1	Land Use	0.201	0.200	0.200	0.195	0.194	0.195	0.187	0.186	0.187	0.179	0.177	0.177	0.180	0.177	**71%**	4
E-4.2	Loss of Biodiversity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0%	
E-5.1	Cumulative Embodied Water Consumption	0.025	0.024	0.024	0.000	0.000	0.000	0.025	0.013	0.015	0.000	0.000	0.000	0.000	0.000	8%	
E-6.1	Cumulative Energy Demand	0.208	0.208	0.208	0.200	0.199	0.200	0.208	0.207	0.208	0.200	0.197	0.198	0.197	0.198	**66%**	5
E-7.1	Cumulative Fossil Energy Consumption	0.282	0.282	0.282	0.279	0.279	0.279	0.282	0.282	0.282	0.279	0.278	0.278	0.278	0.278	**87%**	6
E-8.1	C & D waste	0.069	0.069	0.069	0.081	0.081	0.081	0.067	0.051	0.051	0.079	0.057	0.057	0.069	0.081	26%	
E-8.2	Recycling potential	0.004	0.003	0.003	0.000	0.000	0.000	0.002	0.005	0.005	0.000	0.001	0.001	0.001	0.001	10%	
S-1.1	House Affordability	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0%	
S-1.2	Indoor Living Conditions	0.062	0.062	0.062	0.000	0.000	0.000	0.062	0.068	0.068	0.000	0.002	0.002	0.015	0.028	24%	
S-1.3	Thermal Comfort	0.107	0.107	0.107	0.081	0.081	0.081	0.107	0.107	0.107	0.081	0.081	0.081	0.081	0.081	33%	
S-1.4	Noise	0.002	0.002	0.002	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	10%	
S-1.5	Local material sourcing	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0%	
S-2.1	Energy Conservation	0.321	0.321	0.321	0.279	0.270	0.275	0.321	0.321	0.321	0.280	0.246	0.251	0.241	0.254	**100%**	7
EC-1.1	Life Cycle Cost	0.104	0.103	0.103	0.069	0.068	0.068	0.108	0.088	0.088	0.074	0.049	0.048	0.061	0.073	31%	
EC-1.2	Potential Savings	0.242	0.242	0.242	0.137	0.137	0.137	0.242	0.151	0.151	0.137	0.022	0.022	0.058	0.096	**100%**	8
EC-1.3	Benefit Cost ratio	0.192	0.190	0.189	0.000	0.000	0.000	0.220	0.116	0.116	0.000	0.000	0.000	0.000	0.000	**85%**	9
EC-2.1	Net benefit	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0%	
EC-2.2	Carbon Tax Saving	0.208	0.208	0.208	0.201	0.193	0.195	0.208	0.208	0.208	0.202	0.182	0.184	0.172	0.177	**100%**	10

Note: Colour bars represent the range of the performance gap for KPIs (Longer the colour bar, higher the value and vice versa)

Note: Colour bars represent the range of the performance gap for KPIs (Longer the colour bar, higher the value and vice versa).

Table 8
Summary of CPS used for treating hotspots.

Hotspots	Energy consumption	CPS	Options recommended	Energy saving after implementation of CPS
Appliances and lighting	34–39% of annual energy consumption	Technology modification	Use of the solar photovoltaic system	75%
Heating and cooling	19–28% of annual energy consumption	Product modification	Replacement of single glazed windows with double glazed windows	[a]12% in brick wall buildings and 10% in concrete block wall buildings.
Water heater	37–42% of annual energy consumption	Technology modification	Flat type solar water heater with collector azimuth of 330°	65%

[a] These two buildings have different U values.

using a 7% net benefit on minimum cost per square meter of a medium finish house in Perth excluding 10% fit-out cost (Rawlinsons 2018). Interestingly, the calculated construction cost of all the case study buildings was less than the minimum construction cost or threshold, resulting in an increased net benefit.

4.3.1. Life cycle cost (KPI– EC-1.1)

The performance gaps for KPI–EC-1.1 varied from 0.048 to 0.108 for the case study buildings (Table 5). Building 7 (SF-CB-CC) has a gap of 0.108 (26.2% higher than the reference building) due to more replacement of building components, a relatively short ESL (57 years), and high operational energy requirement during the use stage. Building 12 (SF-DB-GGBFS) with 66 years ESL, have the smallest performance gap (52.3% lower than the reference building) due to longer ESL resulting in lower annual impact and it has lower operational energy cost (11.14%) due to the use of lower thermal mass material (bricks) and also 9.3% less material cost is involved as no rendering or reinforcement required for double brick walls.

4.3.2. Potential savings (KPI– EC-1.2)

The performance gap for KPI– EC-1.2 is higher for concrete block buildings (Buildings 1–3, 7–9) as compared to brick wall buildings (Buildings 4–6, 10–14) (Table 5). Buildings 1–3 and 7 with an ESL of 57 years have a performance gap of 0.242 for EC-1.2 due to high energy cost (11.14%) during the use stage and also due to the use of energy-intensive costly building materials (concrete blocks, concrete, terracotta tiles, and ceramic tiles). Both Building 11 (SF-DB-FAGC) and Building 12 (SF-DB-GGBFS) have a performance gap of only 0.022 due to the lower energy cost (11.14%) of double brick wall building (as a result of lower operational energy demand) and also for its longer ESL (66 years).

4.3.3. Benefit to cost ratio (KPI– EC-1.3)

The buildings made of brick walls (Building 3–6, 10–14) met the threshold value for KPI–EC-1.3 due to lower operational energy demand (12.1%) during the use stage (Table 5). Building 7 (SF-CB-CC) showed

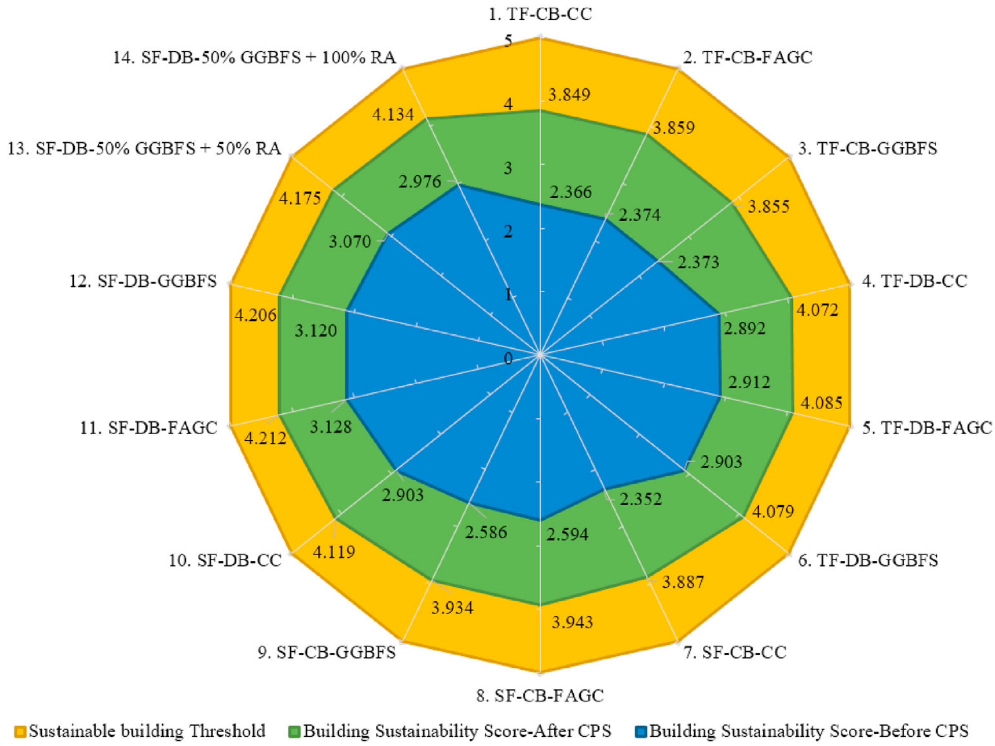
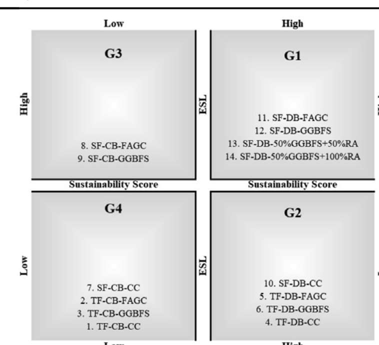


Fig. 4. Sustainability score of case study buildings: Before and after applying CPS.

Table 9
Sustainability Ranking/Matrix of case study buildings based on sustainability score and ESL.

3. **Group G3** of the ESL-sustainability quadrant included Buildings 8–9 with sustainability ranking 9–10 and an ESL of 65 years. The use of concrete blocks of lower thermal mass and higher coefficient of heat transmission (U-Value = 2.71 W/m2K) contributed to higher operational energy demand (24.63%), thus increased the TBL sustainability performance. Rendering (ESL–16 years) applied to concrete block walls as an extra measure to reduce the porosity of concrete blocks, has also contributed adversely to the sustainability performance of the building by increasing the overall energy consumption.
4. **Group G4** of the ESL-sustainability quadrant included Buiding 7 and Buildings 1–3 with sustainability ranking 11–14 and an ESL of 57 years. The annual pre-use impacts of TBL sustainability were increased due to shorter ESL of these buildings. The shorter ESL is due to lower service life of timber framed roof and footing made of conventional concrete. Use of virgin materials, higher operational energy demand (24.63%) due to use of concrete block walls (U-Value = 2.71 W/m2K) and frequent replacements of non-structural components (ceramic tiles, roof covering, windows, doors, plaster, rendering) increased the TBL impacts of G4 buildings.

Ranking	Buildings	ESL	Sustainability score	Group	Quadrant Matrix
1	11. SF-DB-FAGC	66	4.212	G1	
2	12. SF-DB-GGBFS	66	4.206		
3	13. SF-DB-50%GGBFS+50% RA	63	4.175		
4	14. SF-DB-50%GGBFS+100% RA	60	4.134		
5	10. SF-DB-CC	57	4.119	G2	
6	5. TF-DB-FAGC	57	4.085		
7	6. TF-DB-GGBFS	57	4.079		
8	4. TF-DB-CC	57	4.072		
9	8. SF-CB-FAGC	65	3.943	G3	
10	9. SF-CB-GGBFS	65	3.934		
11	7. SF-CB-CC	57	3.887	G4	
12	2. TF-CB-FAGC	57	3.859		
13	3. TF-CB-GGBFS	57	3.855		
14	1. TF-CB-CC	57	3.849		

the highest performance gap of 0.220 due to the use of expensive conventional building materials for structural components, and there are also operational and maintenance costs involved due to the frequent replacements of energy-intensive building components with comparatively shorter ESL.

4.3.4. Carbon tax saving (KPI– EC-2.2)

The performance gap for KPI– EC-2.2 varies from 0.172 to 0.208 (ESM_Table B5). Carbon tax saving has the largest performance gap of 0.208 for buildings made of concrete block wall (Buildings 1–3, 7–9), due to use of carbon-intensive OPC and natural aggregates with high energy consumption (12.1%) and subsequent GHG emissions resulting from building operation during the use stage, and due to the frequent replacements of building components (ceramic tiles, terracotta tiles, render, plaster). Building 4–6, 10–14, and Building 13 (SF-DB-50% GGBFS + 50% RA) have the lowest performance gap of 0.172, mainly due to longer ESL (63 years), and for using industrial by-products and recycled aggregate.

4.4. Impact of the quality of LCI on the environmental impact results

The case study buildings have variations in terms of service life estimation and material specifications and quantities that could potentially lead to uncertainties of LCA results. To evaluate the uncertainties associated with material specifications and quantities on environmental KPIs (E-1.1, E-2.1, E-3.1, E-4.1, E-5.1, E-6.1, E-7.1), Monte Carlo Simulation (PRe'-Consultants 2016) was conducted for the LCA of these buildings.

The uncertainty analysis (ESM_Table B5) showed that the mean and median values for these KPIs are very close to the calculated values and the coefficient of variation values have a lower degree of uncertainty and increased confidence level in the environmental LCA of the case study buildings. The coefficient of variation for KPI land use is comparatively higher (4.42% to 4.84%) for Building 1–6. This may be because these buildings are made of plant-based materials resulting in uncertainty associated with the rate of cropland expansion in Australia (Prestele et al., 2016). However, life cycle assessment studies with the coefficient of variance below 5% are acceptable (Grant, 2009; Lo et al., 2005; Biswas and Cooling 2013).

4.5. Impact of the variation in ESL on the overall sustainability score

Table 6 shows how the variation in ESL as discussed in Table 3, which could also vary the sustainability score of the case study buildings. The overall sustainability score of the case study buildings varies between 0 and 26% with ESL (Table 4).

The variation of sustainability score for Buildings 1–3 is very high due to variation in quality of building materials (i.e., timber, rendering, plaster, concrete). The sustainability score of Building 13 (SF-DB-50% GGBFS+50%RA) and Building 14 (SF-DB-50% GGBFS+100%RA) are not affected by the variation of service life due to use of recycled materials and industrial byproducts with lower environmental impacts (Table 4).

4.6. Sustainability improvement strategies

A hotspot analysis was carried out to identify the poorly performing KPIs for case study buildings (identified as the red color bars in Table 7) and devise potential improvement strategies.

4.6.1. Observations based on hotspot analysis

Hotspot analysis identified that ten of 22 KPIs (E-1.1 Carbon footprint, E-2.1 Acidification, E-3.1 Eutrophication, E-4.1 Land Use, E-6.1 Cumulative energy demand, E-7.1 Cumulative fossil energy consumption, S-2.1 Energy Conservation, EC-1.2 Potential savings, EC-1.3 Benefit-cost ratio, EC- 2.2 carbon tax saving) contributed significantly to lower the sustainability performance of the case study buildings (Table 7).

The LCSA results showed that energy consumption and maintenance activities during use stage, has contributed between 65% (E-4.1 Land use) and 100% (EC-1.2 Potential savings) of the TBL impacts for case study buildings; hence these activities have been identified as the hotspot.

4.6.2. Improvement options

To reduce the impacts of sustainability hotspots, two CPS, including technology modification, and product modification can potentially be considered for the case study buildings (UNEP 2015). The summary of CPS and their effects on hotspot are shown in Table 8.

Overall, the integration of these three sustainability improvement strategies reduced the annual electricity demand by 51% for the concrete block buildings (Building 1–3, 7–9) and 57% for the double brick wall buildings (Building 4–6, 10–14). In buildings with the steel-framed roof (Buildings 7–14) the recycled steel trusses were used to replace virgin steel roof frame to further reduce the environmental impacts of buildings.

4.7. Follow up LCA for improvement scenario

A follow-up ELCA was carried out by incorporating the revised data using the SimaPro software to determine the environmental KPIs. KPI values were calculated for the case study buildings (ESM_Table C1). Then the revised KPI position values and gaps were calculated using the LCSA framework (ESM_Table C2-C3). The performance gap for KPIs, impact categories, sustainability objectives, and case study buildings were calculated to find out the sustainability improvement of KPIs (ESM_Table C4-C7).

The improvement in the performance gap of KPIs in terms of percentage for fourteen case study buildings before and after the application of CPS are presented in ESM_Table C7. Interestingly, the changes or improvement in the environmetnal indicators affected both social and economic indicators as these indicators are interlinked through this LCSA framework. In the revised sustainability performance assessment, six additional KPIs (E-5.1 Cumulative embodied water consumption, S-1.3 Thermal comfort, S-2.1 Energy conservation, EC-1.2 Potential savings, EC-1.3 Benefit Cost Ratio and EC-2.2 Carbon tax saving) met the threshold values. The remaining 6 of 10 KPIs (E-1.1 Carbon footprint, E-2.1 Acidification, E-3.1 Eutrophication, E-4.1 Land use, E-6.1 Cumulative energy demand, E-7.1 Cumulative fossil energy consumption) showed improved results for performance gap due to implementation of the CPS.

A reduction in energy demand during the operational stage has reduced the performance gap of KPI–EC-1.1 (Life cycle cost) significantly (24.6–75.9%) mainly due to reduction in operational cost by 70.26% for the brick wall buildings (Building 4–6, 10–14) and 61.48% for the concrete block wall buildings (Building 1–3, 7–9). Maximum performance gap reduction of 75.9% is observed for Building 11 (SF-DB-FAGC) and Building 12 (SF-DB-GGBFS) with an ESL of 66 years, due to reduced operational energy cost (70.26%) after the implementation of CPS. Fig. 4 shows that the sustainability score (i.e., 5-$\sum$ performance gaps of TBL sustainability objectives) of the case study buildings improved significantly after applying CPS. The implementation of CPS resulted in an average improvement of 48% in the sustainability performance of Buildings 1–3, 34% for Building 4–6, 49% for Building 7, 41% for Building 8–9, 35% for Building 10, 30% for Building 11, 31% for Building 13 and 33% for Building 14.

4.8. ESL- sustainability quadrant

The case study buildings have been ranked from 1 to 14 based on the sustainability score calculated after applying CPS, with sustainability rank-1 for building with the highest sustainability score (Table 9). Buildings made of brick wall (Building 4–6, 10–14) have achieved the highest sustainability score among all the case study buildings, mainly due to having lower energy consumption (24.63%) during the use stage as compared to buildings made of concrete block walls (Building 1–3,7-9) and also due to the absence of frequently replaced building components (i.e., rendering). The reference building (Building 50) with a service life of 50 years has the lowest sustainability score of 2.449, due to shorter service life of 50 years that has increased the annual impacts during pre-use and use stages due to higher energy demand (78.86% higher than brick wall buildings and 57% higher than concrete block wall buildings). Based on the ESL and sustainability score of the buildings, an 'ESL-sustainability quadrant' was made to classify the buildings in terms of TBL sustainability score and corresponding ESL.

1. **Group G1** of the ESL-sustainability quadrant included Buildings 11–14 with sustainability ranking 1–4 and longer ESL (66-60 years). G1 buildings have high sustainability scores and longer ESL among case study buildings. The impacts during pre-use stage and use stage maintenance of these buildings were reduced due to longer ESL. The use of industrial by-products and recycled materials reduced the environmental impacts of buildings. The use of bricks, with high thermal mass and lower heat transmission tendency (U-Value = 1.58W/m2K), in building envelope, lowered the use stage energy demand (24.63%) of buildings.
2. **Group G2** of the ESL-sustainability quadrant included Buiding 10 and Buildings 4–6 with sustainability ranking 5–8 and lower ESL (57

years). Pre-use stage impacts of the buildings increased due to the use of plant-based materials (i.e., timber) in Building 4–6 and virgin materials (i.e., 100 % OPC conventional concrete, virgin steel) in Building 10. Also the frequent replacements of less durable non-structural components (i.e., ceramic tiles, roof covering, windows, doors, plaster) increased the maintenance during the use stage of these buildings. However, the operational energy demand and costs of these buildings were significantly reduced thanks to the thermal performance of the brick walls (U-Value = 1.58W/m2K).

5. Comparative analysis and limitations

The incorporation of ESL into LCSA in residential buildings was not considered previously, therefore the findings of this study have been compared with the existing LCSA studies having the same system boundary orLCA stages. A study on different types of buildings (timber and concrete frame buildings) concluded that building sustainability is dependent on the operational energy rather than pre-use stage (manufacturing of materials), thus confirming the use stage as hotspot, however, use stage replacements were not considered by Hossaini et al. (2015). Onat et al. (2014) carried out an LCSA study of US buildings and concluded that the electricity use was the most important component of the sustainability assessment of buildings. Another study by Dong and Ng (2016) studied building construction for pre-use stage (A1-A5 module of building life cycle– EN 15978:2011) and identified the manufacturing of materials as hotspot. In the current study, the use stage has been identified as the hotspot like previous studies, and the manufacturing stage is spotted as the second hotspot.

This LCSA study has selected region-specific KPIs and can only be applied to Australian residential buildings. However, the LCSA framework is flexible as it can be applied to other states and countries, incorporating region-specific socio-economic and climatic differences and by taking into account the durability and structural performance of building components, based on the KPI selection methodology (Janjua et al., 2020). To determine the position values of TBL sustainability KPIs, the use stage energy demand for cooling and heating was calculated by simulating building models in AccuRate sustainability software. This software has material libraries for conventional materials used in building envelops only. Since this research highlighted that the implications of thermal mass of both structural and non-structural components on building energy consumption in the use stage, there is an opportunity for upgrading the software by including more libraries for alternative materials for non-structural and envelop components (e.g. wood, by-products and recycled materials). . The service life of the buildings was estimated using the available data from reliable sources, however, a participatory approach in factors selection for the service life estimation can enhance the confidence level of the service life estimation. The threshold values may need to be updated at least every 5 years due to policy and technological changes.

6. Conclusions

The LCSA framework has been successfully applied to buildings made of a wide range of building materials including recycled materials, industrial by-products, virgin materials and to demonstrate how the integration of service life estimation of the building and building components' affect the TBL sustainability performance of residential buildings.

The proposed LCSA framework identified the TBL hotspots of Western Australia's residential buildings to select relevant CPS strategies, including solar electricity and heating, use of recycled metals, and double glazing to further enhance the sustainability performance of buildings. A maximum of 49% improvement in the sustainability performance of Building 7 (SF-CB-CC) and a minimum of 30% for Building 11 (SF-DB-FAGC) and Building 12 (SF-DB-GGBFS) could potentially achieved using these strategies. A combination of longer life and durability of construction materials, use of industrial by-products and recycled as well as low U-value materials, reduced level maintenance during the use stage, and the application of CPS were found to contribute to the best sustainability performance of these buildings. Longer service life does not always attain sustainable buildings due to complexity of building material specifications as identified in Group 3 of ESL-sustainability quadrant for Building 8 (SF-CB-FAGC) and Building 9 (SF-CB-GGBFS) with 65 years of ESL. The selection of building materials for structural components affects the building sustainability performance in a twofold way i.e., durability and thermal efficiency. Both these properties affect the use stage of LCSA. However, using less durable building materials for non-structural components, adversely impact the sustainability performance of buildings by increasing the replacements and repairs in use stage and vice versa.Assessment of the case study buildings using the LCSA framework has revealed that the overall sustainability of residential buildings is dependent on the use stage in the life cycle of buildings. Frequent replacements and energy consumption during the use stage were identified as the major hotspots in the residential buildings. Therefore, service life estimation is deemed crucial to avoid uncertainties in TBL impact assessment.

Last but not least, this paper fulfils the objectives of circular economy which is to retain the value of resources and to prevent the use of virgin materials and waste outputs, not only by recycling and reusing, but primarily by reducing the need for resource (Joensuu et al., 2020). Firstly, the use of recycled aggregates as a replacement for virgin aggregates in concrete to avoid the dependence on virgin rocks and the use of cementitious by-products fly ash and GGBFS as a replacement of energy intensive cement in concrete helps conserve limestones. Secondly, the integration of service life into the LCSA framework enabled the determination of the implication of durability on resource conservation. The more the service life, the more is the opportunity of resource conservation as it slows down the rate of resource exploitation. Thirdly, intergenerational social equity has been considered as one the social indicators in this LCSA framework to measure the amount of embodied energy that can be saved by different building specifications for the future generation. It considered the application of photovoltaic panel and solar water heater during the use stage of a building to conserver non-renewable resources like coal and natural gas. Finally this paper emphasising the need for incorporating sustainable engineering strategies during the design stages so that the service life of the building can be enhanced while improving the sustainability performance of buildings.

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Appendix A. Supplementary data

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References

ABCB, 2019. National Construction Codes (NCC) - Volume 2. Commonwealth of Australia and States and Territories Canberra. ACT, Australia.

ABS, 1995. 4102.0- Australian social trends, 1995. Australian Bureau of Statistics, Canberra, Australia. https://www.abs.gov.au/AUSSTATS/abs@.nsf/2f762f95845417aeca25706c00834efa/cd6c2ea981520095ca2570ec007530a4!OpenDocument. (Accessed 12 December 2019).

ABS, 2000. 4182.0- Australian housing survey- Housing characteristics, Costs and Conditions, 1999. Australian Bureau of Statistics, Canberra, Australia. https://www.abs.gov.au/ausstats/abs@.nsf/mf/4182.0. (Accessed 12 December 2019).

ABS, 2010. 1304.5- stats talk WA, sep 2010. Australian Bureau of Statistics, Canberra, Australia. https://www.abs.gov.au/AUSSTATS/abs@.Nsf/39433889d406eeb9ca2570610019e9a5/b82e429726cf6975ca2577f9000f1c0c!OpenDocument. (Accessed 12 December 2019).

ABS, 2019. 8782.0.65.001 - construction activity: chain volume measures, Australia, mar 2019, canberra. Australian Bureau of Statistics, Canberra, Australia. Available from: https://www.abs.gov.au/ausstats/abs@.nsf/0/EDD60A6A5408DD1BCA2576B00014308C?Opendocument. Accessed 10-3-2020.

APH, 2018. Sustainable buildings: Australian Government's role in the development of cities. Department of Parliamentary Services, Parliament of Australia, Canberra, Australia. https://www.aph.gov.au/Parliamentary_Business/Committees/House/ITC/DevelopmentofCities/Report/section?id=committees%2Freportrep%2F024151%2F25690. (Accessed 19 December 2019).

AS, 2011. AS2870:2011Residential Slabs and Footings. Standards Australia, NSW, Australia.

AS, 2018. AS 3700:2018 Masonry Structure. Standards Australia. NSW, Australia.

ASRIS, 2019. Soil groups of western Australia. Australian Soil Resource Information System, Canberra, Australia. http://www.asris.csiro.au/mapping/viewer.htm. (Accessed 9 December 2019).

Balasbaneh, A.T., Marsono, A.K., Khaleghi, S.J., 2018. Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: environmental, economic and social assessment. J. Build. Eng. 20, 235–247. https://doi.org/10.1016/j.jobe.2018.07.006.

Biswas, W.K., Cooling, D., 2013. Sustainability assessment of red sand as a substitute for virgin sand and crushed limestone. J. Ind. Ecol. 17, 756–762. https://doi.org/10.1111/jiec.12030.

BOM, 2018. Average annual, seasonal and monthly rainfall. Bureau of Metrology, Australian Government, Australia. http://www.bom.gov.au/climate/current/annual/aus/2019/annual-summary-table.shtml. (Accessed 10 October 2018).

Carre, A., 2011. PNA147-0809: a comparative life cycle assessment of alternative constructions of a typical Australian house design. Forest & Wood Products Australia, Melbourne, Australia. https://www.fwpa.com.au/resources/market-access/204-comparative-life-cycle-assessment-of-alternative-constructions-of-a-typical-australian-house-design.html. (Accessed 19 December 2018).

CBA, 2019. Extra home loan fact sheet. Commonwealth Bank of Australia. https://www.commbank.com.au/home-loans/extra-home-loan.html. (Accessed 9 December 2019).

CCAA, 2003. CCAA T49-2003: guide to residential floors. Cement concrete & aggregates Australia, NSW, Australia. Cement Concrete Aggregates Australia. https://www.ccaa.com.au/iMIS_Prod/CCAA/Public_Content/PUBLICATIONS/Technical_Publications/Guides/Guide_to_Residential_Floors.pdf. (Accessed 11 November 2018).

Chen, Z., Csiro, 2019. AccuRate Sustainability 2.3.3.13 SP4 Software. Energy Inspection, Australia.

Clarke, D., Hockings, B., McGee, C., 2013. Concrete slab floors. Department of the environment and energy, Commonwealth of Australia. https://www.yourhome.gov.au/materials/concrete-slab-floors. (Accessed 13 October 2017).

Cmaa, 2019. CM-1: concrete masonry - handbook. Concrete Masonry Association of Australia, NSW, Australia. https://cmaa.blob.core.windows.net/media/1007/cm01-2017_concrete-masonry-handbook.pdf. (Accessed 11 December 2019).

community, id, 2019. Australia- Community profile, Western Australia- Number of Bedrooms per dwelling. id the population experts. https://profile.id.com.au/australia/bedrooms?WebID=140. (Accessed 12 December 2019).

Cuéllar-Franca, 2012. Sustainability assessment framework for the residential construction sector in the UK. Dissertation. In: School of Chemical Engineering and Analytical Science. University of Manchester, Manchester UK.

DOCWA, 2016a. Building commission compliance report: a summary of technical building inspections_ 2015/2016 Report. Department of Commerce WA, Government of Western Australia. https://www.commerce.wa.gov.au/sites/default/files/atoms/files/a_summary_of_technical_building_inspections_201516_final.pdf. (Accessed 15 July 2018).

DOCWA, 2016b. General Inspection Report One: a general inspection into metal roof construction in Western Australia. Build. Energy. Department of commerce, Government of Western Australia. https://www.commerce.wa.gov.au/sites/default/files/atoms/files/general_inspection_report_2016.pdf. (Accessed 15 July 2018).

DOCWA, 2017a. Building commission compliance report: a summary of technical building inspections_ 2016/2017 report. Department of Commerce, Government of Western Australia. https://www.commerce.wa.gov.au/sites/default/files/atoms/files/a_summary_of_technical_building_inspections_2016-17.pdf. (Accessed 15 July 2018).

DOCWA, 2017b. Building commission compliance report: a summary of technical building inspections_ Mid-year 2016/2017 Report. Department of Commerce WA, Government of Western Australia. https://www.commerce.wa.gov.au/publications/summary-technical-building-inspections-2016-17-mid-year. (Accessed 15 July 2018).

DOCWA, 2019. Building commission compliance audit. Building and Energy. Department of commerce, Government of Western Australia. http://www.commerce.wa.gov.au/search/site/building%2520commission %2520compliance%2520audits. (Accessed 13 December 2018).

DOEE, 2019. State and territory greenhouse gas inventories 2017. Australia's National Greenhouse Accounts. Department of Environment and Energy, Canberra, Australia. https://www.environment.gov.au. (Accessed 7 August 2019).

Dong, Y.H., Ng, S.T., 2016. A modelling framework to evaluate sustainability of building construction based on LCSA. Int. J. Life Cycle Assess. 21, 555–568. https://doi.org/10.1007/s11367-016-1044-6.

EN 15978:2011, 2018. PN 326 Rev 0.0 – BRE Global methodology for the environmental assessment of buildings using EN 15978:2011. BRE Global Ltd. Available at: www.bregroup.com. (Accessed 20 July 2020).

Fthenakis, V., Kim, H.C., 2009. Land use and electricity generation: a life-cycle analysis. Renew. Sustain. Energy Rev. 13, 1465–1474. https://doi.org/10.1016/j.rser.2008.09.017.

Geng, S., Wang, Y., Zuo, J., Zhou, Z., Mao, G., 2017. Building life cycle assessment research: a review by bibliometric analysis. Renew. Sustain. Energy Rev. 76, 176–184. https://doi.org/10.1016/j.rser.2017.03.068.

Gloria, T., 2016. EPD- roll formed steel panels. Canadian Sheet Steel Building Institute, Canada. https://cssbi.ca/assets/resources/EPD/101-1_EPD_CSSBI-Canadian-Sheet-Steel-Building-Institute_Roll-Formed-Steel-Panels_02262016.pdf. (Accessed 13 December 2019).

Grant, T., 2009. Inclusion of uncertainty in LCA. Centre for Design at RMIT University, Melbourne, Australia. https://p2infohouse.org/ref/12/11598.pdf. (Accessed 13 December 2019).

Grant, A., Ries, R., 2013. Impact of building service life models on life cycle assessment. Build. Res. Inf. 41, 168–186. https://doi.org/10.1080/09613218.2012.730735.

Grant, A., Ries, R., Kibert, C., 2014. Life cycle assessment and service life prediction. J. Ind. Ecol. 18 (2), 187–200. https://doi.org/10.1111/jiec.12089.

Guinée, J., 2015. Chapter 3: life cycle sustainability assessment: what is it and what are its challenges? In: Clift, R., Druckman, A. (Eds.), Taking Stock of Industrial Ecology. Springer Cham Heidelberg New York, Dordrecht London.

Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., Hewage, K., 2015. AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. J. Environ. Plann. Manag. 58, 1217–1241. https://doi.org/10.1080/09640568.2014.920704.

Hosseinian, S.M., Nezamoleslami, R., 2018. Water footprint and virtual water assessment in cement industry: a case study in Iran. J. Clean. Prod. 172, 2454–2463. https://doi.org/10.1016/j.jclepro.2017.11.164.

Hovde, P.J., Moser, K., 2004. Performance based methods for service life prediction, state of art reports, report of CIB W080/RILEM 175-SLM: service life methodologies. Norwegian University of Science and Technology (NTNU), Department of Building and Construction Engineering, Trondheim, Norway. Available at: http://www.irbnet.de/daten/iconda/CIB1305.pdf. (Accessed 10 August 2017).

Inglis, C., Downton, P., 2013. Brickwork and blockwork. Department of the environment and energy, Commonwealth of Australia. https://www.yourhome.gov.au/materials/brickwork-and-blockwork. (Accessed 13 October 2017).

ISO, 2000. ISO 15686-1:2000 - Part 1: General Principals and Framework, Building and Constructed Assets – Service Life Planning. International Standards Organisation, Geneva, Switzerland.

ISO, 2006. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. International Standards Organization, Geneva, Switzerland.

ISO, 2008. ISO 15686-8:2008 - Part 8: Reference Service Life and Service-Life Estimation, Buildings and Constructed Assets - Service-Life Planning. International Standards Organisation, Switzerland.

Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019. A review of residential buildings' sustainability performance using a life cycle assessment approach. J. Sustain. Res. 1, e190006 https://doi.org/10.20900/jsr20190006.

Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019a. Impact of service life on the environmental performance of buildings. Buildings 9, 9. https://doi.org/10.3390/buildings9010009.

Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019b. Sustainability Implication of a residential building using a lifecycle assessment approach. Chem. Eng. Trans. 72, 19–24. https://doi.org/10.3303/CET1972004.

Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2020. Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings. J. Environ. Manag. 264, 110476. https://doi.org/10.1016/j.jenvman.2020.110476.

Joensuu, T., Edelman, H., Saari, A., 2020. Circular economy practices in the built environment. J. Clean. Prod. 276, 124215. https://doi.org/10.1016/j.jclepro.2020.124215.

Kamali, M., Hewage, K., Milani, A.S., 2018. Life cycle sustainability performance assessment framework for residential modular buildings: aggregated sustainability indices. Build. Environ. 138, 21–41. https://doi.org/10.1016/j.buildenv.2018.04.019.

Kim, T.H., Chae, C.U., 2016. Environmental impact analysis of acidification and eutrophication due to emissions from the production of concrete. Sustainability 8, 578. https://doi.org/10.3390/su8060578.

Klöppfer, W., 2008. Life cycle sustainability assessment of products. Int. J. Life Cycle Assess. 13, 89–95.

LEED, 2016. Regional materials, MRc 5; LEED BD+C: new construction | V3-LEED 2009. Leadership in energy and environmental design. https://www.usgbc.org/node/1731029?return¼/credits/new-construction/v2009. (Accessed 14 June 2019).

Lo, S.C., Ma, H.W., Lo, S.L., 2005. Quantifying and reducing uncertainty in life cycle assessment using the Bayesian Monte Carlo method. Sci. Total Environ. 340, 23–33. https://doi.org/10.1016/j.scitotenv.2004.08.020.

Majer, J.D., Beeston, G., 1996. The biodiversity integrity index: an illustration using ants in Western Australia Conservation biology. Conserv. Biol. 1, 65–73. https://doi.org/10.1046/j.1523- 1739.1996.10010065.x.

Mathur, V.N., Price, A.D.F., Austin, S., 2008. Conceptualizing stakeholder engagement in the context of sustainability and its assessment. Construct. Manag. Econ. 26, 601–609. https://doi.org/10.1080/01446190802061233.

McCormack, M., Treloar, G.J., Palmowski, L., Crawford, R., 2007. Modelling direct and indirect water requirements of construction. Build. Res. Inf. 35, 156–162. https://doi.org/10.1080/09613210601125383.

Miglietta, P.P., Morrone, D., Leo, F.D., 2018. The water footprint assessment of electricity production: an overview of the economic-water-energy nexus in Italy. Sustainability 10. https://doi.org/10.3390/su10010228.

NASH, 2018. Home builders & buyers guide to steel framed construction. National association of steel framed housing. https://www.nash.asn.au/nash/publications/home-builders-buyers-guide. (Accessed 13 December 2019).

Nath, P., Sarker, P.K., Biswas, W.K., 2018. Effect of fly ash on the service life, carbon footprint and embodied energy of high strength concrete in the marine environment. Energy Build. 158, 1694–1702. https://doi.org/10.1016/j.enbuild.2017.12.011.

NHSC, 2011. The Key Findings of 2011, the State of Supply Report. National Housing Supply Council, Australia the Australian government.

Onat, N.C., Kucukar, M., Tatari, O., 2014. Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings. Int. J. Life Cycle Assess. 19, 1488–1505. https://doi.org/10.1007/s11367- 014-0753-y.

Pelzeter, A., 2007. Building optimization with life cycle costs- the influence of calculation methods. J. Facil. Manag. 5, 115–128. https://doi.org/10.1108/14725960710751861.

PRe'-Consultants, 2016. SimaPro 8.4 LCA Software. Netherlands.

Prestele, R., Alexander, P., Rounsevell, M.D.A., Arneth, A., Calvin, K., Doelman, J., et al., 2016. Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. Global Change Biol. 22, 3967–3983. https://doi.org/10.1111/gcb.13337.

Rawlinsons Group, 2018. Rawlinsons Construction Cost Guide 2011. Rawlinsons Quality Surveyors and Construction Cost Consultants, edn. Rawlinsons Publishing, Perth WA, p. 36.

RBA, 2019. Statement on monetary policy- november 2019. Australia. https://www.rba.gov.au/publications/smp/2019/nov/. (Accessed 19 December 2019).

Reardon, C., Davis, T., Downton, P., 2013. Lightweight framing. Department of the environment and energy, Commonwealth of Australia. https://www.yourhome.gov.au/materials/lightweight-framing. (Accessed 13 October 2017).

SETAC/UNEP, 2012. Towards a life cycle sustainability assessment: making informed choices on products. United Nation environment Programme, Paris, France. Life Cycle Initiative. https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Towards%20LCSA.pdf. (Accessed 10 June 2018).

SFIA, 2013. A Guide to Fire & Acoustic data for Cold-Framed steel floor, wall & roof assemblies. Steel Framing Industry Association, Washington, DC, USA. http://www.steelframing.org. (Accessed 15 June 2019).

Shaikh, F.U.A., Nath, P., Hosan, M.A., Biswas, W.K., 2019. Sustainability assessment of recycled aggregates concrete mixes containing industrial by-products. Mater. Today Sustain. 5, e100013 https://doi.org/10.1016/j.mtsust.2019.100013.

Silva, A., De Brito, J., Gaspar, P.L., 2016. Methodologies for service life prediction of buildings, with a focus on facade claddings; green energy and technology. Springer international publishing Switzerland. https://doi.org/10.1007/978-3-319-33290-1.

Trainor, A.M., McDonald, R.I., Fargione, J., 2016. Energy sprawl is the largest driver of land use change in United States. PloS One 11 (9), e0162269. https://doi.org/10.1371/journal.pone.0162269.

UN, 2015. Paris agreement. United Nations framework convention on climate change (UNFCCC). United Nations. Le bourget, paris, France. https://unfccc.int. (Accessed 10 January 2019).

UNEP, 2015. Introduction to Cleaner Production Concepts and Practices. Division of Technology, Industry and Economic, Institute of Environmental Engineering (APINI) Kaunas University of Technology, Lithuanis.

UNEP, 2018. Towards zero-emission, efficient, and resilient buildings and construction sector. In: Global Status Report 2018. United Nation Environment Programme. Global Allience for Buildings and Construction (GABC), Paris, France. https://www.globalabc.org/uploads/media/default/0001/01/f64f6de67d55037cd9984cc29308f3609829797a.pdf. (Accessed 30 June 2018).

Vale, M., Pentalone, M., Bragagnolo, M., 2017. Collaborative perspective in bio-economy development: a mixed method approach. IFIP Adv. Inf. Commun. Technol. 506, 553–563. https://doi.org/10.1007/978-3-319-65151-4_49.

PAPER 5: ELECTRONIC SUPPLEMENTARY MATERIAL

Sustainability Implications of service life on residential buildings – An application of Life Cycle Sustainability Assessment Framework

Appendix A

Table A1: Ranking of factors A - G for Service life estimation

Factor	Description	Ranking	Building Component	Reason for Ranking
A	Quality of components including manufacturing, storage, transport, and protective coating, etc.	1.10	Timber truss, Steel Truss, Terracotta tiles, gypsum board ceiling, concrete block wall, double brick wall, SG windows, metal frame wooden doors, ceramic floor tiles	Manufactured in factory-controlled conditions with high-quality materials as per national standards
		1.10	On grade slab– FAGC On grade slab– GGBFS	By-products added to concrete to replace 30% OPC and increase the quality of ready- mix concrete by reducing the heat of hydration, permeability, and improving strength and durability.
		1.05	Plaster, Render	Prepared on-site as per national standards
		1.00	On grade Slab– 50% GGBFS+50% RA On grade Slab– 50% GGBFS+100% RA	50% OPC in ready-mix concrete was replaced by GGBFS and the natural aggregates were replaced by 50% recycled aggregates. The studies (Shaikh et al. 2019; Kou et al., 2011; Ma et al. 2019) showed that the use of recycled aggregate increase shrinkage value, chloride permeability, carbonation, and abrasion of concrete. Nonetheless, these values can be reduced by the addition of industrial by-products in the concrete mix. A mix ratio of 50% GGBFS with 50% recycled aggregate provides the best resistance against the dry shrinkage and chloride penetration as compared to conventional concrete, it decreased by increasing the RA quantity (Kou et al. 2011)
		0.95	On grade slab – CC	Conventional ready-mix concrete with 100% OPC

https://ars.els-cdn.com/content/image/1-s2.0-S2665972721000106-mmc1.docx

Factor	Description	Ranking	Building Component	Reason for Ranking
B	Design level (incorporation, sheltering by rest of structure)	1.1	Timber Truss, Steel Truss, concrete block wall, on grade slab	Best design with special consideration to improve the structural performance i.e., Roof sarking, ventilation, reinforcing to block walls, higher grade mesh reinforcement
		1.05	Double brick wall, Plaster, render	Best design practice as per standards
		1.00	Terracotta tiles, Gypsum board ceiling, Ceramic floor tiles, SG windows, metal frame wooden door	Not Applicable
C	Work execution level, site management, workmanship level, weather condition during work	1.05	Gypsum Board Ceiling	Workmanship satisfaction level between 70 - 80% in official reports by the department of commerce, the government of WA (DOCWA 2016a; 2016b; 2017a; 2017b; 2019)
		0.95	Render, On grade Slab, Ceramic tiles	Workmanship satisfaction level between 80 - 90% in official reports by the department of commerce, the government of WA (DOCWA 2016a; 2016b; 2017a; 2017b; 2019)
		0.90	Timber truss, steel truss roof, Terracotta tiles, Gypsum board ceiling, concrete block wall, double brick wall, SG windows, metal frame wood doors	Workmanship satisfaction level ≤ 70% in official reports by the department of commerce, the government of WA (DOCWA 2016a; 2016b; 2017a; 2017b; 2019)
D	Indoor environment conditions, humidity, ventilation, and condensation, etc.	1.00	Timber truss, steel truss roof, Terracotta tiles, concrete block wall, double brick wall, Render, On grade Slab	Not Applicable
		0.95	Gypsum board ceiling, Plaster, Ceramic tiles, SG Windows, Metal frame wood door	Mild deterioration
E	Outdoor environment, micro- environmental conditions, weathering factors, building elevation etc.	1.00	Timber truss, steel truss roof, Gypsum board ceiling, Concrete block wall, Plaster, ceramic floor tiles	Not Applicable
		0.95	Terracotta tiles, double brick wall, Render, On grade Slab, SG windows, metal frame wood doors	Mild deterioration

Factor	Description	Ranking	Building Component	Reason for Ranking
F	In-use conditions, mechanical impact, wear and tear, category user, etc.	1.00	All building components	Not considered in the study as it depends on user behaviour
G	Maintenance level, quality, and frequency	1.05	Timber truss, steel truss roof, terracotta tiles, Gypsum board ceiling, double brick wall, Plaster, Render, ceramic tiles, SG Windows, Metal frame wood door	Supportive
		1.00	Concrete block wall, On grade slab	Not applicable

Table A2: Estimated Service life of Building Components

	Roof System				Wall System				Footing System						Fenestration	
									On grade Slab							
	Timber Truss	Steel Truss	Terracotta Tiles	Gypsum board ceiling	Concrete Block wall	Double Brick wall	Plaster	Render	CC	30% FA	30% GGBFS	50% GGBFS+100% RA	50 % GGBFS + 50% RA	Ceramic Floor Tiles	SG Window	Metal Frame, Wood Door
A	1.10	1.10	1.10	1.10	1.10	1.10	1.05	1.05	0.95	1.10	1.10	1.00	1.05	1.10	1.10	1.10
B	1.10	1.10	1.00	1.00	1.10	1.05	1.05	1.05	1.10	1.10	1.10	1.10	1.10	1.00	1.00	1.00
C	0.90	0.90	0.90	1.05	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.90	0.90
D	1.00	1.00	1.00	1.00	1.00	1.00	0.95	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.95	0.95
E	1.00	1.00	0.95	1.00	1.00	0.95	1.00	0.90	0.95	0.95	0.95	0.95	0.95	1.00	0.95	0.95
F	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
G	1.05	1.05	1.05	1.05	1.00	1.05	1.05	1.05	1.00	1.00	1.00	1.00	1.00	1.05	1.05	1.05
RSL	50	75	50	25	60	80	25	16	60	60	60	60	60	50	25	25
ESL	57	86	49	30	65	83	25	16	57	66	66	60	63	52	23	23

Table A3: Estimated Service life of Roof System of Case study Buildings

Building Components	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS+ 50%RA	14. SF-DB-50%GGBFS+ 100%RA
Roof frame	57	57	57	57	57	57	86	86	86	86	86	86	86	86
Roof covering	49	49	49	49	49	49	49	49	49	49	49	49	49	49
Ceiling	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Roof System	57	57	57	57	57	57	86	86	86	86	86	86	86	86

Table A4: Estimated Service life of Wall System of Case study Buildings

Building Components	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS + 50%RA	14. SF-DB-50%GGBFS+ 100%RA
Render	16	16	16				16	16	16					
SG Windows	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Doors	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Wall frame	65	65	65	83	83	83	65	65	65	83	83	83	83	83
Plaster	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Wall System	65	65	65	83	83	83	65	65	65	83	83	83	83	83

Table A5: Estimated Service life of Footing of System of Case study Buildings

Building Components	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS+ 50%RA	14. SF-DB-50%GGBFS+ 100%RA
Ceramic tiles	52	52	52	52	52	52	52	52	52	52	52	52	52	52
On Grade Slab	57	66	66	57	66	66	57	66	66	57	66	66	60	63
Footing system	57	66	66	57	66	66	57	66	66	57	66	66	60	63

Table A6: Estimated Service life of Case study Buildings

Building Components	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS+ 50%RA	14. SF-DB-50%GGBFS+ 100%RA
Roof System	57	57	57	57	57	57	86	86	86	86	86	86	86	86
Wall System	65	65	65	83	83	83	65	65	65	83	83	83	83	83
Footing system	57	66	66	57	66	66	57	66	66	57	66	66	60	63
Building	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**65**	**65**	**57**	**66**	**66**	**60**	**63**

Table A7: Number of replacements of non-structural building components of Case study Buildings

Building Components' replacements	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS+ 50%RA	14. SF-DB-50%GGBFS+ 100%RA
Roof covering		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ceiling	1	1	1	1	1	1	1	1	2	2	1	2	2	2	2
Render		3	3	3				3	3	3					
SG Windows	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Doors	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Plaster	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3
Ceramic tiles		1	1	1	1	1	1	1	1	1		1	1	1	1

Appendix B

Table B1: Life cycle inventories of materials, transportation, and energy for Case study Buildings

	Buildings	Unit	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS +50%RA	14. SF-DB-50% GGBFS +100%RA
Construction Materials	Excavation of foundation	t	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83	26.83
	Sub base: sand	t	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01	26.01
	water proofing membrane- 0.2mm	t	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Mesh reinforcement fabric- SL92	t	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
	OPC	t	11.19	11.19	7.83	7.83	11.19	7.83	7.83	11.19	7.83	7.83	11.19	7.83	7.83	5.60	5.60
	FA	t	x	x	3.36	x	x	3.36	x	x	3.36	x	x	3.36	x	x	x
	GGBFS	t	x	x	x	3.36	x	x	3.36	x	x	3.36	x	x	3.36	5.60	5.60
	Natural Aggregate-4	t	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	44.78	22.39	x
	Recycled Aggregate-4	t	x	x	x	x	x	x	x	x	x	x	x	x	x	22.39	44.78
	Natural Sand-2	t	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39	22.39
	Floor Tiles (Ceramic)	t	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
	Concrete Blocks- 190x190x390	t	x	36.49	36.49	36.49	x	x	x	36.49	36.49	36.49	x	x	x	x	x
	Concrete Blocks- 90x190x390	t	x	27.5	27.5	27.5	x	x	x	27.5	27.5	27.5	x	x	x	x	x
	Face Bricks- 230x110x76	t	33.3	x	x	x	33.3	33.3	33.3	x	x	x	33.3	33.3	33.3	33.3	33.3
	Utility Bricks-290x90x90 (Ext. wall)	t	29.32	x	x	x	29.32	29.32	29.32	x	x	x	29.32	29.32	29.32	29.32	29.32
	Utility Bricks-290x90x90 (Int. Wall)	t	32.01	x	x	x	32.01	32.01	32.01	x	x	x	32.01	32.01	32.01	32.01	32.01

	Buildings	Unit	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS +50%RA	14. SF-DB-50% GGBFS +100%RA
	rendering (5:1:1): Cement, plaster sand, lime	t	x	3.32	3.32	3.32				3.32	3.32	3.32					
	plaster	t	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54	10.54
	Mortar: cement, brickie sand, lime	t	11.48	10.33	10.33	10.33	11.48	11.48	11.48	10.33	10.33	10.33	11.48	11.48	11.48	11.48	11.48
	Steel rebar, 12mm @ 1.25m c/c	t	x	0.19	0.19	0.19	x	x	x	0.19	0.19	0.19	x	x	x	x	x
	Metal lintels, columns, bracings, wall ties, structural fixtures	t	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
	Wall tiles	t	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
	Suspended ceiling	t	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19
	Bat insulation for roof	t	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
	Roof Timber	t	4.13	4.13	4.13	4.13	4.13	4.13	4.13	x	x	x	x	x	x	x	x
	Roof Steel	t	x	x	x	x	x	x	x	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
	terracotta roof tiles	t	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55
	Metal door frames-12 no.	t	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	Door shutters-12no.	t	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
	Aluminium windows-SG	t	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Replacement	Floor Tiles (Ceramic) @ 52 years	t	x	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
	Suspended ceiling @ 30 years	t	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	4.38	4.38	2.19	4.38	4.38	4.38	4.38
	Render @ 15 years	t	x	9.96	9.96	9.96				9.96	9.96	9.96					
	Plaster @ 25 years	t	10.54	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08

		Buildings	Unit	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50%GGBFS +50%RA	14. SF-DB-50% GGBFS +100%RA
		terracotta roof tiles @ 49 years	t	x	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55	16.55
		Aluminium windows-SG @ 23 years	t	1.43	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86
		Metal Frame, wood Door @ 23 years	t	0.55	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Construction	Carriage	Dirt to Landfill	tkm	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5	1341.5
Construction	Carriage	Sand for levelling	tkm	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5	1300.5
Construction	Carriage	Material to site	tkm	6840	6000	6000	6000	6840	6840	6840	5931.6	5931.6	5931.6	6780	6780	6780	6780	6780
Construction	Carriage	Construction Waste	tkm	342	300	300	300	342	342	342	296.58	296.58	296.58	339	339	339	339	339
Construction	Carriage	Demolition waste to Landfill/ recycling	tkm	11414	10000	10000	10000	11414	11414	11414	9886	9886	9886	11300	11300	11300	11300	11300
Replacement	Carriage	Material to site	tkm	441.3	1417.2	1417.2	1417.2	1118.4	1118.4	1118.4	1417.2	1941.6	1941.6	1118.4	1543.2	1543.2	1543.2	1543.2
Replacement	Carriage	Construction Waste	tkm	22.065	70.86	70.86	70.86	55.92	55.92	55.92	70.86	97.08	97.08	55.92	77.16	77.16	77.16	77.16
Replacement	Carriage	Demolition waste to Landfill/ recycling	tkm	735.5	2362	2362	2362	1864	1864	1864	2362	3236	3236	1864	2572	2572	2572	2572
Energy		Energy consumption for plants and tools during construction activities	GJ	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23	11.23
Energy		Energy consumption for heating, cooling, lighting, home appliances, and hot water during use stage	GJ	2687.8	3457.2	3457.2	3457.2	3064.1	3064.1	3064.1	3457.2	3942.4	3942.4	3064.1	3547.9	3547.9	3386.6	3225.4
Energy		Energy consumption for plants and tools during end of life demolition activities	GJ	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072	9.072

Table B2: Calculated values of KPIs for Case study Buildings

Code	KPIs	Units	KPI Weight	Threshold	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50%	14. SF-DB-50% GGBFS + 100%
E-1.1	Carbon Footprint	kg CO_2 eq/m²/year	0.0741	30.05	64.08	69.88	69.42	69.54	63.66	63.20	63.32	69.94	68.95	69.75	63.72	62.51	62.61	61.87	62.18
E-1.2	Resilience and adaptation	years	0.0037	100	50	57	57	57	57	57	57	57	65	65	57	66	66	63	60
E-2.1	Acidification	kg SO_2 eq/ m²/year	0.0478	0.02	0.11	0.12	0.11	0.12	0.11	0.10	0.11	0.12	0.11	0.12	0.11	0.10	0.10	0.10	0.10
E-3.1	Eutrophication	kg PO_4 eq/ m²/year	0.0452	0.00	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
E-4.1	Land Use	Ha_a/ m²/yr	0.0562	0.00	0.0003799	0.0003981	0.0003972	0.0003975	0.0003711	0.0003701	0.0003705	0.0003415	0.0003363	0.0003400	0.0003144	0.0003078	0.0003081	0.0003165	0.0003083
E-4.2	Loss of Biodiversity	BI index	0.0100	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63
E-5.1	Cumulative Embodied Water Consumption	kl/m²/year	0.0625	0.15	0.15	0.16	0.16	0.16	0.14	0.14	0.14	0.16	0.16	0.16	0.14	0.14	0.14	0.12	0.13
E-6.1	Cumulative Energy Demand	GJ/m²/year	0.0630	0.17	0.49	0.51	0.51	0.51	0.48	0.47	0.48	0.51	0.51	0.51	0.48	0.47	0.47	0.46	0.47
E-7.1	Cumulative Fossil Energy Consumption	GJ/m²/year	0.0651	0.06	0.45	0.47	0.47	0.47	0.44	0.44	0.44	0.48	0.47	0.47	0.44	0.43	0.43	0.43	0.43
E-8.1	C & D waste	tonnes/ m²/year	0.0630	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03
E-8.2	Recycling potential	% /m²/year	0.0095	75.00	73.21	69.37	70.94	70.94	75.49	75.49	75.49	71.37	67.78	67.77	75.93	72.93	72.93	72.85	72.88

Code	KPIs	Units	KPI Weight	Threshold	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50%	14. SF-DB-50% GGBFS + 100%
S-1.1	House Affordability	AUD /m²/year	0.0525	103.57	74.22	62.81	62.71	62.70	61.12	61.03	61.01	63.77	55.84	55.82	62.08	53.53	53.52	55.90	58.60
S-1.2	Indoor Living Conditions	AUD /m²/year	0.0578	9.11	4.08	11.59	11.59	11.59	8.59	8.59	8.59	11.59	11.94	11.94	8.59	9.16	9.16	9.60	10.08
S-1.3	Thermal Comfort	AUD /m²/year	0.0651	14.27	19.02	21.26	21.26	21.26	19.02	19.02	19.02	21.26	21.26	21.26	19.02	19.02	19.02	19.02	19.02
S-1.4	Noise	STC	0.0032	50.00	46.33	45.00	45.00	45.00	46.33	46.33	46.33	51.67	51.67	51.67	53.00	53.00	53.00	53.00	53.00
S-1.5	Local material sourcing	km	0.0037	200.00	50.00	50.00	200.0	50.00	50.00	200.0	50.00	50.00	200.0	50.00	50.00	200.0	50.00	50.00	50.00
S-2.1	Energy Conservation	% /m²/year	0.0641	20.00	0.00	0.00	0.00	0.00	2.60	3.15	2.81	0.00	0.00	0.00	2.55	4.63	4.34	4.99	4.16
EC-1.1	Life Cycle Cost	AUD /m²/year	0.0699	28.04	36.74	39.89	39.83	39.82	34.89	34.83	34.82	40.52	37.46	37.45	35.51	32.56	32.55	33.93	35.49
EC-1.2	Potential Savings	% /m²/year	0.0483	20.00	0.00	0.00	0.00	0.00	8.69	8.69	8.69	0.00	7.46	7.46	8.69	18.20	18.20	15.21	12.05
EC-1.3	Benefit-Cost ratio		0.0515	1.00	0.00	0.25	0.26	0.27	1.00	1.00	1.00	0.15	0.55	0.55	1.00	4.01	4.02	2.49	1.53
EC-2.1	Net benefit	% /m²/year	0.0425	0.14	0.55	0.64	0.65	0.65	0.78	0.79	0.79	0.57	0.51	0.51	0.70	0.61	0.61	0.66	0.70
EC-2.2	Carbon Tax Saving	% /m²/year	0.0415	20.00	0.00	0.00	0.00	0.00	0.64	1.38	1.19	0.00	0.00	0.00	0.56	2.45	2.29	3.44	2.95

Table B3: Position values of KPIs for Case study Buildings

Code	KPIs	Units	Thresholds	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	kg CO_2 eq/m^2/year	5	2.34	2.15	2.16	2.16	2.36	2.38	2.37	2.15	2.18	2.15	2.36	2.40	2.40	2.43	2.42
E-1.2	Resilience and adaptation	years	5	2.50	2.85	2.85	2.85	2.85	2.85	2.85	2.85	3.25	3.25	2.85	3.30	3.30	3.15	3.00
E-2.1	Acidification	kg SO_2 eq/ m^2/year	5	0.98	0.91	0.92	0.91	0.99	1.00	0.99	0.90	0.92	0.90	0.98	1.01	1.00	1.02	1.01
E-3.1	Eutrophication	kg PO_4 eq/ m^2/year	5	0.75	0.69	0.70	0.69	0.76	0.77	0.77	0.69	0.71	0.70	0.76	0.78	0.78	0.79	0.79
E-4.1	Land Use	Ha_a/ m^2/yr	5	1.50	1.43	1.44	1.43	1.54	1.54	1.54	1.67	1.69	1.68	1.81	1.85	1.85	1.80	1.85
E-4.2	Loss of Biodiversity	BI index	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
E-5.1	Cumulative Embodied Water Consumption	kl/m^2/year	5	5.00	4.60	4.62	4.61	5.00	5.00	5.00	4.60	4.80	4.76	5.00	5.00	5.00	5.00	5.00
E-6.1	Cumulative Energy Demand	GJ/m^2/year	5	1.78	1.70	1.70	1.70	1.83	1.84	1.83	1.69	1.72	1.70	1.83	1.87	1.86	1.87	1.86
E-7.1	Cumulative Fossil Energy Consumption	GJ/m^2/year	5	0.70	0.67	0.67	0.67	0.72	0.72	0.72	0.66	0.67	0.66	0.71	0.73	0.73	0.73	0.73
E-8.1	C & D waste	tonnes/ m^2/year	5	3.51	3.91	3.91	3.91	3.72	3.72	3.72	3.94	4.19	4.19	3.75	4.10	4.10	3.90	3.72
E-8.2	Recycling potential	% /m^2/year	5	4.88	4.62	4.73	4.73	5.00	5.00	5.00	4.76	4.52	4.52	5.00	4.86	4.86	4.86	4.86
S-1.1	House Affordability	AUD /m^2/year	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
S-1.2	Indoor Living Conditions	AUD /m^2/year	5	5.00	3.93	3.93	3.93	5.00	5.00	5.00	3.93	3.82	3.82	5.00	4.97	4.97	4.75	4.52
S-1.3	Thermal Comfort	AUD /m^2/year	5	3.75	3.36	3.36	3.36	3.75	3.75	3.75	3.36	3.36	3.36	3.75	3.75	3.75	3.75	3.75
S-1.4	Noise	STC	5	4.63	4.50	4.50	4.50	4.63	4.63	4.63	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
S-1.5	Local material sourcing	km	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Code	KPIs	Units	Thresholds	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
S-2.1	Energy Conservation	% /m²/year	5	0.00	0.00	0.00	0.00	0.65	0.79	0.70	0.00	0.00	0.00	0.64	1.16	1.09	1.25	1.04
EC-1.1	Life Cycle Cost	AUD /m²/year	5	3.82	3.51	3.52	3.52	4.02	4.03	4.03	3.46	3.74	3.74	3.95	4.31	4.31	4.13	3.95
EC-1.2	Potential Savings	AUD /m²/year	5	0.00	0.00	0.00	0.00	2.17	2.17	2.17	0.00	1.87	1.87	2.17	4.55	4.55	3.80	3.01
EC-1.3	Benefit-Cost ratio		5	0.00	1.27	1.32	1.33	5.00	5.00	5.00	0.73	2.74	2.75	5.00	5.00	5.00	5.00	5.00
EC-2.1	Net benefit	% /m²/year	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
EC-2.2	Carbon Tax Saving	% /m²/year	5	0.00	0.00	0.00	0.00	0.16	0.34	0.30	0.00	0.00	0.00	0.14	0.61	0.57	0.86	0.74

Table B4: Gap to the sustainability of KPIs for Case study Buildings

Code	KPIs	Units	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	kg CO_2 eq/m²/year	2.655	2.850	2.836	2.839	2.640	2.623	2.627	2.852	2.821	2.846	2.642	2.596	2.600	2.572	2.584
E-1.2	Resilience and adaptation	years	2.500	2.150	2.150	2.150	2.150	2.150	2.150	2.150	1.750	1.750	2.150	1.700	1.700	1.850	2.000
E-2.1	Acidification	kg SO_2 eq/ m²/year	4.024	4.092	4.083	4.091	4.011	4.000	4.009	4.099	4.080	4.095	4.019	3.991	4.000	3.978	3.986
E-3.1	Eutrophication	kg PO_4 eq/ m²/year	4.248	4.310	4.304	4.307	4.238	4.231	4.234	4.310	4.295	4.304	4.238	4.218	4.220	4.207	4.213

Code	KPIs	Units	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-4.1	Land Use	Ha_a/ m^2/yr	3.500	3.568	3.565	3.566	3.464	3.460	3.462	3.331	3.305	3.323	3.187	3.148	3.150	3.199	3.151
E-4.2	Loss of Biodiversity	BI index	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E-5.1	Cumulative Embodied Water Consumption	kl/m^2/year	0.000	0.404	0.381	0.389	0.000	0.000	0.000	0.403	0.202	0.244	0.000	0.000	0.000	0.000	0.000
E-6.1	Cumulative Energy Demand	GJ/m^2/year	3.221	3.304	3.296	3.301	3.173	3.163	3.169	3.305	3.281	3.302	3.174	3.134	3.140	3.127	3.144
E-7.1	Cumulative Fossil Energy Consumption	GJ/m^2/year	4.301	4.335	4.331	4.334	4.283	4.279	4.282	4.338	4.328	4.336	4.287	4.270	4.273	4.267	4.273
E-8.1	C & D waste	tonnes/ m^2/year	1.490	1.090	1.090	1.090	1.279	1.279	1.279	1.062	0.807	0.808	1.254	0.898	0.898	1.098	1.279
E-8.2	Recycling potential	% /m^2/year	0.119	0.375	0.271	0.271	0.000	0.000	0.000	0.242	0.482	0.482	0.000	0.138	0.138	0.144	0.141
S-1.1	House Affordability	AUD /m^2/year	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.2	Indoor Living Conditions	AUD /m^2/year	0.000	1.071	1.071	1.071	0.000	0.000	0.000	1.071	1.185	1.185	0.000	0.028	0.028	0.254	0.480
S-1.3	Thermal Comfort	AUD /m^2/year	1.248	1.644	1.644	1.644	1.248	1.248	1.248	1.644	1.644	1.644	1.248	1.248	1.248	1.248	1.248
S-1.4	Noise	STC	0.367	0.500	0.500	0.500	0.367	0.367	0.367	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.5	Local material sourcing	km	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-2.1	Energy Conservation	% /m^2/year	5.000	5.000	5.000	5.000	4.350	4.213	4.297	5.000	5.000	5.000	4.364	3.842	3.915	3.752	3.961
EC-1.1	Life Cycle Cost	AUD /m^2/year	1.184	1.485	1.480	1.479	0.981	0.974	0.973	1.540	1.257	1.256	1.052	0.694	0.693	0.868	1.050
EC-1.2	Potential Savings	AUD /m^2/year	5.000	5.000	5.000	5.000	2.827	2.827	2.827	5.000	3.135	3.135	2.827	0.451	0.451	1.196	1.987
EC-1.3	Benefit-Cost ratio		5.000	3.734	3.681	3.672	0.000	0.000	0.000	4.271	2.261	2.253	0.000	0.000	0.000	0.000	0.000
EC-2.1	Net benefit	% /m^2/year	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-2.2	Carbon Tax Saving	% /m^2/year	5.000	5.000	5.000	5.000	4.839	4.656	4.703	5.000	5.000	5.000	4.860	4.388	4.429	4.140	4.261

Table B5: Performance gap of KPI for Case study Buildings

Code	KPIs	Building-50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	0.197	0.211	0.210	0.210	0.196	0.194	0.195	0.211	0.209	0.211	0.196	0.192	0.193	0.191	0.191
E-1.2	Resilience and adaptation	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.006	0.006	0.008	0.006	0.006	0.007	0.007
E-2.1	Acidification	0.192	0.196	0.195	0.196	0.192	0.191	0.192	0.196	0.195	0.196	0.192	0.191	0.191	0.190	0.191
E-3.1	Eutrophication	0.192	0.195	0.195	0.195	0.192	0.191	0.191	0.195	0.194	0.195	0.192	0.191	0.191	0.190	0.190
E-4.1	Land Use	0.197	0.201	0.200	0.200	0.195	0.194	0.195	0.187	0.186	0.187	0.179	0.177	0.177	0.180	0.177
E-4.2	Loss of Biodiversity	2.71E-07	2.89E-07	2.88E-07	2.89E-07	2.62E-07	2.61E-07	2.61E-07	2.31E-07	2.26E-07	2.30E-07	2.04E-07	1.97E-07	1.98E-07	2.06E-07	1.98E-07
E-5.1	Cumulative Embodied Water Consumption	0.000	0.025	0.024	0.024	0.000	0.000	0.000	0.025	0.013	0.015	0.000	0.000	0.000	0.000	0.000
E-6.1	Cumulative Energy Demand	0.203	0.208	0.208	0.208	0.200	0.199	0.200	0.208	0.207	0.208	0.200	0.197	0.198	0.197	0.198
E-7.1	Cumulative Fossil Energy Consumption	0.280	0.282	0.282	0.282	0.279	0.279	0.279	0.282	0.282	0.282	0.279	0.278	0.278	0.278	0.278
E-8.1	C & D waste	0.094	0.069	0.069	0.069	0.081	0.081	0.081	0.067	0.051	0.051	0.079	0.057	0.057	0.069	0.081
E-8.2	Recycling potential	0.001	0.004	0.003	0.003	0.000	0.000	0.000	0.002	0.005	0.005	0.000	0.001	0.001	0.001	0.001
S-1.1	House Affordability	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

S-1.2	Indoor Living Conditions	0.000	0.062	0.062	0.062	0.000	0.000	0.000	0.062	0.068	0.068	0.000	0.002	0.002	0.015	0.028
S-1.3	Thermal Comfort	0.081	0.107	0.107	0.107	0.081	0.081	0.081	0.107	0.107	0.107	0.081	0.081	0.081	0.081	0.081
S-1.4	Noise	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.5	Local material sourcing	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-2.1	Energy Conservation	0.321	0.321	0.321	0.321	0.279	0.270	0.275	0.321	0.321	0.321	0.280	0.246	0.251	0.241	0.254
EC-1.1	Life Cycle Cost	0.083	0.104	0.103	0.103	0.069	0.068	0.068	0.108	0.088	0.088	0.074	0.049	0.048	0.061	0.073
EC-1.2	Potential Savings	0.242	0.242	0.242	0.242	0.137	0.137	0.137	0.242	0.151	0.151	0.137	0.022	0.022	0.058	0.096
EC-1.3	Benefit Cost ratio	0.258	0.192	0.190	0.189	0.000	0.000	0.000	0.220	0.116	0.116	0.000	0.000	0.000	0.000	0.000
EC-2.1	Net benefit	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-2.2	Carbon Tax Saving	0.208	0.208	0.208	0.208	0.201	0.193	0.195	0.208	0.208	0.208	0.202	0.182	0.184	0.172	0.177

Table B6: Coefficient of variation (%) for environmental KPIs for case study buildings

Code	KPIs	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	0.07	0.07	0.07	0.09	0.08	0.08	0.07	0.07	0.07	0.09	0.08	0.08	0.08	0.09
E-2.1	Acidification	0.20	0.20	0.21	0.24	0.25	0.25	0.20	0.18	0.19	0.23	0.22	0.22	0.24	0.26
E-3.1	Eutrophication	0.22	0.21	0.21	0.26	0.24	0.24	0.20	0.19	0.18	0.25	0.23	0.22	0.25	0.25
E-4.1	Land Use	4.42	4.53	4.59	4.84	4.74	4.78	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.06
E-5.1	Cumulative Embodied Water Consumption	0.22	0.22	0.23	0.28	0.27	0.27	0.23	0.21	0.22	0.28	0.26	0.25	0.33	0.43

Code	KPIs	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-6.1	Cumulative Energy Demand	0.17	0.18	0.18	0.21	0.20	0.20	0.17	0.16	0.16	0.19	0.18	0.18	0.19	0.20
E-7.1	Cumulative Fossil Energy Consumption	0.18	0.19	0.19	0.22	0.21	0.22	1.08	0.97	1.02	0.20	0.19	0.19	0.20	0.21

Table B7: Performance gap of Impact Category for Case study Buildings

Code	Impact category	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1	Climate change	0.206	0.219	0.218	0.218	0.204	0.202	0.203	0.219	0.216	0.217	0.204	0.199	0.20	0.1974	0.199
E-2	Air quality	0.192	0.196	0.195	0.196	0.192	0.191	0.192	0.196	0.195	0.196	0.192	0.191	0.19	0.1902	0.191
E-3	Water quality	0.192	0.195	0.195	0.195	0.192	0.191	0.191	0.195	0.194	0.195	0.192	0.191	0.19	0.1902	0.190
E-4	Ecological footprint	0.197	0.201	0.200	0.200	0.195	0.194	0.195	0.187	0.186	0.187	0.179	0.177	0.18	0.1798	0.177
E-5	Water scarcity	0.000	0.025	0.024	0.024	0.000	0.000	0.000	0.025	0.013	0.015	0.000	0.000	0.00	0.0000	0.000
E-6	Energy scarcity	0.203	0.208	0.208	0.208	0.200	0.199	0.200	0.208	0.207	0.208	0.200	0.197	0.20	0.1970	0.198
E-7	Abiotic resource depletion	0.280	0.282	0.282	0.282	0.279	0.279	0.279	0.282	0.282	0.282	0.279	0.278	0.28	0.2778	0.278
E-8	Waste generation	0.095	0.072	0.071	0.071	0.081	0.081	0.081	0.069	0.055	0.056	0.079	0.058	0.06	0.0706	0.082
S-1	Intra-generational Equity	0.082	0.171	0.171	0.171	0.082	0.082	0.082	0.169	0.176	0.176	0.081	0.083	0.08	0.0959	0.109
S-2	Inter-generational Equity	0.321	0.321	0.321	0.321	0.279	0.270	0.275	0.321	0.321	0.321	0.280	0.246	0.25	0.2405	0.254

Code	Impact category	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
EC-1	User Perspective	0.582	0.538	0.535	0.534	0.205	0.205	0.205	0.569	0.356	0.355	0.210	0.070	0.07	0.1185	0.169
EC-2	Developer Perspective	0.208	0.208	0.208	0.208	0.201	0.193	0.195	0.208	0.208	0.208	0.202	0.182	0.18	0.1718	0.177

Table B8: Performance gap of Sustainability objectives for Case study Buildings

Code	Sustainability Objectives	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E	Environmental Objectives	1.365	1.398	1.393	1.395	1.341	1.338	1.339	1.382	1.347	1.355	1.324	1.290	1.292	1.303	1.315
S	Social Objectives	0.403	0.491	0.491	0.491	0.361	0.352	0.358	0.489	0.496	0.496	0.361	0.329	0.334	0.336	0.363
EC	Economic Objectives	0.789	0.745	0.742	0.741	0.406	0.398	0.400	0.777	0.563	0.563	0.412	0.252	0.254	0.290	0.346

Appendix C

Table C1: Calculated Values of KPIs for Case study Buildings- after CPS

Code	KPIs	Units	KPI Weight	Threshold	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	kg CO_2 eq/m²/year	0.0741	30.05	64.08	37.88	37.41	37.53	32.01	31.54	31.66	37.80	36.82	37.16	31.93	30.73	30.83	30.09	30.39
E-1.2	Resilience and adaptation	years	0.0037	100.0	50.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	65.00	65.00	57.00	66.00	66.00	63.00	60.00
E-2.1	Acidification	kg SO_2 eq/m²/year	0.0478	0.02	0.11	0.07	0.06	0.07	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.05
E-3.1	Eutrophication	kg PO_4 eq/m²/year	0.0452	0.00	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
E-4.1	Land Use	Ha_a/ m²/year	0.0562	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E-4.2	Loss of Biodiversity	BI index	0.010	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63
E-5.1	Cumulative Embodied Water Consumption	kl/m²/year	0.0625	0.15	0.15	0.11	0.11	0.11	0.09	0.09	0.09	0.11	0.10	0.10	0.09	0.08	0.08	0.07	0.08
E-6.1	Cumulative Energy Demand	GJ/m²/year	0.063	0.17	0.49	0.29	0.29	0.29	0.26	0.25	0.26	0.29	0.28	0.28	0.25	0.24	0.25	0.24	0.25
E-7.1	Cumulative Fossil Energy Consumption	GJ/m²/year	0.0651	0.06	0.45	0.27	0.26	0.27	0.23	0.23	0.23	0.27	0.26	0.26	0.23	0.22	0.23	0.22	0.23

Code	KPIs	Units	KPI Weight	Threshold	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-8.1	C & D waste	tonnes/ m²/year	0.063	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
E-8.2	Recycling potential	% /m²/year	0.0095	75.00	73.21	69.78	71.39	71.39	76.01	76.01	76.01	71.84	68.22	68.22	76.47	73.49	73.49	73.38	73.39
S-1.1	House Affordability	AUD /m²/year	0.0525	103.5	74.22	62.81	62.71	62.70	61.12	61.03	61.01	63.77	55.84	55.82	62.08	53.53	53.52	55.90	58.60
S-1.2	Indoor Living Conditions	AUD /m²/year	0.0578	9.11	4.08	11.59	11.59	11.59	8.59	8.59	8.59	11.59	11.94	11.94	8.59	9.16	9.16	9.60	10.08
S-1.3	Thermal Comfort	AUD /m²/year	0.0651	14.27	19.02	11.26	11.26	11.26	9.13	9.13	9.13	11.26	11.26	11.26	9.13	9.13	9.13	9.13	9.13
S-1.4	Noise	STC	0.0032	50.00	46.33	45.00	45.00	45.00	46.33	46.33	46.33	51.67	51.67	51.67	53.00	53.00	53.00	53.00	53.00
S-1.5	Local material sourcing	km	0.0037	200.0	50.00	50.00	200.0	50.00	50.00	200.0	50.00	50.00	200.0	50.00	50.00	200.0	50.00	50.00	50.00
S-2.1	Energy Conservation	% /m²/year	0.0641	20.00	0.00	40.35	40.90	40.56	47.40	47.94	47.61	40.84	42.34	41.72	47.88	49.96	49.67	50.35	49.56
EC-1.1	Life Cycle Cost	AUD /m²/year	0.0699	28.04	36.74	35.89	35.83	35.82	30.93	30.87	30.86	36.51	33.83	33.82	31.56	29.02	29.01	30.26	31.68
EC-1.2	Potential Savings	% /m²/year	0.0483	20.00	0.00	45.92	45.92	45.92	56.16	56.16	56.16	45.92	50.98	50.98	56.16	60.73	60.73	59.30	57.78
EC-1.3	Benefit-Cost ratio		0.0515	1.00	0.00	2.58	2.60	2.60	1.00	1.00	1.00	2.41	2.84	2.84	1.00	12.66	12.66	8.74	6.33
EC-2.1	Net benefit	% /m²/year	0.0425	0.14	0.55	0.64	0.65	0.65	0.78	0.79	0.79	0.57	0.51	0.51	0.70	0.61	0.61	0.66	0.70
EC-2.2	Carbon Tax Saving	% /m²/year	0.0415	20.00	0.00	40.89	41.62	41.43	50.05	50.78	50.59	41.00	42.54	42.01	50.16	52.04	51.88	53.05	52.58

Table C2: Position Values of KPIs for Case study Buildings- after CPS

Code	KPIs	Units	Thresholds	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	kg CO_2 eq/m^2/year	5	2.34	3.97	4.02	4.00	4.69	4.76	4.75	3.97	4.08	4.04	4.70	4.89	4.87	4.99	4.94
E-1.2	Resilience and adaptation	years	5	2.50	2.85	2.85	2.85	2.85	2.85	2.85	2.85	3.25	3.25	2.85	3.30	3.30	3.15	3.00
E-2.1	Acidification	kg SO_2 eq/ m^2/year	5	0.98	1.59	1.62	1.60	1.84	1.88	1.85	1.60	1.66	1.63	1.86	1.95	1.92	2.00	1.98
E-3.1	Eutrophication	kg PO_4 eq/ m^2/year	5	0.75	1.22	1.23	1.22	1.44	1.47	1.46	1.22	1.27	1.25	1.45	1.53	1.52	1.57	1.55
E-4.1	Land Use	Ha_a/ m^2/year	5	1.50	2.32	2.33	2.33	2.59	2.60	2.60	2.96	3.05	3.03	3.41	3.56	3.55	3.37	3.54
E-4.2	Loss of Biodiversity	BI index	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
E-5.1	Cumulative Embodied Water Consumption	kl/m^2/year	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
E-6.1	Cumulative Energy Demand	GJ/m^2/year	5	1.78	2.98	3.01	2.99	3.38	3.42	3.40	3.01	3.09	3.05	3.41	3.56	3.53	3.58	3.53
E-7.1	Cumulative Fossil Energy Consumption	GJ/m^2/year	5	0.70	1.18	1.19	1.18	1.34	1.36	1.35	1.18	1.22	1.20	1.34	1.40	1.39	1.42	1.39
E-8.1	C & D waste	tonnes/ m^2/year	5	3.51	3.99	3.99	3.99	3.79	3.79	3.79	4.02	4.29	4.29	3.82	4.20	4.20	3.99	3.80
E-8.2	Recycling potential	% /m^2/year	5	4.88	4.65	4.76	4.76	5.00	5.00	5.00	4.79	4.55	4.55	5.00	4.90	4.90	4.89	4.89
S-1.1	House Affordability	AUD /m^2/year	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
S-1.2	Indoor Living Conditions	AUD /m^2/year	5	5.00	3.93	3.93	3.93	5.00	5.00	5.00	3.93	3.82	3.82	5.00	4.97	4.97	4.75	4.52
S-1.3	Thermal Comfort	AUD /m^2/year	5	3.75	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
S-1.4	Noise	STC	5	4.63	4.50	4.50	4.50	4.63	4.63	4.63	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
S-1.5	Local material sourcing	km	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
S-2.1	Energy Conservation	% /m^2/year	5	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Code	KPIs	Units	Thresholds	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
EC-1.1	Life Cycle Cost	AUD /m²/year	5	3.82	3.91	3.91	3.91	4.53	4.54	4.54	3.84	4.14	4.15	4.44	4.83	4.83	4.63	4.43
EC-1.2	Potential Savings	AUD /m²/year	5	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
EC-1.3	Benefit-Cost ratio		5	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
EC-2.1	Net benefit	% /m²/year	5	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
EC-2.2	Carbon Tax Saving	% /m²/year	5	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Table C3: Gap to the sustainability of KPIs for Case study Buildings- after CPS

Code	KPIs	Units	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	kg CO_2 eq/m²/year	2.66	1.03	0.98	1.00	0.31	0.24	0.25	1.03	0.92	0.96	0.30	0.11	0.13	0.01	0.06
E-1.2	Resilience and adaptation	years	2.50	2.15	2.15	2.15	2.15	2.15	2.15	2.15	1.75	1.75	2.15	1.70	1.70	1.85	2.00
E-2.1	Acidification	kg SO_2 eq/ m²/year	4.02	3.41	3.38	3.40	3.16	3.12	3.15	3.40	3.34	3.37	3.14	3.05	3.08	3.00	3.02
E-3.1	Eutrophication	kg PO_4 eq/ m²/year	4.25	3.78	3.77	3.78	3.56	3.53	3.54	3.78	3.73	3.75	3.55	3.47	3.48	3.43	3.45
E-4.1	Land Use	Ha_a/ m²/yr	3.50	2.68	2.67	2.67	2.41	2.40	2.40	2.04	1.95	1.97	1.59	1.44	1.45	1.63	1.46

Code	KPIs	Units	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-4.2	Loss of Biodiversity	BI index	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E-5.1	Cumulative Embodied Water Consumption	kl/m²/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E-6.1	Cumulative Energy Demand	GJ/m²/year	3.22	2.02	1.99	2.01	1.62	1.58	1.60	1.99	1.91	1.95	1.59	1.44	1.47	1.42	1.47
E-7.1	Cumulative Fossil Energy Consumption	GJ/m²/year	4.30	3.82	3.81	3.82	3.66	3.64	3.65	3.82	3.78	3.80	3.66	3.60	3.61	3.58	3.61
E-8.1	C & D waste	tonnes/ m²/year	1.49	1.01	1.01	1.01	1.21	1.21	1.21	0.98	0.71	0.71	1.18	0.80	0.80	1.01	1.20
E-8.2	Recycling potential	% /m²/year	0.12	0.35	0.24	0.24	0.00	0.00	0.00	0.21	0.45	0.45	0.00	0.10	0.10	0.11	0.11
S-1.1	House Affordability	AUD /m²/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S-1.2	Indoor Living Conditions	AUD /m²/year	0.00	1.07	1.07	1.07	0.00	0.00	0.00	1.07	1.18	1.18	0.00	0.03	0.03	0.25	0.48
S-1.3	Thermal Comfort	AUD /m²/year	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S-1.4	Noise	STC	0.37	0.50	0.50	0.50	0.37	0.37	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S-1.5	Local material sourcing	km	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S-2.1	Energy Conservation	% /m²/year	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC-1.1	Life Cycle Cost	AUD /m²/year	1.18	1.09	1.09	1.09	0.47	0.46	0.46	1.16	0.86	0.85	0.56	0.17	0.17	0.37	0.57
EC-1.2	Potential Savings	AUD /m²/year	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC-1.3	Benefit-Cost ratio		5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC-2.1	Net benefit	% /m²/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC-2.2	Carbon Tax Saving	% /m²/year	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table C4: Performance gap of KPI for Case study Buildings- after CPS

Code	KPIs	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	0.197	0.077	0.073	0.074	0.023	0.018	0.019	0.076	0.068	0.071	0.022	0.008	0.009	0.000	0.004
E-1.2	Resilience and adaptation	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.006	0.006	0.008	0.006	0.006	0.007	0.007
E-2.1	Acidification	0.192	0.163	0.162	0.163	0.151	0.149	0.151	0.162	0.160	0.161	0.150	0.146	0.147	0.143	0.145
E-3.1	Eutrophication	0.192	0.171	0.170	0.171	0.161	0.160	0.160	0.171	0.169	0.169	0.160	0.157	0.157	0.155	0.156
E-4.1	Land Use	0.197	0.150	0.150	0.150	0.135	0.135	0.135	0.115	0.110	0.111	0.089	0.081	0.081	0.091	0.082
E-4.2	Loss of Biodiversity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E-5.1	Cumulative Embodied Water Consumption	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E-6.1	Cumulative Energy Demand	0.203	0.127	0.125	0.126	0.102	0.100	0.101	0.126	0.121	0.123	0.100	0.091	0.092	0.089	0.093
E-7.1	Cumulative Fossil Energy Consumption	0.280	0.249	0.248	0.248	0.238	0.237	0.238	0.248	0.246	0.247	0.238	0.234	0.235	0.233	0.235
E-8.1	C & D waste	0.094	0.064	0.064	0.064	0.076	0.076	0.076	0.062	0.044	0.044	0.074	0.051	0.051	0.064	0.076
E-8.2	Recycling potential	0.001	0.003	0.002	0.002	0.000	0.000	0.000	0.002	0.004	0.004	0.000	0.001	0.001	0.001	0.001
S-1.1	House Affordability	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.2	Indoor Living Conditions	0.000	0.062	0.062	0.062	0.000	0.000	0.000	0.062	0.068	0.068	0.000	0.002	0.002	0.015	0.028
S-1.3	Thermal Comfort	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.4	Noise	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-1.5	Local material sourcing	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-2.1	Energy Conservation	0.321	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-1.1	Life Cycle Cost	0.083	0.076	0.076	0.076	0.033	0.032	0.032	0.081	0.060	0.060	0.039	0.012	0.012	0.026	0.040

Code	KPIs	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
EC-1.2	Potential Savings	0.242	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-1.3	Benefit-Cost ratio	0.258	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-2.1	Net benefit	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC-2.2	Carbon Tax Saving	0.208	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table C5: Performance gap of Impact category for Case study Buildings- after CPS

Code	Impact category	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1	Climate change	0.206	0.085	0.081	0.082	0.031	0.025	0.027	0.084	0.075	0.077	0.030	0.014	0.02	0.0073	0.012
E-2	Air quality	0.192	0.163	0.162	0.163	0.151	0.149	0.151	0.162	0.160	0.161	0.150	0.146	0.15	0.1432	0.145
E-3	Water quality	0.192	0.171	0.170	0.171	0.161	0.160	0.160	0.171	0.169	0.169	0.160	0.157	0.16	0.1552	0.156
E-4	Ecological footprint	0.197	0.150	0.150	0.150	0.135	0.135	0.135	0.115	0.110	0.111	0.089	0.081	0.08	0.0913	0.082
E-5	Water scarcity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.0000	0.000
E-6	Energy scarcity	0.203	0.127	0.125	0.126	0.102	0.100	0.101	0.126	0.121	0.123	0.100	0.091	0.09	0.0892	0.093
E-7	Abiotic resource depletion	0.280	0.249	0.248	0.248	0.238	0.237	0.238	0.248	0.246	0.247	0.238	0.234	0.23	0.2333	0.235
E-8	Waste generation	0.095	0.067	0.066	0.066	0.076	0.076	0.076	0.064	0.049	0.049	0.074	0.052	0.05	0.0647	0.077

Code	Impact category	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
S-1	Intra-generational Equity	0.082	0.064	0.064	0.064	0.001	0.001	0.001	0.062	0.068	0.068	0.000	0.002	0.00	0.0147	0.028
S-2	Inter-generational Equity	0.321	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.0000	0.000
EC-1	User Perspective	0.582	0.076	0.076	0.076	0.033	0.032	0.032	0.081	0.060	0.060	0.039	0.012	0.01	0.0256	0.040
EC-2	Developer Perspective	0.208	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.0000	0.000

Table C6: Performance gap of sustainability Objectives for Case study Buildings- after CPS

Code	Sustainability Objectives	Building 50	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E	Environmental Objectives	1.365	1.011	1.002	1.006	0.894	0.882	0.887	0.970	0.928	0.938	0.842	0.775	0.780	0.784	0.798
S	Social Objectives	0.403	0.064	0.064	0.064	0.001	0.001	0.001	0.062	0.068	0.068	0.000	0.002	0.002	0.015	0.028
EC	Economic Objectives	0.789	0.076	0.076	0.076	0.033	0.032	0.032	0.081	0.060	0.060	0.039	0.012	0.012	0.026	0.040

Table C7: Percentage improvement in performance gap of KPIs after applying CPS to case study buildings

Code	KPIs	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
E-1.1	Carbon Footprint	63.7%	65.3%	64.9%	88.4%	91.0%	90.3%	64.0%	67.4%	66.4%	88.8%	95.7%	95.1%	99.8%	97.9%
E-1.2	Resilience and adaptation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E-2.1	Acidification	16.7%	17.2%	16.8%	21.3%	22.0%	21.4%	17.1%	18.1%	17.7%	21.7%	23.6%	23.0%	24.7%	24.1%
E-3.1	Eutrophication	12.2%	12.5%	12.3%	16.1%	16.5%	16.3%	12.3%	13.1%	13.0%	16.3%	17.6%	17.5%	18.4%	18.0%
E-4.1	Land Use	25.0%	25.2%	25.1%	30.5%	30.7%	30.6%	38.8%	41.0%	40.6%	50.1%	54.3%	54.1%	49.2%	53.7%
E-4.2	Loss of Biodiversity	53.8%	54.0%	53.9%	58.8%	59.0%	58.9%	65.5%	67.2%	67.1%	73.4%	76.2%	76.1%	72.9%	75.8%
E-5.1	Cumulative Embodied Water Consumption	100.0%	100.0%	100.0%	-	-	-	100.0%	100.0%	100.0%	-	-	-	-	-
E-6.1	Cumulative Energy Demand	39.0%	39.6%	39.2%	49.0%	50.0%	49.4%	39.7%	41.6%	41.0%	50.0%	53.9%	53.3%	54.7%	53.2%
E-7.1	Cumulative Fossil Energy Consumption	11.9%	12.1%	12.0%	14.6%	14.8%	14.7%	12.0%	12.5%	12.4%	14.7%	15.7%	15.6%	16.0%	15.6%
E-8.1	C & D waste	7.5%	7.5%	7.5%	5.7%	5.7%	5.7%	7.8%	12.6%	12.7%	6.0%	10.7%	10.7%	8.0%	6.3%
E-8.2	Recycling potential	7.3%	11.2%	11.2%	-	-	-	12.9%	6.2%	6.2%	-	26.8%	26.8%	24.7%	24.3%
S-1.1	House Affordability	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S-1.2	Indoor Living Conditions	0.0%	0.0%	0.0%	-	-	-	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%
S-1.3	Thermal Comfort	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
S-1.4	Noise	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-	-	-	-	-	-	-	-
S-1.5	Local material sourcing	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S-2.1	Energy Conservation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
EC-1.1	Life Cycle Cost	26.4%	26.6%	26.6%	52.4%	53.0%	53.1%	24.6%	31.9%	32.0%	47.1%	75.8%	75.9%	57.8%	45.3%

Code	KPIs	1. TF-CB-CC	2. TF-CB-FAGC	3. TF-CB-GGBFS	4. TF-DB-CC	5. TF-DB-FAGC	6. TF-DB-GGBFS	7. SF-CB-CC	8. SF-CB-FAGC	9. SF-CB-GGBFS	10. SF-DB-CC	11. SF-DB-FAGC	12. SF-DB-GGBFS	13. SF-DB-50% GGBFS + 50% RA	14. SF-DB-50% GGBFS + 100% RA
EC-1.2	Potential Savings	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
EC-1.3	Benefit-Cost ratio	100.0%	100.0%	100.0%	-	-	-	100.0%	100.0%	100.0%	-	-	-	-	-
EC-2.1	Net benefit	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EC-2.2	Carbon Tax Saving	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Reference:

DOCWA (2016a) Building commission compliance report: A summary of technical building inspections_ 2015/2016 Report. Department of Commerce WA, Government of Western Australia. https://www.commerce.wa.gov.au/sites/default/files/atoms/files/a_summary_of_technical_building_inspections_201516_final.pdf. Accessed 15 July 2018

DOCWA (2016b) General Inspection Report One: A general inspection into metal roof construction in Western Australia. Building and Energy, Department of commerce, Government of Western Australia. https://www.commerce.wa.gov.au/sites/default/files/atoms/files/general_inspection_report_2016.pdf. Accessed 15 July 2018

DOCWA (2017a) Building commission compliance report: A summary of technical building inspections_ 2016/2017 Report. Department of Commerce, Government of Western Australia. https://www.commerce.wa.gov.au/sites/default/files/atoms/files/a_summary_of_technical_building_inspections_2016-17.pdf. Accessed 15 July 2018

DOCWA (2017b) Building commission compliance report: A summary of technical building inspections_ Mid-year 2016/2017 Report. Department of Commerce WA, Government of Western Australia. https://www.commerce.wa.gov.au/publications/summary-technical-building-inspections-2016-17-mid-year. Accessed 15 July 2018

DOCWA (2019) Building commission compliance audit. Building and Energy, Department of commerce, Government of Western Australia. http://www.commerce.wa.gov.au/search/site/building%2520commission%2520compliance%2520audits. Accessed 13 Dec. 2018

Kou SC, Poon CS, Agrela F (2011) Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. Cement and concrete composites. 33:788-795

Ma Z, Tang Q, Yang D, Ba G (2019) Durability Studies on the Recycled Aggregate Concrete in China over the Past Decade: A Review. Advances in Civil Engineering 2019:10. https://doi.org/10.1155/2019/4073130

Shaikh FUA, Nath P, Hosan MA, Biswas WK (2019) Sustainability assessment of recycled aggregates concrete mixes containing industrial by-products. Materials Today Sustainability. 5:e100013. http://doi.org//10.1016/j.mtsust.2019.100013

APPENDIX-6: HUMAN ETHICS APPROVAL

Curtin University

Office of Research and Development

GPO Box U1987
Perth Western Australia 6845

Telephone +61 8 9266 7863
Facsimile +61 8 9266 3793
Web research.curtin.edu.au

30-May-2018

Name: Prabir Sarker
Department/School: School of Civil and Mechanical Engineering (CME)
Email: P.Sarker@curtin.edu.au

Dear Prabir Sarker

RE: Ethics Office approval
Approval number: HRE2018-0307

Thank you for submitting your application to the Human Research Ethics Office for the project **SUSTAINABILITY IMPLICATION OF BUILDING MATERIALS CONSIDERING SERVICE LIFE VARIABILITY**.

Your application was reviewed through the Curtin University Negligible risk review process.

The review outcome is: **Approved**.

Your proposal meets the requirements described in the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research (2007).*

Approval is granted for a period of one year from **30-May-2018** to **29-May-2019**. Continuation of approval will be granted on an annual basis following submission of an annual report.

Personnel authorised to work on this project:

Name	Role
Janjua, Shahana	Student
Sarker, Prabir	Supervisor
Biswas, Wahidul	Supervisor

Approved documents:

Document

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:

- proposed changes to the approved proposal or conduct of the study
- unanticipated problems that might affect continued ethical acceptability of the project
- major deviations from the approved proposal and/or regulatory guidelines
- serious adverse events

3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)
4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
11. Approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Special Conditions of Approval

None

This letter constitutes low risk/negligible risk approval only. This project may not proceed until you have met all of the Curtin University research governance requirements.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Catherine Gangell
Manager, Research Integrity

Curtin University

Research Office at Curtin

GPO Box U1987
Perth Western Australia 6845

Telephone +61 8 9266 7863
Facsimile +61 8 9266 3793
Web research.curtin.edu.au

10-Jun-2019

Name: Prabir Sarker
Department/School: School of Civil and Mechanical Engineering (CME)
Email: P.Sarker@curtin.edu.au

Dear Prabir Sarker

RE: Annual report acknowledgment
Approval number: HRE2018-0307

Thank you for submitting an annual report to the Human Research Ethics Office for the project **SUSTAINABILITY IMPLICATION OF BUILDING MATERIALS CONSIDERING SERVICE LIFE VARIABILITY**.

The Human Research Ethics Office acknowledges the project is ongoing and approval will remain current until 28-May-2020.

Any special conditions noted in the original approval letter still apply.

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
    - proposed changes to the approved proposal or conduct of the study
    - unanticipated problems that might affect continued ethical acceptability of the project
    - major deviations from the HREC approved protocol procedures and/or regulatory guidelines
    - serious adverse events
3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)
4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
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10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
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12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Amy Bowater
Ethics, Team Lead

Curtin University

Research Office at Curtin

GPO Box U1987
Perth Western Australia 6845

Telephone +61 8 9266 7863
Facsimile +61 8 9266 3793
Web research.curtin.edu.au

19-May-2020

Name: Prabir Sarker
Department/School: School of Civil and Mechanical Engineering (CME)
Email: P.Sarker@curtin.edu.au

Dear Prabir Sarker

RE: Annual report acknowledgment
Approval number: HRE2018-0307

Thank you for submitting an annual report to the Human Research Ethics Office for the project **SUSTAINABILITY IMPLICATION OF BUILDING MATERIALS CONSIDERING SERVICE LIFE VARIABILITY**.

The Human Research Ethics Office acknowledges the project is ongoing and approval will remain current until 27-May-2021.

Special Condition of Approval Extension.

It is the responsibility of the Chief Investigator to ensure that any activity undertaken under this project adheres to the latest available advice from the Government or the University regarding COVID-19.

Any special conditions noted in the original approval letter still apply.

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
    - proposed changes to the approved proposal or conduct of the study
    - unanticipated problems that might affect continued ethical acceptability of the project
    - major deviations from the HREC approved protocol procedures and/or regulatory guidelines
    - serious adverse events
3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)
4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
11. Ethics approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Yours sincerely

Bowater

Amy Bowater
Ethics, Team Lead

BIBLIOGRAPHY

1. ABCB. *Handbook: Sound Transmission and Insulation in Buildings*. 2018. Australian Building Codes Board. Canberra, ACT, Australia. Retrieved from: https://www.abcb.gov.au/Resources/Publications/Education-Training/Sound-Insulation Accessed on:14-6-2019.

2. Abdulmatin A, Tangchirapat W, Jaturapitakkul C. *An investigation of bottom ash as a pozzolanic material*. Construction and building materials. 2018;186:155-62. https://doi.org/10.1016/j.conbuildmat.2018.07.101

3. Abeysundara UG, Babel S, Gheewala S. *A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka*. Building and environment. 2009;44(5):997-1004. https://doi.org/10.1016/j.buildenv.2008.07.005

4. ABS, *3222.0 - Population Projections, Australia, 2012 (Base) to 2101, Canberra*. 2013, Australian Bureau of Statistices Canberra Australia. Retrieved from: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/3222.0main+features52012%20(base)%20to%202101 Accessed: 14-5-2020.

5. ABS, *8731.0 - Building Approvals, Australia, Mar 2020*. 2020, Australian Bureau of Statistices Canberra Australia. Retrieved from: https://www.abs.gov.au/ausstats/abs@.nsf/mf/8731.0 Accessed: 14-5-2020.

6. ABS, *8782.0.65.001 - Construction Activity: Chain Volume Measures, Australia, Mar 2019, Canberra.* 2019, Australian Bureau of Statistices, Canberra, Australia. Retrieved from: https://www.abs.gov.au/ausstats/abs@.nsf/0/EDD60A6A5408DD1BCA2576B00014308C?Opendocument Accessed: 10-3-2020.

7. ABS, *Labour Force Region-SA4 Data*. 2018, Department of Jobs and Small Business-Australian Government, Australian Bureau of Statistics, Canberra Australia. Retrieved from: http://lmip.gov.au/default.aspx?LMIP/Downloads/ABSLabourForceRegion Accessed: 10-06-2019.

8. ABS. *6523.0 - Household Income and Wealth*, Australia, 2015-16. 2017. Australian Bureau of Statistics, Canberra, Australia. Retrieved from: https://www.abs.gov.au/ausstats/abs@.nsf/mf/6523.0 Accessed: 24-1-2019.

9. ABS. *8755.0 - Construction Work Done, Australia, Preliminary, Sep 2018*. 2018. Australian Bureau of Statistics. Canberra, Australia. Retrieved from: https://www.abs.gov.au›ausstats›8755 Accessed: 24-1-2019.

10. Agyekum EO, Fortuin K, Harst ED. *Environmental and social life cycle assessment of bamboo bicycle frames made in Ghana. Journal of cleaner production*. 2017;143:1069-80. https://doi.org/10.1016/j.jclepro.2016.12.012

11. Ahmad T, Thaheem MJ. Economic sustainability assessment of residential buildings: A dedicated assessment framework and implications for BIM. Sustainable cities and society. 2018;38:476-91. https://doi.org/10.1016/j.scs.2018.01.035

12. AHURI. *Understanding the 30:40 indicator of housing affordability stress, in Comparing household income with housing costs*. 2016. Australian Housing and Urban Research Institute. Melbourne, Australia. Retrieved from: https://www.ahuri.edu.au/policy/ahuri-briefs/2016/3040-indicator Accessed: 24-1-2019.

13. Ajayia S, Oyedele LO, Ilori OM. *Changing significance of embodied energy: A comparative study of material specifications and building energy sources*. Journal of Green Building. 2019;23:324-33. https://doi.org/10.3992/1943-4618.15.1.185

14. Akadiri P, Chinyio E, Olomolaiye P. *Design of sustainable building: A conceptual framework implementing sustainability in the building sector*. Buildings. 2012:2, 126-152. http://doi.org/10.3390/buildings2020126.

15. Akadiri PO. *Understanding barriers affecting the selection of sustainable materials in building projects*. Journal of Building Engineering, 2015. 4: p. 86-93. https://doi.org/10.1016/j.jobe.2015.08.006

16. Alinta. 2019. *Understanding your Alinta Energy Bill. Alinta Energy. Perth Australia.* Retrieved from: https://www.alintaenergy.com.au/wa/natural-gas/your-gas-bill/understanding-your-bill Accessed: 17-6-2019.

17. Allacker K, Maia de Souza D, Sala S. *Land use impact assessment in the construction sector: An analysis of lcia models and case study application*. International journal of life cycle assessment. 2014:19, 1799–1809. https://doi.org/10.1007/s11367-014-0781-7

18. Allacker K, Trigaux D, Troyer FD. An approach for handling environmental and economic conflicts in the context of sustainable building. In: Passerini G, Brebbia CA, editors.

Environ Impact II. WIT Transactions on Ecology and the Environment. Southampton (UK): WIT Press; 2014. p. 79-90. http://doi.org/10.2495/EID140071

19. Allacker K. *Sustainable Building: The Developement of an Evaluation Method*. PhD Thesis, Katholieke Universiteit Leuven, Leuven, Belgium, 2010.

20. Alwaer H, Clements-Croome DJ. Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. Building and environment. 2010;45(4):799-807. https://doi.org/10.1016/j.buildenv.2009.08.019

21. Anderson JE, Wulfhorst G, Lang W. *Expanding the use of life-cycle assessment to capture induced impacts in the built environment*. Building environment. 2015:94, 403–416. https://doi.org/10.1016/j.buildenv.2015.08.008

22. Aneurin Grant RR. *Impact of building service life models on life cycle assessment*. Build Res Info. 2013;41(2):168-86. https://doi.org/10.1080/09613218.2012.730735

23. Araújo C, Almeida M, Bragança L. Barbosa JA. *Cost-benefit analysis method for building solutions*. Applied Energy. 2016:173, 124-133. https://doi.org/10.1016/j.apenergy.2016.04.005

24. Argent RM. Inland Water, Australia State of the Environment 2016, Australian government department of the environment and energy, Canberra, Australia. 2017. Retrieved from: https://soe.environment.gov.au/sites/default/files/soe2016-inlandwater-final-web-v2.pdf?v=1495087097

25. Ashby M, Johnson K. Materials and Design: the Art and Science of Material Selection in Product Design. 2002. 1st ed. Oxford, Butterworth-Heinemann, UK.

26. Atmaca A. *Life-cycle assessment and cost analysis of residential buildings in south east of turkey: Part 2—A case study*. International journal of life cycle assessment. 2016:21, 925–942. https://doi.org/10.1007/s11367-016-1051-7

27. Atmaca A. *Life-cycle assessment and cost analysis of residential buildings in southeast of turkey: Part 2—Acase study*. International Journal of life cycle assessment. 2016:21, 925–942.https://doi.org/10.1007/s11367-016-1051-7

28. Audenaert A, de Cleyn SH, Buyle M. *LCA of low energy flats using the eco-indicator 99 method: Impact of insulation materials*. Energy and buildings. 2012:47, 68–73. https://doi.org/10.1016/j.enbuild.2011.11.028

29. Australia's Emissions: What Do the Numbers Really Mean? The Climate Institute, Sydney Australia, 2015. Retrieved from: http://www.climateinstitute.org.au/articles/publications/australias-emissions-what-do-the-numbers-really-mean.html

30. Azeem S, Naeem MA, Waheed A, Thaheem MJ. *Examining barriers and measures to promote the adoption of green building practices in Pakistan.* Smart and Sustainable Built Environment, 2017. 6(3): p. 86-100. https://doi.org/10.1108/SASBE-06-2017-0023

31. Babaizadeh H, Haghighi N, Asadi A, Broun R, Riley D. Life cycle assessment of exterior window shadings in residential buildings in different climate zones. Building and environment. 2015;90:168-77. https://doi.org/10.1016/j.buildenv.2015.03.038

32. Balasbaneh A, Marsono AK, Khaleghi SJ. Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment. Journal of Building Engineering, 2018. 20: p. 235-247. https://doi.org/10.1016/j.jobe.2018.07.006

33. Balasbaneh AT, Bin Marsono AK, Kermanshahi KE. *Balancing of life cycle carbon and cost appraisal on alternative wall and roof design verification for residential building*. Construction Innovation. 2018;18(3):274-300. https://doi.org/10.1108/CI-03-2017-0024

34. Bardhan S. *Assessment of water resource consumption in building construction in India*. WIT Transactions on Ecology and the Environment. 2011:144, 93–101. https://doi.org/10.2495/ECO110081

35. Barreca F, Praticò P. *Post-occupancy evaluation of buildings for sustainable agri-food production—A method applied to an olive oil mill*. Buidings. 2018:8, 83. https://doi.org/10.3390/buildings8070083

36. Barthel L, Wolf MA, Eyerer P. *Methodology of life cycle sustainability assessments*. 2005. In 11th Annual International Sustainable Development Research Conference (AISDRC). Helsinki, Finland. http://doi.org/10.14359/51689426

37. BBC. *Planet Under Pressure.* 2004. British Broadcasting Corporation news. http://news.bbc.co.uk/2/hi/science/nature/3686106.stm

38. Bekker PCF. *A life cycle approach in building*. Building and environment. 1982;17(1):3-13. https://doi.org/10.1016/0360-1323(82)90009-9

39. Berkel RV. *Cleaner production and eco-efficiency initiatives in Western Australia 1996-2004.* Journal of Cleaner Production, 2006. 15: p. 741-55. https://doi.org/10.1016/j.jclepro.2006.06.012

40. Bhardwaj B, Kumar P. *Waste foundry sand in concrete: A review*. Construction and building materials. 2017;156:661-74. https://doi.org/10.1016/j.conbuildmat.2017.09.010

41. Biswas WK, Alhorr Y, Lawania KK, Sarker PK, Elsarrag E. *Life cycle assessment for environmental product declaration of concrete in the gulf states*. Sustainable cities and society. 2017:35, 36–46. https://doi.org/10.1016/j.scs.2017.07.011

42. Biswas WK, Barton L, Carter D. *Global warming potential of wheat production western australia: A life cycle assessment*. Water and environment journal. 2008:22, 206–216. https://doi.org/10.1111/j.1747-6593.2008.00127.x

43. Biswas WK, Cooling D. *Sustainability Assessment of Red Sand as a Substitute for Virgin Sand and Crushed Limestone.* Journal of Industrial Ecology, 2013. 17(5): p. 756-762. https://doi.org/10.1111/jiec.12030

44. Biswas WK. *Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia*. International journal of life cycle assessment. 2014:19, 732–744. https://doi.org/10.1007/s11367-013-0681-2

45. Blengini GA, Carlo TD. *Energy-Saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy)*. International journal of life cycle assessment. 2010;15(7):652-65. https://doi.org/10.1007/s11367-010-0190-5

46. Blengini GA, Di CT. *The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings.* Energy and Buildings, 2009. 42: p. 869-80. https://doi.org/10.1016/j.enbuild.2009.12.009

47. BOM. Average Annual, Seasonal and Monthly Rainfall, Bureau of metreology, Australian government, Melbourne, Australia, 2018. Retrieved from: http://www.bom.gov.au/climate/current/statement_archives.shtml Accessed on: 10-11-2018

48. Braga AM, Silvestre JD, Brito JD. *Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates*. Journal of cleaner production. 2017;162:529-43. https://doi.org/10.1016/j.jclepro.2017.06.057

49. Bragança L, Mateus R, Koukkari H. *Building Sustainability Assessment*. Sustainability. 2010;2:2101-23. https://doi.org/10.3390/su2072010

50. Brundtland GH. *Our Common Future: Report of the World Commission on Environment and Developement*. 1987, World Commission on Environment and Developement: New York, NY, USA. Retrieved from: http://www.un-documents.net/wced-ocf.htm Accessed: 10-01-2019.

51. *Business strategy for sustainable development: leadership and accountability for the '90s*. Business Council for Sustainable Development, Deloitte & Touche, International Institute for Sustainable Development, 1992, Winnipeg, Canada.

52. Buyle M, Braet J, Audenaert A. *Life cycle assessment in the construction sector: A review.* Renewable and Sustainable Energy review, 2013. 26: p. 379-388. https://doi.org/10.1016/j.rser.2013.05.001

53. Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. *Life cycle assessment (LCA) and life cycle energyanalysis (LCEA) of buildings and the building sector: A review*. Renewable and sustainable energy reviews. 2014:29, 394–416. http://doi.org/10.1016/j.rser.2013.08.037

54. Cabrera-Covarrubias FG, Gómez-Soberón JM, Almaral-Sánchez JL, Arredondo-Rea SP, Gómez-Soberón MC, Corral-Higuera R. *An Experimental Study of Mortars with Recycled Ceramic Aggregates: Deduction and Prediction of the Stress-Strain*. Materials. 2016;9(12):1029. https://doi.org/10.3390/ma9121029

55. Carre A, Crossin E. PRA344-1415. *A comparative life cycle assessment of two multistorey residential apartment buildings.* 2015. Forest & Wood Products Australia, Melbourne, Australia. Available at: http://www.fwpa.com.au/images/marketaccess/PRA344-1415-Australand.pdf Accessed: 19-12-2018.

56. Carre A. PNA-147-0809. *A comparative life cycle assessment of alternative constructions of a typical Australian house design*. 2011. Forest & Wood Products Australia, Melbourne, Australia. Availalble at: https://www.fwpa.com.au/resources/market-access/204-comparative-life-cycle-assessment-of-alternative-constructions-of-a-typical-australian-house-design.html Accessed: 19-12-2018.

57. CCC, Fourth carbon budget review – part 2 the cost-effective path to the 2050 target, in UK: Committee on Climate Change. 2013, Retrieved from:

https://www.theccc.org.uk/publication/fourth-carbon-budget-review/. Accessed: 16-06-2019.

58. Cecconi F. *Performance lead the way to service life prediction*. In Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 17–20 March 2002. https://www.irbnet.de/daten/iconda/CIB9307.pdf

59. Chen CJ, Juan YK. Hsu YH. Developing a systematic approach to evaluate and predict building service life. Journal of civil engineering and management. 2017:23, 890–901. https://doi.org/10.3846/13923730.2017.1341956

60. Chen Z. *Accurate Sustainability Tool Version 2.3.3.13 SP4*. 2018, CSIRO Land & Water Flagship and distributed by Energy Inspection Pty Ltd. Austrailia.

61. Cheng K, Hsu SC, Li WM, Ma HW. *Quantifying potential anthropogenic resources of buildings through hot spot analysis*. Resources, Conservations and Recycling. 2018;133:10-20. https://doi.org/10.1016/j.resconrec.2018.02.003

62. Chiang YH, Li J, Zhou L, Wong FK, Lam PT. The nexus among employment opportunities, life-cycle costs, and carbon emissions: A case study of sustainable building maintenance in Hong Kong. Journal of cleaner production. 2015;109: 326-35. https://doi.org/10.1016/j.jclepro.2014.07.069

63. COFA. *Clean Energy Act 2011. Act No. 103.2013*. 2011. Parliamentary Counsel, Commonwealth of Australia. Accessed: 10-8-2019, Retrieved from: https://www.legislation.gov.au/Details/C2013C00372/Download

64. Coles RJ. *Energy and greenhouse gas emissions associated with the construction of alternative structural systems*. Building and environment. 1998;34(3): 335-48. https://doi.org/10.1016/S0360-1323(98)00020-1

65. Counsoli F, Allen D, Boustead I, Fava J, Franklin W, Jensen A. Guidelines for life-cycle assessment: a "code of practice". 1st ed. Pensacola (US): Society of Environmental Toxicology and Chemistry (SETAC); 1993.

66. Crawford RH, Czerniakowski I, Fuller RJ. *A comprehensive framework for assessing the life-cycle energy of building construction assemblies*. Architectural science review. 2010;53(3):288. https://doi.org/10.3763/asre.2010.0020

67. Crawford RH, Rauf A. *Energy and greenhouse gas emissions implications of alternative housing types for Australia*. In Proceedings of the State of Australian Cities National

Conference Australian Sustainable Cities and Regions Network (ASCRN), Melbourne, VIC, Australia, 29 November–2 December 2011; pp. 1–12. http://hdl.handle.net/10536/DRO/DU:30042312

68. Crilly N, Moultrie J, Clarkson PJ. Seeing things: consumer response to the visual domain in product design. Design studies. 2004;25(6):547-77.

69. Crowther P. *Design for disassembly to recover embodied energy*. In Proceedings of the 16th International conference on Passive and Low Energy Architecture, Melbourne/Brisbane/Cairns, Australia, 22–24 September 1999. http://eprints.qut.edu.au/2846/1/Crowther-PLEA1999.PDF

70. Cuellar-Franca RM, Azapagic A. Environmental impacts of the UK residential sector: Life cycle assessment of houses. Building environment. 2012:54, 86–99.

71. Cuellar-Franca RM, Azapagic A. Life cycle cost analysis of the UK housing stock. International journal of life cycle assessment. 2014;19:174-93. https://doi.org/10.1007/s11367-013-0610-4

72. Cuellar-Franca RM. *Sustainability Assessment Framework for the Residential Construction Sector in the UK*, 2012. In School of Chemical Engineering and Analytical Science. University of Manchester. Manchester UK.

73. Cullen R. *TW13022 - C&D waste recycling resource kit.* 2014. Talis consultants Pty Ltd., Leederville, WA, Australia. Retrieved from:https://www.wasteauthority.wa.gov.au/media/files/documents/East_Fremantle_CD_Recycling_Trial_and_Directory.pdf Accessed: 10-8-2019.

74. Dale VH, Beyeler SC. *Challenges in the development and use of ecological indicators.* Ecological indicators. 2001;1(1):3-10. https://doi.org/10.1016/S1470-160X(01)00003-6

75. Danso H. *Properties of Coconut, Oil Palm and Bagasse Fibres: As Potential Building Materials*. Procedia engineering. 2017;200:1-9. https://doi.org/10.1016/j.proeng.2017.07.002

76. Dawood MH. BIM based optimal life cycle cost of sustainable house framework. In: Proceedings of 3rd MEC International Conference on Big Data and Smart City; 2016 Mar 15-16; Muscat, Oman. Piscataway (US): IEEE; 2016. https:doi.org/10.1109/ICBDSC.2016.7460381

77. De Luca P, Carbone I, Nagy JB. *Green building materials: a review of state of the art studies of innovative materials*. Journal of Green Building. 2017;12(4):141-61. https://doi.org/10.3992/1943-4618.12.4.141

78. Dean B, Dulac J, Petrichenko K, Graham P. *Towards zero-emission efficient and resilient buildings.* Global Status Report 2016. Paris (France): Global Allience for Buildings and Construction (GABC); 2016.

79. Ding T, Xiao J, Tam VWY. *A closed-loop life cycle assessment of recycled aggregate concrete utilization in China*. Waste management. 2016;56:367-75. https://doi.org/10.1016/j.wasman.2016.05.031

80. DOE, *Australia's 2030 emissions reduction target*, 2015. Department of the Environment, Australian Government, Canberra, Australia. Available at: https://www.environment.gov.au/system/files/resources/f52d7587-8103-49a3-aeb6-651885fa6095/files/summary-australias-2030-emissions-reduction-target.pdf Accessed: 29-05-2018

81. DOEE. *Australian Energy Statistics, Table O, April 2018.* 2018. Department of Environment and Energy. Canberra, Australia. Retrieved from: *https://www.energy.gov.au/publications/australian-energy-statistics-table-o-electricity-generation-fuel-type-2017-18-and-2018* Accessed: 7-7-2019.

82. DOEE. *Australian Energy Update 2018.* 2018. Department of Environment and Energy. Canberra, Australia. Retrieved from: *https://www.energy.gov.au/sites/default/files/australian_energy_update_2018.pdf* Accessed: 7-7-2019.

83. DOEE. *Construction and Demolition waste guide- recycling and re-use across the supply chain.* 2012. Department of sustainability, environment, Water, population and Communities. Canberra, Australia. Retrieved from: https://www.environment.gov.au/system/files/resources/b0ac5ce4-4253-4d2b-b001-0becf84b52b8/files/case-studies.pdf Accessed: 7-7-2019.

84. DOEE. *Quarterly Update of Australia's National Greenhouse Gas Inventory*: December 2018, In Australia's National Greenhouse Accounts. 2019. Department of Environment and Energy. Canberra, Australia. Retrieved from:https://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/quarterly-update-australias-nggi-mar-2019. Accessed: 7-7-2019.

85. DOEE. *State and Territory Greenhouse Gas Inventories 2017*, In Australia's National Greenhouse Accounts. 2019. Department of Environment and Energy. Canberra, Australia. Retrieved from: https://www.environment.gov.au › system › files › resources › files ›state-territory-inventories-2017. Accessed: 7-7-2019.

86. Dong YH, Ng ST. *A social life cycle assessment model for building construction in Hong Kong*. International journal of life cycle assessment.2015;20(8):1166-80. https://doi.org/10.1007/s11367-015-0908-5

87. Dong YH, Ng T. *A modeling framework to evaluate sustainability of building construction based on LCSA*. International journal of life cycle assessment., 2016. 21: p. 555-568. https://doi.org/10.1007/s11367-016-1044-6

88. Dreyer LC, Hauschild MZ, Schierbeck J. *A Framework for Social Life Cycle Impact Assessment*. International journal of life cycle assessment. 2006:11, 89-99. https://doi.org/10.1065/lca2005.08.223.

89. Durgun MY, Sevinc AH. High temperature resistance of concretes with GGBFS, waste glass powder, and colemanite ore wastes after different cooling conditions. Construction and building materials. 2019;196:66-81. https://doi.org/10.1016/j.conbuildmat.2018.11.087

90. Ecoinvent Centre. Ecoinvent Databases 2019. Retrieved from: http://www.ecoinvent.org/database/database.html. Access 2019 Apr 28.

91. Ede AN, Adebayo SO, Ugwu EI, Emenike CPG. Life Cycle Assessment of Environmental Impacts of Using Concrete or Timber to Construct a Duplex Residential Building. Journal of mechanical and civil engineering. 2014:11, 62-72. http://eprints.covenantuniversity.edu.ng/id/eprint/9629

92. Eggenberger M, Partidário MR. *Development of a framework to assist the integration of environmental, social and economic issues in spatial planning.* Impact Assessment and Project Appraisal, 2000. 18(3): p. 201-207. https://doi.org/10.3152/147154600781767448

93. Ekener-Petersen E, Finnveden G. *Potential hotspots identified by social LCA - Part 1: A case study of a laptop computer*. International journal of life cycle assessment.2013;18(1):127-43. https://doi.org/10.1007/s11367-012-0442-7

94. Ekener-Petersen E, Hansson J, Gustavsson M. *Addressing positive impacts in social LCA discussing current and new approaches exemplified by the case of vehicle fuels.*

International journal of life cycle assessment.2018;23(3):556-68. https://doi.org/10.1007/s11367-016-1058-0

95. Emídio F, Brito JD, Gaspar PL, Silva A. *Application of the factor method to the estimation of the service life of natural stone cladding*. Construction and building materials. 2014;66:484-93. https://doi.org/10.1016/j.conbuildmat.2014.05.073

96. Estokova A, Vilcekova S, Porhincak M. *Analyzing embodied energy, global warming and acidification potentials of materials in residential buildings*. 2016. In International High-Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), Sydney, Australia. Procedia engineering. https://doi.org/10.1016/j.proeng.2017.04.330

97. European Committee for Standardisation. EN 16309:2014+A1, *Sustainability of Construction Works—Assessment of Social Performance of Buildings—Calculation Methodology*. Brussels (Belgium): CEN—European Committee for Standardisation; 2014.

98. Evangelista PPA, Kiperstock A, Torres EA, Gonçalves JP. *Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA)*. Construction and building materials. 2018;169:748-61.

99. Fay R, Treloar G, Iyer-Raniga U. *Life-cycle energy analysis of buildings: A case study*. Building research and information. 2000:28, 31–41. https://doi.org/10.1080/096132100369073

100. Fenton GG, Gerofi JP. *Desalination in australia-past and future*. Desalination. 1981:39, 399–411. https://doi.org/10.1016/S0011-9164(00)86144-5

101. Fernández-Membrive VJ, Lastra-Bravo XB, Tolón-Becerra A. *Cost-benefit analysis of changes in energy in building technology in Southeast Spain*. Energy and buildings. 2015:03, 29-37. https://doi.org/10.1016/j.enbuild.2015.06.026

102. Fouquet M, Levasseur A, Margni M, Lebert A, Lasvaux S, Souyri B, et al. Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. Building and Environment. 2015;90:51-9. https://doi.org/10.1016/j.buildenv.2015.03.022S

103. Franzitta V, Gennusa ML, Peri G, Rizzo G, Scaccianoce G. *Toward a european eco-label brand for residential buildings: Holistic or by-components approaches?* Energy. 2011:36, 1884–1892. https://doi.org/10.1016/j.energy.2010.09.021

104. Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Heck T, et al. *The ecoinvent database: Overview and methodological framework.* International Journal of life cycle assessment. 2005;10(1):3-9. https://doi.org/10.1065/lca2004.10.181.1

105. Frischknecht R, Wyss F, Knöpfel BS, Lützkendorf T, Balouktsi M. *Cumulative energy demand in LCA: the energy harvested approach*. International journal of life cycle assessment. 2015:20, 957-969. https://doi.org/10.1007/s11367-015-0897-4.

106. Fu F, Pan L, Ma L, Li Z. *A simplified method to estimate the energy-saving potentials of frequent construction and demolition process in China*. Energy. 2013;49:316-22. https://doi.org/10.1016/j.energy.2012.10.021

107. Fufa SM, Skaar C, Gradeci K, Labonnote N. *Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA*. Journal of cleaner production. 2018;44:319-33. https://doi.org/10.1016/j.jclepro.2018.06.006

108. Galle W, Temmerman ND, Meyer RD. *Integrating scenarios into life cycle assessment: Understanding the value and financial feasibility of a demountable building*. Buidings. 2017:7, 64. https://doi.org/10.3390/buildings7030064

109. Gámez-García DC, Gómez-Soberón JM, Corral-Higuera R, Saldaña-Márquez H, Gómez-Soberón MC, Arredondo-Rea SP. *A Cradle to Handover Life Cycle Assessment of External Walls: Choice of Materials and Prognosis of Elements*. Sustainability. 2018;10(8):2748. https://doi.org/10.3390/su10082748

110. GBCA. *Local Procurement, In Innovation Challenges Handbook*. 2019. Green Building Council of Australia. NSW, Australia. Retrieved from: https://www.gbca.org.au/uploads/68/34884/Local%20Procurement.pdf Accessed: 14-6-2019.

111. Geng S, Wang Y, Zuo J, Zhou Z, Mao G. *Building life cycle assessment research: A review by bibliometric analysis*. Renewable and sustainable energy reviews. 2017; 76:176-84. https://doi.org/10.1016/j.rser.2017.03.068

112. Ghose A, Pizzol M, McLaren S. *Consequential LCA modelling of building refurbishment in New Zealand—an evaluation of resource and waste management scenarios*. Journal of cleaner production. 2017; 165:119-33. https://doi.org/10.1016/j.jclepro.2017.07.099

113. Ghosh A, Ghosh A, Neogi S. *Reuse of fly ash and bottom ash in mortars with improved thermal conductivity performance for buildings*. Heliyon. 2018;4(11):e00934. https://doi.org/10.1016/j.heliyon.2018.e00934

114. Glover J, Whilte DO, Langrish TAG. *Wood versus concrete and steel in house construction*. Journal of forestry. 2002;100(8):34-41. https://doi.org/10.1093/jof/100.8.34

115. Gluch P, Baumann H. *The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making*. Building and environment. 2014:39, 571–580. https://doi.org/10.1016/j.buildenv.2003.10.008

116. Goh BH, Sun Y. *The development of life-cycle costing for buildings*. Building research and information. 2016;44(3):319-33. https://doi.org/10.1080/09613218.2014.993566

117. Gómez-Soberón JM, Cabrera-Covarrubias FG, Almaral-Sánchez JL, Gómez-Soberón MC. *Fresh-State Properties of Mortars with Recycled Glass Aggregates: Global Unification of Behavior.* Adv Mater Sci Eng. 2018;2018:1386946. https://doi.org/10.1155/2018/1386946

118. Göswein V, Goncalves AB, Silvestre JD, Freire F, Kurda R. Transportation matters—does it? GIS-based comparative environmental assessment of concrete mixes with cement, fly ash, natural and recycled aggregates. Resources, conservation and recycling. 2018;137:1-10. https://doi.org/10.1016/j.resconrec.2018.05.021

119. Grant A, Ries R, Kibert C. *Life cycle assessment and service life prediction: A case study of building envelope materials.* Journal of Industrial Ecology, 2014. 18(2): p. 187-200. https://doi.org/10.1111/jiec.12089

120. Grant A, Robert R, Charles K. *Life Cycle Assessment and Service Life Prediction*, Journal of Industrial Energy, 2014:18 (2), 187-200. https://doi.org/10.1111/jiec.12089

121. Gray J, Isaacs N, Kernohan D, McIndoe G. *Building Evaluation techniques*. Baird G, editor. New York (US): McGraw-Hill Co. Inc.; 1995.

122. Greene G. Caring for the earth: The world conservation union, the United Nations environment programme, and the world wide fund for nature. Environment: Science and Policy for Sustainable Development. 1994:36, 25-28. http://doi.org/10.1080/00139157.1994.9929182

123. Griggs D, Smith MS, Gaffney O, Rockström J, Öhman MC, Shyamsundar P, et al. *Sustainable development goals for people and planet*. Nature. 2013;495(7441):305-7. https://doi.org/10.1038/495305a

124. Guinee JB, Haes UD, Huppes G. *Quantitative life cycle assessment of products: 1: goal definition and inventory*. Journal of cleaner production. 1993;1(1):3-13. https://doi.org/10.1016/0959-6526(93)90027-9

125. Guinee JB, Udo de Haes HA, Huppes G. *Quantitative life cycle assessment of products: 1: Goal definition and inventory*. Journal of cleaner production, 1993:1, 3–13. https://doi.org/10.1016/0959-6526(93)90027-9

126. Guinée, J. Chapter 3: Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges?, in Taking Stock of Industrial Ecology, Clift R, Druckman A (Ed). 2015, Springer Cham: Heidelberg New York, Dordrecht, London.

127. Guo Y, Xie J, Zhao J, Zuo K. *Utilization of unprocessed steel slag as fine aggregate in normal- and high-strength concrete*. Construction and building materials. 2019;204:41-9. https://doi.org/10.1016/j.conbuildmat.2019.01.178

128. Harish VSKV, Kumar A. *A review on modeling and simulation of building energy systems*. Renewable and sustainable energy reviews. 2016;56:1272-92. https://doi.org/10.1016/j.rser.2015.12.040

129. Hed G. Service life planning of building components. Durability of building materials and componente. 1999, 8, 1543–1551. http://www.irbnet.de/daten/iconda/CIB2305.pdf

130. Hegger M, Drexler H, Zeumer M. *Basics Materials*. 2007. Basel, Birkhauser, Switzerland.

131. Heijungs R, Settanni E, Guinée J. Toward a computational structure for life cycle sustainability analysis: Unifying LCA and LCC. International journal of life cycle assessment. 2012;18(9):1722-33. https://doi.org/10.1007/s11367-012-0461-4

132. Hossain MU, Poon CS, Lo IC, Cheng JP. *Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach*. International journal of life cycle assessment. 2016;21(1):70-84. https://doi.org/10.1007/s11367-015-0988-2

133. Hossaini N, Reza B, Akhtar S, Sadiq R, Hewage K. AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame

buildings in Vancouver. Journal of Environmental planning and Management, 2015. 58(7): p. 1217-1241. https://doi.org/10.1080/09640568.2014.920704

134. Hosseinijou SA, Mansour S, Shirazi MA. *Social life cycle assessment for material selection: a case study of building materials*. International journal of life cycle assessment. 2014;19(3):620-45. https://doi.org/10.1007/s11367-013-0658-1

135. Hovde PJ, Konrad M. Performance based Methods for Service life Prediction, State of Art Reports, Report of CIB W080/RILEM 175-SLM: Service Life Methodologies. 2004. Norwegian University of Science and Technology (NTNU), Department of Building and Construction Engineering, Trondheim, Norway. Available at: http://www.irbnet.de/daten/iconda/CIB1305.pdf

136. Hovde PJ, Moser, K. Performance Based Methods for Service Life Prediction; In-House Publishing: Rotterdam, The Netherlands, 2004.

137. Hovde PJ. *Evaluation of the Factor Method to Estimate the Service Life of Building Components*. Department of Building and Construction Engineering, The Norwegian University of Science and Technology, Trondheim, Norway, 1998.

138. Hovde PJ. *Performance Based Methods for Service Life Prediction, Part A: Factor Methods for Service Life Prediction*. Available online: http://site.cibworld.nl/dl/publications/Pub294.pdf Accessed: 01-01-2019

139. Huang B, Chen Y, McDowall W, Türkeli S, Geng Y. *Embodied GHG emissions of building materials in Shanghai*. Journal of cleaner production. 2019;210:777-85. https://doi.org/10.1016/j.jclepro.2018.11.030

140. Huang H, Zhang L, Liu Z, Sutherland JW. *Multi-criteria decision making and uncertainty analysis for materials selection in environmentally conscious design*. International journal of advanced manufacturing technology. 2011;52(5-8):421-32. https://doi.org/10.1007/s00170-010-2745-9

141. Huijbregts et al. *Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?* Environmental science and technology. 2006:40, 641-648. http://doi.org/10.1021/es051689g

142. Hunkeler D. Societal LCA methodology and case study. International journal of life cycle assessment. 2006:11, 371-382. http://doi.org/10.1065/lca2006.08.261

143. Iffa E, Tariku F. *Hygrothermal performance assessment of ICF walls with different moisture control strategies and wall designs*. Journal of Green Building. 2017;12(4):35-53. https://doi.org/10.3992/1943-4618.12.4.35

144. Ingrao C, Arcidiacono C, Bezama A, Ioppolo G, Schmid AG. Virtual Special Issue on sustainability issues of by-product and waste management systems to produce building material commodities. Resources, conservation and recycling. 2017;126:A4-5. https://doi.org/10.1016/j.resconrec.2019.04.001

145. Intini F, Kühtz S. Recycling in buildings: an LCA case study of a thermal insulation panel made of polyester fiber, recycled from post-consumer PET bottles. International journal of life cycle assessment. 2011;16(4):306-15. https://doi.org/10.1007/s11367-011-0267-9

146. Islam H, Jollands M, Setunge S, Ahmed I, Haque N. Life cycle assessment and life cycle cost implications of wall assemblages designs. Energy and buildings. 2014:84, 33-45. https://doi.org/10.1016/j.enbuild.2014.07.041

147. Islam H, Jollands M, Setunge S. *Life cycle assessment and life cycle cost implication of residential buildings—A review*. Renewable and sustainable energy reviews. 2015:42, 129–140. https://doi.org/10.1016/j.rser.2014.10.006

148. ISO, ISO 15686-1, Buildings and constructed assets - Service life Planning, in Part-1: General principles and framework. 2011, International standards organisation, Geneva, Switzerland.

149. ISO, ISO 15686-2, Buildings and constructed assets - Service life Planning, in Part-2: Service life prediction procedures. 2012, International standards organisation, Geneva, Switzerland.

150. ISO, ISO 15686-8, Buildings and constructed assets - Service-life planning, in Part 8: Reference service life and service-life estimation. 2008, International Standards Organisation, Geneva, Switzerland.

151. ISO, ISO/TS 21929-1. Sustainability in building construction-Sustainability indicators. In Part 1: Framework for the developementvof indicators for buildings. 2006. International standards organisation. Switezerland.

152. ISO, ISO-14040: Environmental management - Life cycle assessment - Principles and framework. 2006, International standards organisation, Geneva, Switzerland.

153. Iyer-Raniga U, ChewWong JP. *Evaluation of whole life cycle assessment for heritage buildings in Australia.* Building and environment. 2012:47, 138–149. https://doi.org/10.1016/j.buildenv.2011.08.001

154. Janjua SY, Sarker PK, Biswas WK. *A review of residential buildings' sustainability performance using a life cycle assessment approach.* J Sustainability Res, 2019. 1: p. e190006. https://doi.org/10.20900/jsr20190006

155. Janjua SY, Sarker PK, Biswas WK. *Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings.* Journal of Environmental Management, 2020. 264:110476. https://doi.org/10.1016/j.jenvman.2020.110476

156. Janjua SY, Sarker PK, Biswas WK. *Impact of Service Life on the Environmental Performance of Buildings.* Buidings, 2019. 9. https://doi.org/10.3390/buildings9010009

157. Janjua SY, Sarker PK, Biswas WK. *Sustainability Implication of a residential building using a lifecycle assessment approach.* Chemical Engineering Transactions, 2019. 72: p. 19-24. https://doi.org/10.3303/CET1972004.

158. Janjua SY, Sarker PK, Biswas WK. Sustainability Implications of the service life of residential buildings - A Life Cycle Sustainability Assessment Approach. Intl. Journal of life cycle assessment, 2020.

159. Jeurissen R, Elkington J. Cannibals With Forks: The Triple Bottom Line of 21st Century Business. *Journal of Business Ethics* 23, 229–231 (2000). https://doi.org/10.1023/A:1006129603978

160. Joseph P, Tretsiakova-McNally S. *Sustainable Non-metallic Building Materials*. Sustainability. 2010;2(2):400-27.

161. Kamali M, Hewage K, Milani AS. Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices. Building and Environment, 2018. 138: p. 21-41. https://doi.org/10.1016/j.buildenv.2018.04.019

162. Klöppfer W, *Life Cycle Sustainability assessment of products.* International journal of life cycle assessment., 2008. 13: p. 89-95.

163. Kovacic I, Waltenbereger L, Gourlis G. Tool for life cycle analysis of facade-systems for industrial buildings. Journal of cleaner production. 2016;130(1):260-72. https://doi.org/10.1016/j.jclepro.2015.10.063

164. Kucukvar M, Tatari O. *Towards a triple bottom-line sustainability assessment of the U.S. construction industry.* The international journal of life cycle assessment, 2013. 18: p. 958-72. https://doi.org/10.1007/s11367-013-0545-9

165. Langade S, Gilke N, Patil K. *Bagasse Ash for Manufacturing Construction Products*. Materials today proceedings. 2018;5(9):19954-62. https://doi.org/10.1016/j.matpr.2018.06.361

166. Lasvaux S, Achim F, Garat P, Peuportier B, Chevalier J, Habert G. *Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: what matters?* Ecological indicators. 2016;67:174-82. https://doi.org/10.1016/j.ecolind.2016.01.056

167. Lawania K, Biswas WK. *Achieving environmental friendly building envelope for Western Australia's housing sector: A life cycle assessment approach*. International journal of sustainable built environment. 2016;5(2):210-24. https://doi.org/10.1016/j.ijsbe.2016.04.005

168. Lawania K, Biswas WK. *Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia*. International journal of life cycle assessment. 2018;23:204-24. https://doi.org/10.1007/s11367-017-1314-y

169. Lawania K, Sarker PK, Biswas WK. *Global Warming Implications of the Use of By-Products and Recycled Materials in Western Australia's Housing Sector*. Materials. 2015;8(10):6909-25. https://doi.org/10.3390/ma9121029

170. Lawania KK, Biswas WK. *Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia*. International journal of life cycle assessment. 2018:23, 204–224. https://doi.org/10.1007/s11367-017-1314-y

171. Lawania KK, Biswas WK. Cost-effective GHG mitigation strategies for Western Australia's housing sector: A life cycle management approach. Clean technologies & environmental policy. 2016;18(8):2419-28. http://doi.org/10.1007/s10098-016-1217-9.

172. Lawania KK. Improving the Sustainability Performance of Western Australian House Construction: A Life Cycle Management Approach, in School of Civil and Mechanical Engineering. 2016, PhD Thesis, Curtin University, Perth, Australia.

173. Lawn P. *Sustainable Development Indicators in Ecological Economics*. 2006. Edward Elgar Publishing Limited. Cheltenham, UK.

174. LEED. *Regional materials, MRc 5; LEED BD+C: New construction | v3-LEED 2009*. 2016. Leadership in energy and environmental design. Retrieved from: https://www.usgbc.org/node/1731029?return=/credits/new-construction/v2009 Accessed: 14-6-2019.

175. Ligotski R, Sager U, Schneiderwind U, Asbach C, Schmidt F. Prediction of VOC adsorption performance for estimation of service life of activated carbon based filter media for indoor air purification. Building and environment. 2019;149:146-56. https://doi.org/10.1016/j.buildenv.2018.12.001

176. Lim CI, Biswas WK. *An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia*. Sustainability. 2015;7: 16561-7. https://doi.org/10.3390/su71215833

177. Lim CI, Biswas WK. *Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry.* Clean Technologies and Environmental Policy, 2018. 20: p. 539-560. https://doi.org/10.1007/s10098-017-1453-7

178. Linstone HA, Turroff M. *The Delphi Method: Techniques and Applications*. 1975. Addison -Wesley Publishers and Co.

179. Liu S, Qian S. *Evaluation of social life-cycle performance of buildings: Theoretical framework and impact assessment approach*. Journal of cleaner production. 2019;213:792-807. https://doi.org/10.1016/j.jclepro.2018.12.200

180. Lombard R. *It's not easy being green: Difficulties in sourcing sustainable building materials.* QScience Connect. 2017;2:1. https://doi.org/10.5339/ connect.2017.qgbc.10

181. Lori AR, Hassani A, Sedghi R. *Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate*. Construction and building materials. 2019;197:130-42. https://doi.org/10.1016/j.conbuildmat.2018.11.230

182. Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. *Critical review of life cycle assessment (lca) for the built environment at the neighborhood scale*. Building environment. 2015, 93, 165–178. https://doi.org/10.1016/j.buildenv.2015.06.029

183. Love PED, Irani Z. An exploratory study of information technology evaluation and benefits management practices of SMEs in the construction industry. Information management. 2004;42(1):227-42.

184. Lyu Y, Kim JH, Gu X. Developing methodology for service life prediction of PV materials: Quantitative effects of light intensity and wavelength on discoloration of a glass/EVA/PPE laminate. Solar Energy. 2018;174:515-26. https://doi.org/10.1016/j.solener.2018.08.067

185. Ma M, Cai W. Do commercial building sector-derived carbon emissions decouple from the economic growth in Tertiary Industry? A case study of four municipalities in China. Science total environment. 2019;560(1):822-34.

186. Maalouf C, Ingrao C, Scrucca F, Moussa T, Asdrubali F. An energy and carbon footprint assessment upon the usage of hemp-lime concrete and recycled-PET façades for office facilities in France and Italy. Journal of cleaner productions. 2018;170:1640-53. https://doi.org/10.1016/j.jclepro.2016.10.111

187. Maddox B, Nunn J. *LCA Fact Sheet: Life cycle analysis of clay brick housing – based on a typical project home.* 2003. The centre for sustainable technology, the unversity of Newcastle, Newcastle, Australia.

188. Madrigal LO, Bretones JF, Lanzarote BS. *Proposed method of estimating the service life of building envelopes*. Journal of construction. 2015;14(1):60-88. http://doi.org/10.4067/S0718-915X2015000100008

189. Majer JD, Beeston G. *The biodiversity integrity index: An illustration using ants in Western Australia*. Conservation biology. 1996:1, 65-73. https://doi.org/10.1046/j.1523-1739.1996.10010065.x

190. Manik Y, Leahy J, Halog A. *Social life cycle assessment of palm oil biodiesel: A case study in Jambi Province of Indonesia*. International journal of life cycle assessment.2013;18(7):1386-92. https://doi.org/10.1007/s11367-013-0581-5

191. Manish, K.; Dixit, J.L.F.; Lavy, S.; Charles, H.C. *Need for an embodied energy measurement protocol for buildings: A review paper*. Renewable and sustainable energy reviews. 2012:16, 3730–3743. https://doi.org/10.1016/j.rser.2012.03.021

192. Marjaba GE, Chidiac SE. *Sustainability and resiliency metrics for buildings—Critical review*. Building and environment. 2016;101:116-25. https://doi.org/10.1016/j.buildenv.2016.03.002

193. Martínez-Blanco J, Lehmann A, Muñoz P, Antón A, Traverso M, Rieradevall J, et al. *Application challenges for the social Life Cycle Assessment of fertilizers within life cycle*

sustainability assessment. Journal of cleaner production. 2014;69:34-48. https://doi.org/10.1016/j.jclepro.2014.01.044

194. Martínez-Rocamora A, Solís-Guzmán J, Marrero M. *LCA databases focused on construction materials: A review*. Renewable and sustainable energy review. 2016;58:565-73. https://doi.org/10.1016/j.rser.2015.12.243

195. Maslesa E, Jensen PA, Birkved M. *Indicators for quantifying environmental building performance: A systematic literature review*. Journal of building engineering. 2018;19:552-60. https://doi.org/10.1016/j.jobe.2018.06.006

196. Masters LW, Brandt E. *Prediction of service life of building materials and components*. Materials and structures. 1987:20, 55–77. https://doi.org/10.1007/BF02472728

197. Mathe S. *Integrating participatory approaches into social life cycle assessment. The SLCA participatory approach*. International journal of life cycle assessment.2014;19(8):1506-14. https://doi.org/10.1007/s11367-014-0758-6

198. MBWA. *Profit Margins in Building*. 2014. Master Builders Western Australia. Perth, Western Australia. Retrieved from: https://www.mbawa.com/profit-margins-in-building/. Accessed: 14-6-2019.

199. McCormack M, Treloar GJ, Palmowski L, Crawford R. *Modelling direct and indirect water requirements of construction*. Building resource and information. 2007:35, 156-162. https://doi.org/10.1080/09613210601125383.

200. Mendivil-Escalante JM, Gómez-Soberón JM, Almaral-Sánchez JL, Cabrera-Covarrubias FG. Metamorphosis in the Porosity of Recycled Concretes Through the Use of a Recycled Polyethylene Terephthalate (PET) Additive. Correlations between the Porous Network and Concrete Properties. Materials. 2017;10:176. https://doi.org/10.3390/ma10020176

201. Milman O. *Australia record biggest emissions drop in a decade as carbon tax kicks in*. 2014. In The Guardian. Australia. Retrieved from: https://www.theguardian.com/environment/2014/dec/24/australia-records-biggest-emissions-drop-in-a-decade-as-carbon-tax-kicks-in Accessed: 08-11-2018.

202. Mirabella N, Röck M, Saade MRM, Spirinckx C, Bosmans M, Allacker K, Passer A. *Strategies to improve the energy performance of buildings: A review of their life cycle impact*. Buildings. 2018:8, 105. https://doi.org/10.3390/buildings8080105

203. Motuziene V, Rogoža A, Lapinskiene V, Vilutiene T. *Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: A case study*. Journal of cleaner production. 2016;112:532-41. https://doi.org/10.1016/j.jclepro.2015.08.103

204. Muthusamy K, Mirza J, Zamri NA, Hussin MW, Budiea AMA. *Properties of high strength palm oil clinker lightweight concrete containing palm oil fuel ash in tropical climate*. Construction and building materials. 2018;199:163-77. https://doi.org/10.1016/j.conbuildmat.2018.11.211

205. Nance A. *Relative energy poverty in Australia, in School of Energy and Resource*. 2013. University College London (UCL Australia). Adelaide, Australia. Retrieved from: https://www.sacoss.org.au›relative-energy-poverty-Australia. Accessed: 10-11-2018.

206. Nath P, Sarker PK, Biswas WK. *Effect of fly ash on the service life, carbon footprint and embodied energy of high strength concrete in the marine environment*. Energy and buildings. 2018;158:1694-702. https://doi.org/10.1016/j.enbuild.2017.12.011

207. Nath P, Sarker PK. *Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition*. Construction and building materials. 2014;66:163-71. https://doi.org/10.1016/j.conbuildmat.2014.05.080

208. Nemet A, Klemeš JJ, Kravanja Z. *GHG emissions reduction by improving efficiency of utilities' transport and use and cross-sectorial energy integration*. Chemical Engineering Transactions, 2018:63, 19-24. https://doi.org/10.3303/CET1863004

209. Nemry F, Uihlein A, Colodel CM, Wetzel C, Braune A, Wittstock B, Hasan I, Kreißig J, Gallon N, Niemeier S et al. *Options to reduce the environmental impacts of residential buildings in the european union-potential and costs*. Energy and buildings. 2010:42, 976–984. https://doi.org/10.1016/j.enbuild.2010.01.009

210. NHSC, The key findings of 2011, *The state of supply report, the Australian government*. 2011. National Housing Supply Council, Australia, https://treasury.gov.au/programs-initiatives-consumerscommunity/the-national-housing-supply-council Accessed 13.05.2018.

211. Norman J, MacLean H, Kennedy CA. *Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions*. J. Urban Plan. Dev. 2006:132, 10–21. https://doi.org/10.1061/(ASCE)0733-9488(2006)132:1(10)

212. Nunen HV. Assessment of the Sustainability of Flexible Building: The Improved Factor Method: Service Life Prediction of Buildings in The Netherlands, Applied to Life Cycle Assessment. PhD Thesis, Universiteit Eindhoven, Eindhoven, The Netherlands, 2010.

213. O'Brien M, Doig A, Clift R. Social and environmental life cycle assessment (SELCA): approach and methodological development. International journal of life cycle assessment. 1996;1(4):231-37. https://doi.org/10.1007/BF02978703

214. Ofori G. *Construction industry and economic growth in Singapore*. Construction management and economics. 2006:6, 57-70. https://doi.org/10.1080/01446198800000007

215. Ofori G. *Indicators for measuring construction industry development in developing countries.* Building resource and information. 2001:29, 40-50. https://doi.org/10.1080/09613210150208787

216. Onat NC, Kucukvar M, Tatari O. Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings. International journal of life cycle assessment., 2014. 19: p. 1488-1505. https://doi.org/10.1007/s11367-014-0753-y

217. Ortiz O, Castells F, Sonnemann G. *Sustainability in the construction industry: A review of recent developments based on LCA.* Construction and building materials. 2009:23, 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

218. Ortiz-Rodríguez O, Castells F, Sonnemann G. *Life cycle assessment of two dwellings: One in spain, a developed country, and one in colombia, a country under development.* Science of total environment. 2010:408, 2435–2443. https://doi.org/10.1016/j.scitotenv.2010.02.021

219. Pant P. *How much you should budget for Home Maintenance*. 2019. Retrieved from: https://www.thebalance.com/home-maintenance-budget-453820 Accessed: 14-6-2019.

220. Passer A, Ouellet-Plamondon C, Keneally P, John V, Habert G. *Impact of future scenarios on building refurbishment strategies towards plus energy buildings*. SBE16 Zurich 2016:124, 2. https://doi.org/10.1016/j.enbuild.2016.04.008

221. Pelzeter A. *Building Optimization with Life Cycle Costs- the influence of calculation methods.* Journal of Facilities Management, 2007. 5(2): p. 115-128. https://doi.org/10.1108/14725960710751861

222. Persson J, Grönkvist S. Drivers for and barriers to low-energy buildings in Sweden. Journal of cleaner production. 2015;109:296-304. https://doi.org/10.1016/j.jclepro.2014.09.094

223. Petrovic B, Myhren JA, Zhang X, Wallhagen M, Eriksson O. *Life Cycle Assessment of Building Materials for a Single-family House in Sweden*. Energy Procedia. 2019;158:3547-52. https://doi.org/10.1016/j.egypro.2019.01.913

224. Pfister S, Koehler A, Hellweg S. *Assessing the environmental impacts of freshwater consumption in lca*. Environmental science and technology. 2009:43, 4098–4104. https://doi.org/10.1021/es802423e

225. Pickin J, Randell P. *National Waste report 2016*. Victoria (Australia). Department of the Environment and Energy. 2017. Retrieved from: https://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2016 Accessed 2018 Dec 18.

226. Pickin, J., Randell, P., Trinh, J., Grant, B., *National Waste Report 2018*. 2018, Department of the Environment and Energy, Australia Victoria, Australia. Retrieved from: http://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018 Accessed: 14-6-2019.

227. Pillai RG, Gettu R, Santhanam M, Rengaraju S, Basavaraj AS. *Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3)*. Cement and concrete research. 2019;118:111-9. https://doi.org/10.1016/j.cemconres.2018.11.019

228. Pope J, Annandale D, Morrison-Saunders A. *Conceptualising sustainability assessment.* Environmental Impact Assessment Review, 2004. 24(6): p. 595-616. https://doi.org/10.1016/j.eiar.2004.03.001

229. PRe'-Consultants, *SimaPro 8.4 LCA software*. 2016, Pre' Consultants,The Netherlands.

230. Prem PR, Verma M, Ambily PS. *Sustainable cleaner production of concrete with high volume copper slag*. Journal of cleaner production. 2018;193:43-58. https://doi.org/10.1016/j.jclepro.2018.04.245

231. Prieto AJ, Silva A, Brito JD, Macías-Bernal JM, Alejandre FJ. *Multiple linear regression and fuzzy logic models applied to the functional service life prediction of*

cultural heritage. Journal of cultural heritage. 2017;27:20-35. https://doi.org/10.1016/j.culher.2017.03.004

232. Qin L, Gao X, Chen T. *Recycling of raw rice husk to manufacture magnesium oxysulfate cement based lightweight building materials*. Journal of cleaner productions. 2018;191:220-32. https://doi.org/10.1016/j.jclepro.2018.04.238

233. Radcliffe JC. *The water energy nexus in australia-the outcome of two crises*. Water-Energy Nexus 2018:1,66–85. https://doi.org/10.1016/j.wen.2018.07.003

234. Rafieizonooz M, Salim MR, Hussin MH, Mirza J, Yunus SM, Khankhaje E. *Workability, compressive strength and leachability of coal ash concrete*. Chemical Engineering Transactions, 2017:56, 439-444. https://doi.org/10.3303/CET1756074

235. Rakha T, Moss TW, Shin D. A decade analysis of residential LEED buildings market share in the United States: Trends for transitioning sustainable societies. Sustainable cities and society. 2018;39:568-77. https://doi.org/10.1016/j.scs.2018.02.040

236. Ramesh T, Prakash R, Shukla KK. *Life cycle energy analysis of a residential building with different envelopes and climates in Indian context*. Applied energy 2012:89, 193–202. https://doi.org/10.1016/j.apenergy.2011.05.054

237. Rao RV. *A material selection model using graph theory and matrix approach*. Material and science engineering. 2006;431(1-2):248-55. https://doi.org/10.1016/j.msea.2006.06.006

238. Rashid AFA, Idris J, Yusoff S. *Environmental Impact Analysis on Residential Building in Malaysia using Life Cycle Assessment*. Sustainability. 2017:9, 329. http://doi.org/10.3390/su9030329

239. Rauf A, Crawford RH. *Building service life and its effect on the life cycle embodied energy of buildings.* Energy, 2015. 79: p. 140-148. https://doi.org/10.1016/j.energy.2014.10.093

240. Rauf A, Crawford RH. *The Effect of Material Service Life on the Life Cycle Embodied Energy of Multi-Unit Residential Buildings*. Paper presented at: World Sustainable Buildings WSB14 Conference; 2014 Oct 28-30; Barcelona, Spain.

241. Rauf A, Crawford RH. *The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia*. Architectural science review. 2013;56(3):252-61. https://doi.org/10.1080/00038628.2013.810548

242. Robert HG, Treloar JT. *An assessment of the energy and water embodied in commercial building construction.* In Proceedings of the 4th Australian Life Cycle Assessment Conference, Sydney, NSW, Australia, 23–25 February 2005; pp. 1–10. http://hdl.handle.net/11343/32211

243. Roh S, Tae S, Kim R. Development of a Streamlined Environmental Life Cycle Costing Model for Buildings in South Korea. Sustainability. 2018;10(6):1733. https://doi.org/10.3390/su10061733

244. Roosa SA. *Sustainable Development Handbook.* 2008. Fairment Press.Lilburn,GA, USA. Fairment Press.

245. Rouwette R. *LCA of Brick Products*. 2010. Think Brick Australia: Melbourne, Australia.

246. Saccani A, Manzi S, Lancellotti I, Lipparini L. *Composites obtained by recycling carbon fibre/epoxy composite wastes in building materials*. Construction and building materials. 2019;204:296-302. https://doi.org/10.1016/j.conbuildmat.2019.01.216

247. Saldaña-Márquez H, Gómez-Soberón JM, Arredondo-Rea SP, Gámez-García DC, Corral-Higuera R. Sustainable social housing: *The comparison of the Mexican funding program for housing solutions and building sustainability rating systems*. Building and Environment. 2018;133:103-22. https://doi.org/10.1016/j.buildenv.2018.02.017

248. Saldaña-Márquez H, Gómez-Soberón JM, Arredondo-Rea SP, Rosell-Balada G. *The passivhaus standard in the mediterranean climate: Evaluation, comparison and profitability*. Journal of green building. 2015;10(4):55-72. https://doi.org/10.3992/jgb.10.4.55

249. Samaratunga M, Ding L, Bishop K, Prasad D, Yee KWK. *Modelling and Analysis of Post-Occupancy Behaviour in Residential Buildings to Inform Basix Sustainability Assessments in NSW.* Procedia Engineering. 2017:180, 343–355. https://doi.org/10.1016/j.proeng.2017.04.193

250. Santos AC, mendes P, Teixeira MR. *Social life cycle analysis as a tool for sustainable management of illegal waste dumping in municipal services*. Journal of cleaner production. 2019;210:1141-9. https://doi.org/10.1016/j.jclepro.2018.11.042

251. Santos P, Pereira AC, Gervásio H, Bettencourt A, Mateus D. *Assessment of health and comfort criteria in a life cycle social context: Application to buildings for higher education.*

Journal of cleaner production. 2017;123:625-48. https://doi.org/10.1016/j.buildenv.2017.07.014

252. Sawe BE. *The World's Driest Continent*. 2018. Retrieved from: https://www.worldatlas.com/articles/which-is-the-world-s-driest-continent.html Accessed. 15-9-2019.

253. Sayed M, Sajid S, Sawant, Priyadarshi H. Financial feasibility analysis of water conservation components in mass housing projects: Suburban Indian Case review. Journal of architectural engineering. 2016;22(2):e04016001-1. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000200

254. Schmidt M, Crawford RH. *A framework for the integrated optimisation of the life cycle greenhouse gas emissions and cost of buildings*. Energy and buildings. 2018;171:155-67. https://doi.org/10.1016/j.enbuild.2018.04.018

255. Settanni E, Tassielli G, Notarnicola B. *Life Cycle Costing (LCC)*. In: Spellerberg I, Fogel DS, Fredericks SE, Butler Harrington LM, editors. Berkshire, encyclopaedia of sustainability 6/10: Measurements, Indicators, and Research Methods for Sustainability. Great Barrington (US): Berkshire Publishing Group; 2012. p. 225-7.

256. Seven questions to sustainability: how to assess the contribution of mining and minerals activities. International Institute for Sustainable Development, 2002: Winnipeg.

257. Shen LY, Hao JL, Tam VW, Yao H. A checklist for assessing sustainability performance of construction projects. Journal of Civil Engineering and Management,. 2007;13(4):273-81. https://doi.org/10.1080/13923730.2007.9636447

258. Sherif YS, Kolarik WJ. *Life cycle costing: concept and practice.* International journal of management science. 1981:9, 287-291. https://doi.org/10.1016/0305-0483(81)90035-9

259. Siddique R, Singh G, Belarbi R, Ait-Mokhtar K, Kunal. Comparative investigation on the influence of spent foundry sand as partial replacement of fine aggregates on the properties of two grades of concrete. Construction and building materials. 2015;83:216-22. https://doi.org/10.1016/j.conbuildmat.2015.03.011

260. Silvestre JD, Silva A, de Brito J. *Uncertainty modelling of service life and environmental performance to reduce risk in building design decisions*. Journal of civil engineering and management. 2015:21, 308–322. https://doi.org/10.3846/13923730.2014.890649

261. Singh D, Tion RK. Development of life cycle costing framework for highway bridges in Myanmar. International journal of project management. 2005;23(1):37-44. https://doi.org/10.1016/j.ijproman.2004.05.010

262. Souza J, Silva A, Brito JD, Bauer E. *Service life prediction of ceramic tiling systems in Brasília-Brazil using the factor method*. Construction and building materials. 2018;192:38-49. https://doi.org/10.1016/j.conbuildmat.2018.10.084

263. Spang ES, Moomaw WR, Gallagher KS, Kirshen PH, Marks DH. *The water consumption of energy production: An international comparison*. Environmental resource letters. 2014:9, 1–14. https://iopscience.iop.org/article/10.1088/1748-9326/9/10/105002

264. Spiekermann C, Donath D. *Digital support of material and product selection in the architectural design and planning process*. In: Gürlebeck K, Könke C, editors. Proceeding of 17th International Conference on the Applications of Computer Science and Mathematics in Architecture and Civil Engineering, 2006 Jul 12-14, Weimar, Germany. Bauhaus-University Weimar; Weimar (Germany). 2006. p. 1-10.

265. Synergy. *Standard Electricity Prices and Charges*. 2019. Synergy Energy. Perth, Australia. Retrieved from: https://www.synergy.net.au›media›Files›PDF-Library›Standard_Electricity_Prices_Charges_brochure.pdf Accessed: 14-6-2019.

266. Tam VWY, Senaratne S, Le KN, Shen LY, Perica J, Illankoon IMCS. Life-cycle cost analysis of green-building implementation using timber applications. Journal of cleaner production. 2017;147:458-69. https://doi.org/10.1016/j.jclepro.2017.01.128

267. Tam WV, Le KN, Tran CN, Wang JY. A review on contemporary computational programs for Building's life-cycle energy consumption and greenhouse-gas emissions assessment: An empirical study in Australia. Journal of cleaner production. 2018;172:4220-30. https://doi.org/10.1016/j.jclepro.2017.11.130

268. Tamimi A, Hassan NM, Fattah K, Talachi A. *Performance of cementitious materials produced by incorporating surface treated multiwall carbon nanotubes and silica fume*. Construction and building materials. 2016;114:934-45. https://doi.org/10.1016/j.conbuildmat.2016.03.216

269. Tayyab A, Thaheem MJ. *Developing a residential building-related social sustainability assessment framework and its implications for BIM*. Sustainable Cities and Society, 2017. 28: p. 1-15. https://doi.org/10.1016/j.scs.2016.08.002

270. Tepper T. *More than meets the mortgage: Survey finds the hidden costs of home ownership.* 2018. Retrieved from: https://www.bankrate.com/mortgages/home-services-survey-0218/ Accessed: 14-6-2019.

271. Tettey UYA, Dodoo A, Gustavsson L. Effect of different frame materials on the primary energy use of a multi storey residential building in a life cycle perspective. Energy and buildings. 2019;185(15):259-71. https://doi.org/10.1016/j.enbuild.2018.12.017

272. Thiers S, Peuportier B. *Energy and environmental assessment of two high energy performance residential buildings*. Buildinging and environment. 2012:51, 276-284. http://doi.org/10.1016/j.buildenv.2011.11.018.

273. Thinkstep. GaBi Databases 2019. Retrieved from: http://www.gabi-software.com/databases/gabi-databases/. Access 2019 Apr 28.

274. Thomas M. *Housing affordability in Australia: Australian Society. 2016.* Parliamentary Library Briefing book- 45th Parliament. Retrieved from: https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/BriefingBook45p/HousingAffordability Accessed: 14-6-2019.

275. Treloar G, Fay R, Love PD, Iyer-Raniga U. *Analysing the life-cycle energy of an australian residential building and its householders*. Building research and information. 2000: 28, 184–195. https://doi.org/10.1080/096132100368957

276. Trimetric, GD-CN0004GO: Key Highlights from Global Construction Outlook 2021. 2018: London (UK): Construction Intelligence Centre, Timetric, London, UK.

277. Tripathi B, Misra A, Chaudhary S. *Strength and abrasion characteristics of ISF slag concrete*. Journal of materials in civil engineering. 2013;25(11):1611-8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000709

278. Uçtuğ FG, Ağralı S. Simple nonlinear optimization-based selection of insulation material and window type in Turkey: effect of heating and cooling base temperatures. Journal of Green Building. 2017;9(6):79-94. https://doi.org/10.3992/1943-4618.12.2.79

279. Umasabor RI, Okovido JO. *Fire resistance evaluation of rice husk ash concrete*. Heliyon. 2018;4(12):e01035. https://doi.org/10.1016/j.heliyon.2018.e01035

280. UNEP, *Eco-Housing guidelines for Tropical regions*. 2006, Regional Resource Centre for Asia and the Pacific. United Nation Environment Programme, Bangkok, Thailand. Retrieved from: www.rrcap.ait.ac.th. Accessed: 10-01-2019.

281. UNEP, *Guidlines for Social Life Cycle Assessment of Products*. 2009. Life Cycle initiative, United Nations Environment Programme. Paris, France. Retrieved from: https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca. Accessed: 30-06-2018.

282. UNEP, *Introduction to Cleaner Production Concepts and Practices*. 2015, Division of Technology, Industry and Economic: Institute of Environmental Engineering (APINI) Kaunas University of Technology, Lithuanis. Retrieved from: http://www.un.org/esa/sustdev/sdissues/technology/cleanerproduction.pdf Accessed: 05-01-2020.

283. UNEP, *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication-A synthesis for Policy Makers*. St-Martin-Bellevue (France): United Nations Environment Programme; 2011. Retrieved from: https://sustainabledevelopment.un.org/content/documents/126GER_synthesisen.pdf. Accessed: 25-12-2018.

284. UNEP, *Towards a Life Cycle Sustainability Assessment. Making informed choices on Products.* 2012. United Nations Environment Programme. Paris, France. Retrieved from: https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/life-cycle-sustainability-assessment. Accessed 2018 Jun 30.

285. UNEP, *Towards zero-emission, efficient, and resilient buildings and construction sector*, in Global status report. 2018, Global Allience for Buildings and Construction (GABC), United Nation Environment Programme, Paris, France. Retrieved from: https://www.globalabc.org/uploads/media/default/0001/01/f64f6de67d55037cd9984cc29308f3609829797a.pdf Accessed: 30-06-2018.

286. UNEP, *Transforming our World: The 2030 Agenda for Sustainable Development,* Paris agreement. United nations framework convention on climate change (UNFCCC), United nations. Le bourget, paris, France. https://unfccc.int 2015, Retrieved from: https://unfccc.int › sites › default › files › english_paris_agreement. Accessed: 10-01-2019.

287. Vale M, Pentalone M, Bragagnolo M. *Collaborative perspective in bio-economy development: A mixed method approach*. 2017. IFIP Advances in Information and Communication Technology, 506, 553-563. https://doi.org/10.1007/978-3-319-65151-4_49.

288. Vass N. *Western Australia Energy Fact Sheet*. Retrieved from: http://www.australianpowerproject.com.au/western-australia-energy-fact-sheet/ Accessed on: 19 December 2018

289. Vieira, M. *Hotspot analysis in the PEF approach*. Quantifying sustaianbility 2016; Retrieved from: https://www.pre-sustainability.com/news/pef-series-hotspot-analysis-in-the-pef-approach Accessed: 10-05-2020.

290. Vitale P, Arena N, Di Gregorio F, Arena U. *Life cycle assessment of the end of life phase of a residential building*. Waste management. 2017:60, 311–321. https://doi.org/10.1016/j.wasman.2016.10.002

291. Vitale P, Arena N, Gregorio F, Arena U. *Life cycle assessment of the end-of-life phase of a residential building*. Waste management. 2017;60:311-21. https://doi.org/10.1016/j.wasman.2016.10.002

292. Vitale P, Arena U. *An attributional life cycle assessment for an italian residential multifamily building*. Environmental technology. 2018:39, 3033–3045. https://doi.org/10.1080/09593330.2017.1371252

293. WA. *Buy Local Policy: A Western Australian Government commitment to supporting local business*. 2002. Department of housing and works. Government of Western Australia. West perth, Western Australia. Accessed: 14-6-2019. Retrieved from: https://www.finance.wa.gov.au/cms/uploadedFiles/Building_Management_and_Works/Consultant_Information/Buy_Local_Policy_July_2002(1).pdf

294. Wang J, Pan W. *Influencing parameters of the life cycle cost-energy relationship of buildings*. Journal of Green Building. 2018;13(4):103-21. https://doi.org/10.3992/1943-4618.13.4.103

295. Wang Y, Suraneni P. *Experimental methods to determine the feasibility of steel slag as supplementary cementitious materials*. Construction and building materials. 2019;204:458-67. https://doi.org/10.1016/j.conbuildmat.2019.01.196

296. WBG. *Fossil Fuel energy consumption (% of total)*. 2019. World Bank Group. The International Energy Agency. Paris, France. Retrieved from: https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS?locations=AU Accessed: 08-01-2019.

297. Werner F, Richter K. *Wooden building products in comparative LCA*. International journal of life cycle assessment. 2007, 12, 470–479. https://doi.org/10.1065/lca2007.04.317

298. Wong IL, Perera S, Eames PC. Goal directed life cycle costing as a method to evaluate the economic feasibility of office buildings with conventional and TI-facades. Construction management and economics. 2010:28, 715-735. https://doi.org/10.1080/01446191003753867

299. WWF. *Environmental problems in Australia: Issues with no end in sight.* 2019. World Wide Fund for Nature. Retrieved from: http://wwf.panda.org/wwf_offices/australia/environmental_problems_in_australia/ Accessed: 18-7-2019.

300. WWF. *Impacts of global warming.* 2019. World Wide Fund for Nature. Retrieved from: https://www.wwf.org.au/what-we-do/climate/impacts-of-global-warming#gs.4v3zax Accessed: 18-7-2019.

301. Yazdanbakhsh A, Bank LC, Baez T, Wernick I. *Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area*. International journal of life cycle assessment. 2018;23(6):1163-73. https://doi.org/10.1007/s11367-017-1360-5

302. Yoshida J, Sugiura A. The Effects of Multiple Green Factors on Condominium Prices. Journal of real estate, finance and economics. 2015;50(3):412-37. https://doi.org/10.1007/s11146-014-9462-3

303. Zhou C, Dai X, Wang R, Huang J. Indicators for evaluating sustainable communities: A review. *Acta Ecologica Sinica*. 2011;31(16):4750-9

304. Zuo J, Zhao ZY. *Green building research current status and future agenda: A review*. Renewable and sustainable energy review. 2014;30:271-81.