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

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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.

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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	×	×	✓	×	×	×	✓

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

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

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%

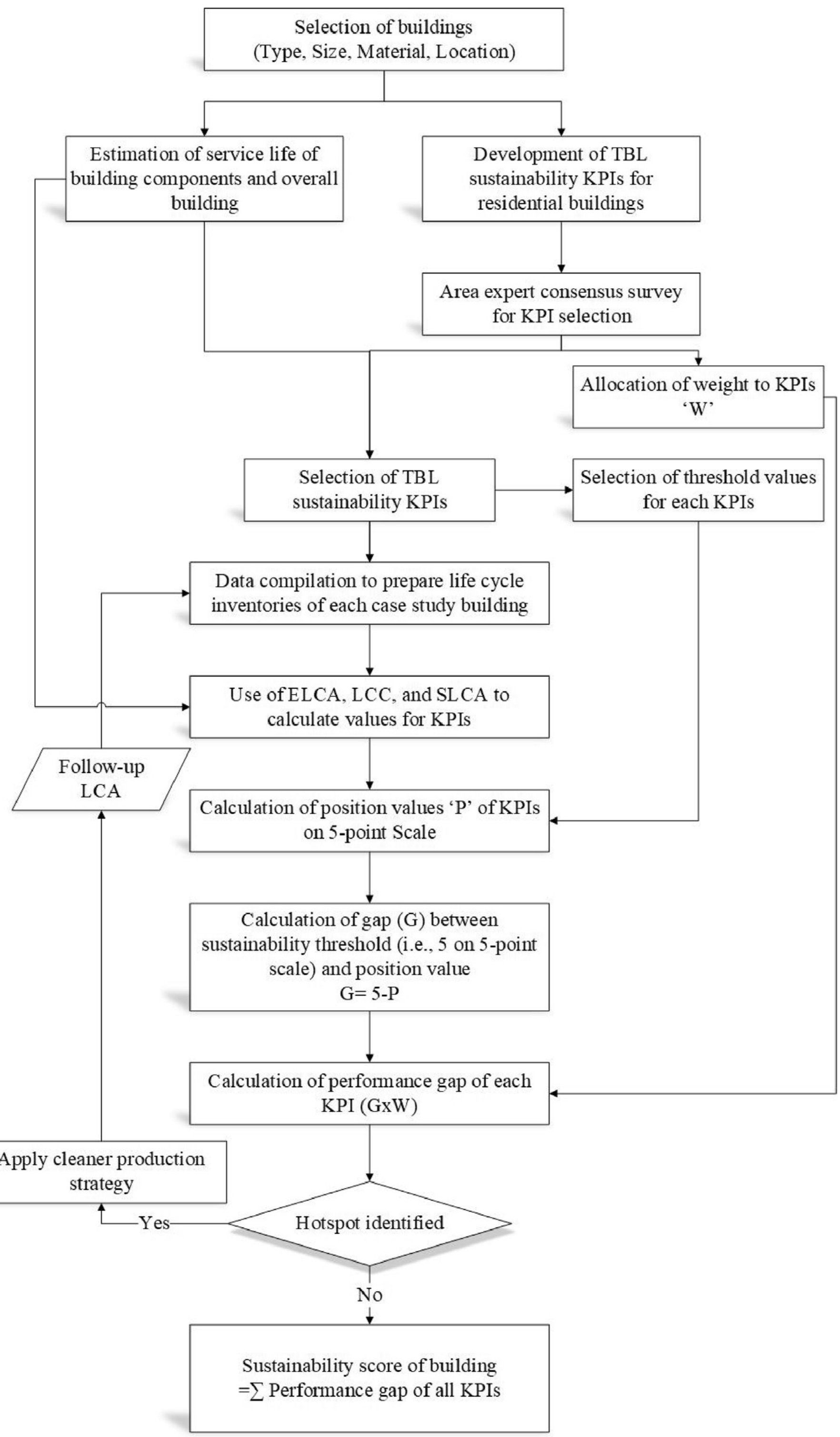

Fig. 1. LCSA implementation framework.

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 $\pm$ 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

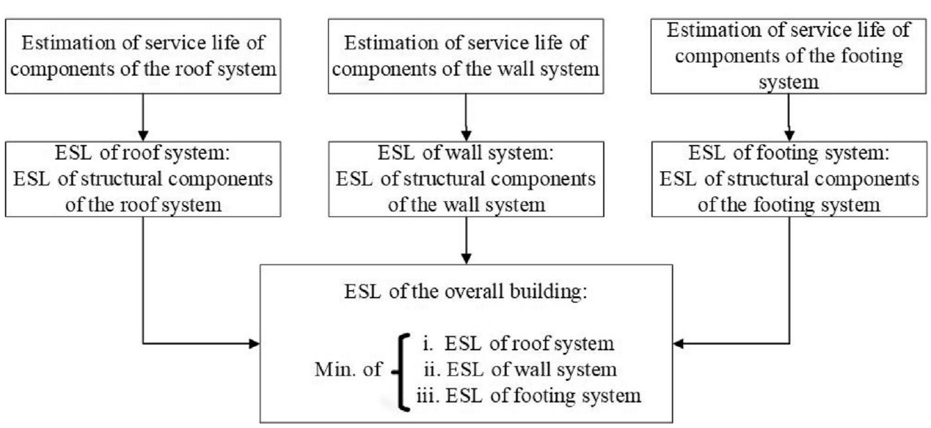

Fig. 2. Flow chart for service life estimation of the overall Building.

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.

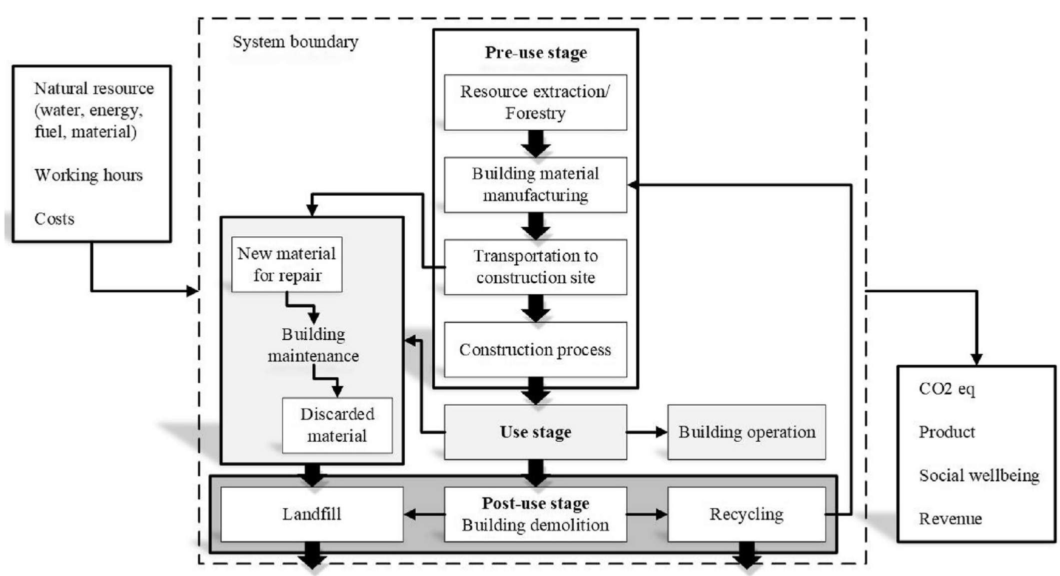

Fig. 3. System boundary of LCSA framework (Shade colors present processes included in one stage). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

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)

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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

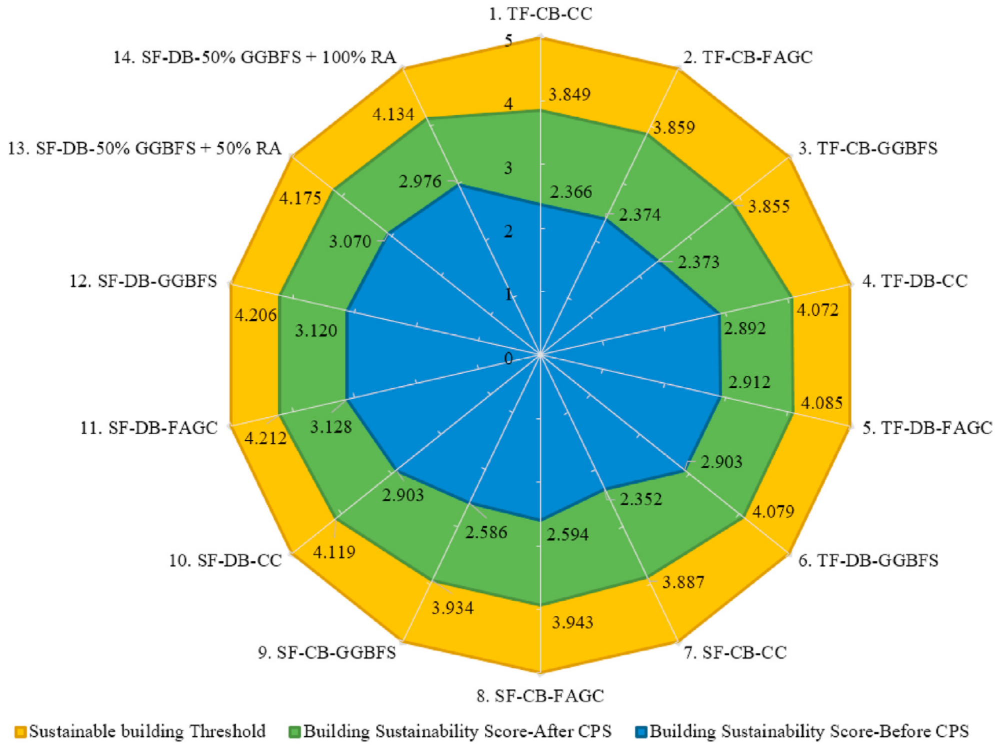
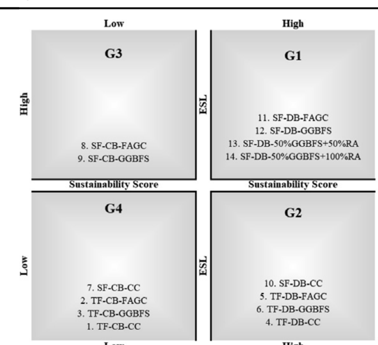


Fig. 4. Sustainability score of case study buildings: Before and after applying CPS.

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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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2021.100109.

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