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Research article

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

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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.

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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.

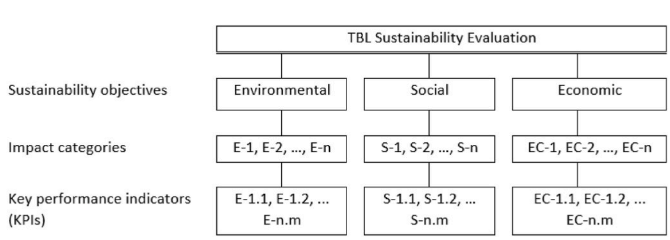

Fig. 1. Hierarchy of TBL sustainability evaluation (Janjua et al., 2019c); E−environmental; S- Social; EC- Economic.

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

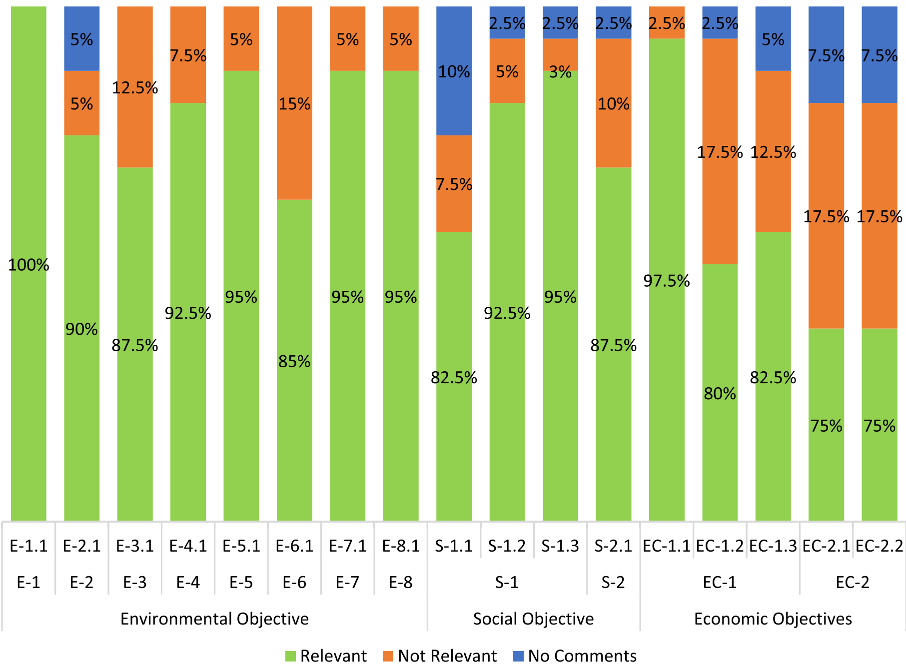

Fig. 2. Level of relevance for TBL KPIs (E−1 Climate change; E−2 Air quality; E−3 Water quality; E−4 Ecological footprint; E−5 Water scarcity; E−6 Energy; E−7 Abiotic resource depletion; E−8 Waste generation; S-1 Intra-generational equity; S-2 Inter-generational equity; EC-1 User perspective; EC-2 Developer 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).

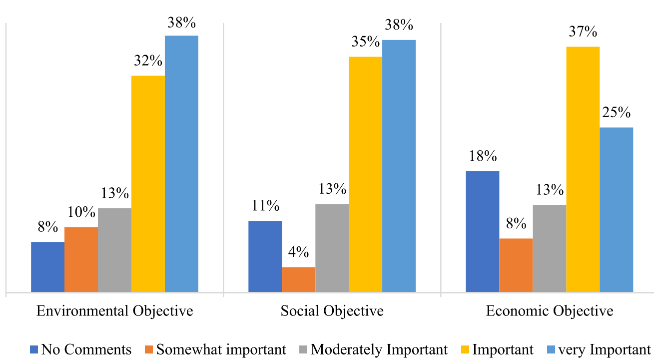

Fig. 3. Level of importance for TBL Objectives for Building Sustainability.

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).

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

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 ($853 \times 52 \times 5\% =$ 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).

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

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).

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

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

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

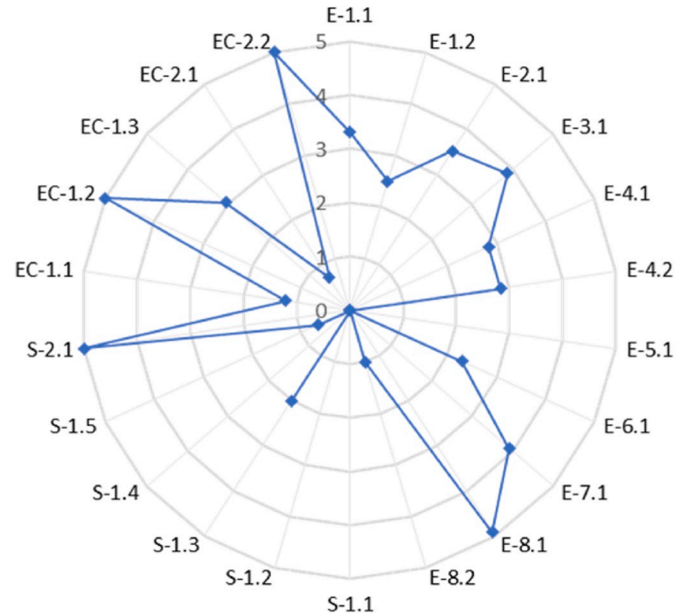

Fig. 4. Gap 'G' of KPIs on 5-point Likert Scale (E−1.1 Carbon footprint; E−1.2 Resilience and adaptation; E−2.1 Acidification; E−3.1 Eutrophication; E−4.1 Land use; E−4.2 Loss of biodiversity; E−5.1 Cumulative embodied water consumption; E−6.1 Cumulative energy demand; E−7.1 Cumulative fossil energy 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

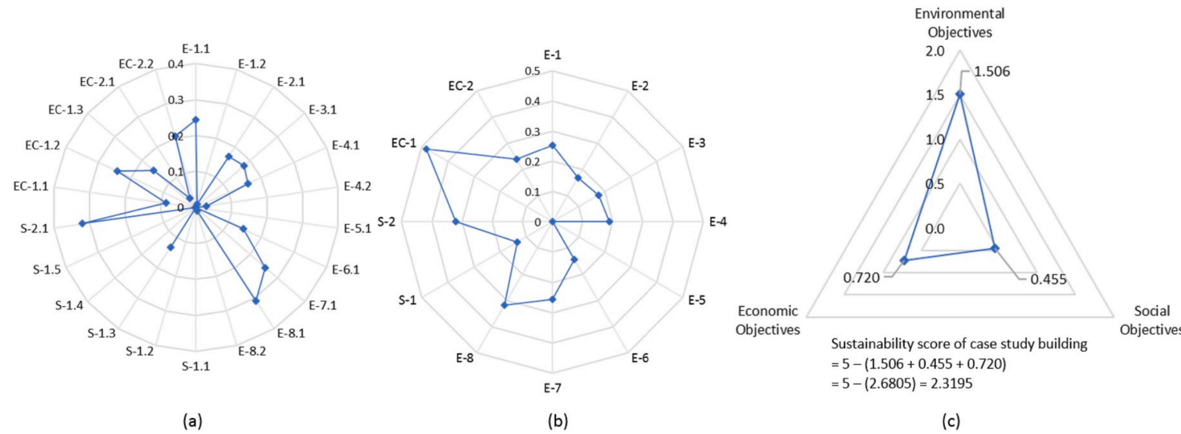

Fig. 5. (a) Performance gaps of KPIs = G × W; (b) Performance gaps of impact categories; (c) Performance gaps of sustainability objectives = ∑ G × W; (E−1 Climate change; E−2 Air quality; E−3 Water quality; E−4 Ecological footprint; E−5 Water scarcity; E−6 Energy; E−7 Abiotic resource depletion; E−8 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

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