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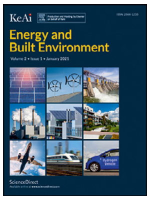

What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings

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ABSTRACT

Residential buildings are one of the major contributors to climate change due to their significant impacts on global energy consumption. Hence, most countries have introduced regulations to minimize energy use in residential buildings. To date, the focus of these regulations has mainly been on operational energy while excluding embodied energy. In recent years, extensive studies have highlighted the necessity of minimizing both embodied energy and operational energy by applying the life-cycle energy assessment (LCEA) approach. However, the absence of a standardized framework and calculation methodology for the analysis of embodied energy has reportedly led to variations in the LCEA results. Retrospective research endeavoured to explore the causes of variations, with a limited focus on calculating embodied impacts. Despite the undertaken attempts, there is still a need to investigate the key parameters causing variations in LCEA results by examining methodological approaches of the current studies toward quantifications of embodied and operational energies. This paper aims to address three primary questions: 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, 40 LCEA studies representing 157 cases of residential buildings across 16 countries have been critically reviewed. The findings reveal four principal categories of parameters that potentially contribute to the varying results of LCEAs: system boundary definition, calculation methods, geographical context, and interpretation of results. This paper also proposes a conceptual framework to minimize variations in LCEA studies by standardizing the process of conducting LCEAs.

1. Introduction

Residential buildings have a higher share in global energy consumption compared to non-residential buildings due to the larger portion both in terms of number of buildings and floor areas [1]. In 2017, the International Energy Agency held residential buildings responsible for nearly 22% of total energy use worldwide [2]. The projections made by the recent study also warn about further increasing global energy consumption in residential buildings within the next few decades owing to rapid urbanization, population growth, and economic development [3,95]. Correspondingly, most countries have strengthened their measures to decrease energy use in residential buildings by legislating various building-related regulations. As an example, the requirements introduced by the Danish government for operational energy use in new buildings have been reduced to less than one third over the last 25 years [4]. In general, the primary objective of such regulations is to improve buildings' thermal performance by imposing minimum requirements on their physical characteristics [5]. Despite the potential of these regulatory standards to minimize operational energy, their implementations can paradoxically result in increasing the total life-cycle energy use of buildings due to ignoring the embodied impacts [6,7]. This is echoed in the findings of Stephan et al. [6] who assessed the life-cycle energy performance of a Belgian passive house. Their results indicated that current certifications developed to promote energy efficiency in buildings cannot assure the reduction of the total energy consumption since embodied impacts are excluded. They also showed that the embodied energy of passive houses may constitute up to 77% of the total building life-cycle energy use over 100 years.

In recent years, academic studies have given more attention to the necessity of minimizing energy use throughout the entire building life cycle by including both embodied and operational energies. To demonstrate the significance of embodied impacts, numerous detailed cases of buildings have been developed by academics using the life-cycle energy assessment (LCEA) approach. Nevertheless, this surge of research has failed to alter the attitude of policymakers toward considering the importance of buildings' embodied energy when planning for the betterment of built environment [8]. Retrospective research has primarily placed the blame on the analysis of embodied energy where the absence of a standardized framework and calculation methodology often leads

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to displaying a significant spread of results in LCEA analyses [9]. Over the last decades, significant efforts have been made to standardize the application of life-cycle assessment in buildings through setting several international standards such as ISO 21929-1 [10], ISO 21931-1 [11], and the European standards developed by Technical Committee TC350, including EN 15643-2 [12] and EN 15978 [13]. However, there is considerable evidence indicating variations in the results of LCEA analyses [4,8,14,15]. Previous research has endeavoured to explore sources of variations, with a focus given only to the calculation of buildings' embodied impacts [16, 17]. Despite the undertaken attempts, there is still a need to investigate the key parameters causing variations in LCEA results by examining methodological approaches of the current studies toward quantifications of embodied and operational energies. Therefore, this paper aims to address three primary questions: 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, we first analysed 40 LCEA papers in order to address the two first questions. This paper then puts forward proposals for standardization of LCEA application in residential buildings by developing a conceptual framework in order to address the third question.

2. An overview of LCEA

Life-cycle assessment (LCA) is an approach toward identification and quantification of environmental loads attributed to services, products, or processes throughout their entire life cycles [18]. The International Organization for Standardization (ISO) introduced the first series of standards (14040, 14041, 14042, and 14043) relating to LCA between 1997 and 2000 [19]. In 2006, these standards were updated by amalgamating prior versions, which led to the current ISO standards 14040 and 14044 [20,21]. These standards set up a framework to perform LCA, consisting of four major steps: (1) defining the goals and scope, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment, and (4) interpretation. The first step involves establishing the goals and scope of the assessment, defining the system boundary, and specifying the quality criteria for inventory data. This is followed by an LCI, where the procedure for collecting and synthesizing data related to energy flows should be determined at each individual stage of a product's life cycle. The next step, life-cycle impact assessment, involves quantifying the environmental impacts of materials and energy flows and assigning them to their corresponding environmental impact categories. In the last step, the results of the LCA are interpreted in relation to the study's goals and scope, and recommendations are made for decision-making purposes.

LCEA is a version of the LCA that considers only the energy inputs at all stages of a building's life cycle [22,23]. Adopting this approach to assess a building's energy performance means quantifying its total energy consumption, by considering both operational and embodied energy (Fig. 1). Embodied energy refers to the amount of energy used for material production (i.e. extraction of raw materials and material manufacturing), assembly (i.e. construction/installation), replacement and maintenance, end-of-life (EOL) processes and transportation required between any of these steps [18,23,24]. The amount of energy consumed in the form of thermal (i.e. heating and cooling) and non-thermal loads (i.e. domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking) over a building's lifespan is known as operational energy [18,23,24].

3. Research methodology

This paper adopts a systematic literature review approach to identify published materials relating to the LCEA application in residential buildings. The review commenced with carrying out a comprehensive searching exercise through multiple databases, namely Web of Science, ProQuest, and Scopus. Using these platforms enables researchers to gain access to numerous international journals, based on which a systematic literature review can be conducted [25,26]. The initial search was conducted using certain keywords, as tabulated in Table 1. The types of searched materials were 'articles' and 'reviews'; and the timespan set for the search was between 1996 and 2020, in which the starting year coincided with the publication of the first series of ISO standards. As a result, more than 750 publications were identified to meet the initial criteria.

An initial screening check was performed based on the titles, abstracts, and conclusions of the identified materials in order to make a preliminary decision about the suitability of identified articles for inclusion. At this stage, certain criteria were considered to weed out irrelevant materials. First, publications written in any language other than English were filtered out, as well as non-peer reviewed articles. In addition, only studies with the application of LCEA approach in 'residential' buildings were considered for further analyses. Considering these criteria led to downsizing the collected materials to about 260.

After the initial screening, the contents of all remaining articles were checked qualitatively to ensure that only those falling within the scope of this paper were selected. Herein, studies that focused solely on embodied energy analysis were filtered out due to their limited approaches for the assessment of buildings' life-cycle energy use. In addition, this review only retained LCEA studies that measured buildings' energy performance based on primary energy because the primary energy is a better measure of the environmental impacts of buildings [27,28]. As a result, 40 papers that analysed 157 cases of residential buildings across 16 countries were selected for detailed examinations. Summaries of these papers were exported to *Excel Spreadsheets* for further analysis (See the Appendix). In this paper, we considered all types of residential buildings for the analysis, i.e. energy-efficient buildings, conventional buildings, high- and low-rise buildings, and urban and suburban buildings. This review considers different versions of a building analysed in one source as one case study.

Following the examination of the reviewed studies, a conceptual framework was developed. This framework primarily aims to simplify the intertwined processes involved in an LCEA by providing a clear description of the system boundary.

4. Analysis and results

The selected studies are analysed based on four main criteria: i) system boundary definitions, ii) methods applied for quantification of embodied energy, iii) methods applied for calculation of operational energy, and iv) approaches taken toward interpreting LCEA results. The Appendix includes a detailed list of analyses carried out in this paper.

4.1 Definition of system boundary

System boundary definition denotes the act of determining a set of variables that distinguish the system under study from other systems in an environment [16,23]. In this paper, the approaches of analysed studies toward delineating system boundaries are analysed to identify: i) the building life-cycle stages excluded by the system boundary, ii) the building components and their systems included within the system boundary to calculate embodied impacts, iii) the parameters included within the system boundary to calculate operational energy, iv) the building lifespan, and v) the key assumptions made by the reviewed studies.

4.1.1. Exclusion of life cycle stages

The building life cycle stages consist of raw material extraction, material manufacturing and processing, construction/installation, operation, maintenance and replacement, transportations between any of these steps, and EOL (Fig. 1). A whole LCEA then refers to the one that accounts for energy consumption throughout the entire buildings' life

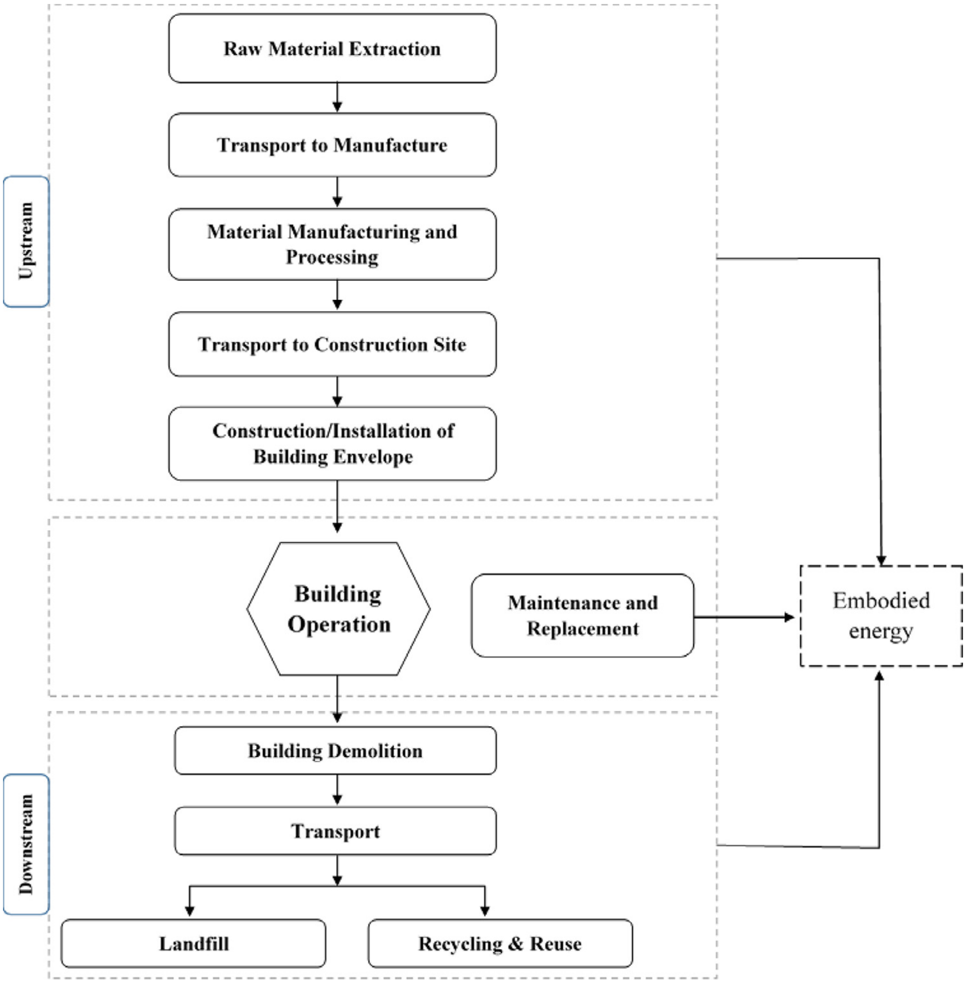

Fig. 1. Building life cycle energy

Table 1
Keywords applied during the initial search

Keywords used to search for life-cycle energy assessment studies
Building life-cycle assessment; building life-cycle energy assessment; building energy performance; building life-cycle impact assessment; building life-cycle environmental assessment; building life-cycle; energy efficient buildings; residential buildings; building primary energy consumption; and building embodied energy analysis.

Table 2
Exclusion of building life cycle stages

Stages of building life cycle	Number of studies	
Production	Raw material extraction	0
	Transport to manufacture	1
	Manufacturing and processing	0
Assembly	Transport to construction site	9
	Construction/installation	11
Maintenance	Maintenance and replacement	14
End of life	De-construction/demolition	23
	Transport	23
	Disposal	24
Reuse, recovery, recycling		26

cycles. Table 2 shows the number of reviewed studies that excluded building life-cycle stages from the system boundary.

The review reveals that 32% of the studies carried out a whole LCEA, while others omitted certain life cycle stages. The processes involved in the EOL stage (i.e. de-construction, transport, and disposal of construction wastage) were excluded by 58% of the studies. This exclusion was commonly justified due to i) the minor contribution of this stage to the total life-cycle energy use of buildings, and ii) uncertainties about deconstruction practices at the EOL [6,29–38]. Amongst those that accounted for energy consumption at EOL, the common trend was to base the calculation on assumptions. For instance, Crawford [39] assumed that the energy needed for building deconstruction and disposal of its materials equated to 1% of the house's total life-cycle energy demand.

In addition, maintenance and replacement (also known as recurrent embodied energy) was excluded by 35% of the studies. Understanding the impacts of recurrent embodied energy is important for many reasons, such as making informed choices about building design and materials, and understanding the impact of the maintenance and management of buildings [9]. Studies have also shown that recurrent embodied energy may have a substantial effect on the total life-cycle energy use; thus, ignoring its impact can underestimate the environmental burdens of buildings. For instance, Stephan and Stephan [33] showed the recurrent embodied energy of a residential building in Lebanon may constitute up to 31% of the total building embodied energy. Crawford [39] also estimated that recurrent embodied energy of an Australian building can be up to 22% of the total building life-cycle energy demands. Further-

Table 3
Energy saved at different stages through reusing, recovering and recycling building materials (kWh/m^2.year)

Reference	Building characteristics	Energy saved at production stage	Energy saved at construction stage	Energy saved at EOL stage	Total energy saving	Total energy saving (%)
Gustavsson et al. [50]	Wood-framed apartment	23.64	NA	11.42	35.06	17.84
Dodoo and Gustavsson [51]	Conventional building with electric heated system	7.78	NA	7.92	15.70	5.36
	Conventional building with heat pump heated system	7.78	NA	7.92	15.70	7.27
	Conventional building with district heated system	7.78	NA	7.92	15.70	7.79
	Passive building with electric heated system	8.0	NA	8.06	16.06	6.05
	Passive building with heat pump heated system	8.0	NA	8.06	16.06	7.77
	Passive building with district heated system	8.0	NA	8.06	16.06	8.22
Cellura et al. [52]	Net zero energy building	NA	NA	22.62	22.62	10.83
Dodoo et al. [53]	Cross laminated timber structure with heat pump heated system	20.92	1.44	11.80	34.16	16.85
	Beam-and-Column system structure with heat pump heated system	20.22	1.26	10.90	32.38	15.35
	Modular timber structure with heat pump heated system	10.18	1.10	9.04	20.32	9.73
	Cross laminated timber structure with district heated system	20.92	1.44	11.80	34.16	17.81
	Beam-and-Column system structure with district heated system	20.22	1.26	10.90	32.38	16.34
	Modular timber structure with district heated system	10.18	1.10	9.04	20.32	10.32
Tettey et al. [54]	Standard building with concrete system	1.92	NA	5.63	7.55	4.90
	Standard building with cross laminated timber structure	20.98	NA	10.67	31.65	21.24
	Standard building with modular timber structure	8.075	NA	6.30	14.38	9.75
	Passive building with concrete system	1.92	NA	5.63	7.55	8.55
	Passive building with modular timber structure	8.53	NA	6.57	15.10	18.37
Zhan et al [55]	Prefabricated building	NA	NA	4.99	4.99	6.84
Thormark [43]	Low energy building	NA	NA	31.12	31.12	36.75
Blengini and Di Carlo [56]	Low energy house	NA	NA	11.11	11.11	13.74
Takano et al. [46]	Detached house with light weight timber structure	NA	NA	21.96	21.96	17.95
	Row house with light weight timber structure	NA	NA	15.17	15.17	15.56
	Townhouse with light weight timber structure	NA	NA	15.42	15.42	17.77
	Apartment block with light weight timber structure	NA	NA	12.96	12.96	18.96
	Detached house with cross laminated timber structure	NA	NA	35.06	35.06	26.03
	Row house with cross laminated timber structure	NA	NA	29.04	29.04	26.93
	Townhouse with cross laminated timber structure	NA	NA	31.9	31.9	32.60
	Apartment block with cross laminated timber structure	NA	NA	28.77	28.77	37.48
	Detached house with reinforced concrete panel structure	NA	NA	14.04	14.04	10.89
	House with reinforced concrete panel structure	NA	NA	10.62	10.62	10.63
	Townhouse with reinforced concrete panel structure	NA	NA	9.31	9.31	10.48
	Apartment block with reinforced concrete panel structure	NA	NA	6.95	6.95	10.64
	Detached house with steel structure	NA	NA	14.66	14.66	11.68
	Row house with steel structure	NA	NA	10.67	10.67	10.70
	Townhouse with steel structure	NA	NA	9.81	9.81	11.04
	Apartment block with steel structure	NA	NA	7.72	7.72	11.08

Note: The detailed numerical values for recycling/reusing potentials were given by nine studies out of fourteen.

more, this paper found that the construction/installation stage was excluded by 27% of the studies. This was mainly due to its perceived minor impact on total building life-cycle energy use [30,31,40,41] and the difficulty in gathering data on the energy consumption of on-site construction operations [37]. Some studies did not discuss the reasons for its exclusion [42–46]. Transportation of materials to the construction site was also excluded by 22% of the reviewed studies, which was mainly justified by its minor impact on total life-cycle energy use.

The reuse, recovery, and recycling of building materials was excluded by 65% of the reviewed studies. This term refers to the processes in which the environmental benefits of building materials beyond the defined system boundary are captured [47]. The use of this strategy has been widely seen as an effective measure to mitigate buildings' environmental impacts [48,49]. This paper found that the amount of energy saved by using this strategy averaged between 5 to 38% of a building's total life-cycle energy use (Table 3).

4.1.2. *The extent of system boundary definition: calculating embodied energy*

Calculating embodied energy largely depends on the extent to which the embodied impacts of building components and their systems are included within the system boundary. Table 4 presents the building components considered by the analysed studies when accounting for buildings' embodied energy. The review showed that the inclusion of embodied energy impacts of building components and their systems within the system boundary was inconsistent. The majority considered the embodied impacts of superstructure, substructure and finishings, whereas only half of the reviewed studies considered the embodied energy of building services. This can be related to the higher weights of the former components in buildings' bill of quantity, and the energy intensiveness of their production processes due to using high amounts of cement or steel [29,33,39,50,57]. On the other hand, 83% of the studies excluded the embodied energy of built-in furniture, fixtures, appliances or elements beyond building components (such as urban infrastructure or

Table 4
The embodied energy of building components considered by the reviewed studies

Elements	Descriptions	Number of studies considered
Superstructure	Structural frame; interior and exterior walls; stairs; floor; roof; windows; interior partitions; interior and exterior doors.	40
Substructure	Foundation; basements.	37
Finishing	Wall, floor and ceiling finishings.	30
Services	Sanitary installation, installations (water, lighting, electrical, ventilation); space heating and air conditioning; firefighting elements.	20
RES	Photovoltaic panels, solar collector, wind turbines.	12
Furniture, fixtures, appliances	Built-in furniture, interior fixtures, or appliances.	7
Elements beyond building	Urban infrastructure (e.g. roads, water, sewage systems); residents' mobility.	5

occupants' transportation) from their system boundaries. Further, the system boundaries defined by studies that investigated life-cycle energy performances of net-zero-energy buildings (NZEBs) were found to be wider than those considering conventional buildings since they also included the embodied impacts of renewable energy systems (RESs), such as photovoltaic panels, solar collectors, or wind turbines, within system boundaries.

The possibility of expanding the system boundary to include parameters beyond the scale of a building has also been pointed out by a number of studies [6,32–34,44]. Stephan et al. [32] proposed a framework to consider the embodied impacts of nearby infrastructure (roads, water, sewage systems, etc.), and the energy used for occupants' transportation. This framework was then employed to analyse the life-cycle energy performances of two residential buildings in Australia and Belgium. The authors concluded that the occupants' transportation made up 25.4% and 33.8% of the entire building life-cycle energy consumption in the Belgian passive house and the Australian building, respectively. Bastos et al. [34] also performed an LCEA to compare energy consumption and greenhouse gas emissions of two buildings, one apartment building located in the city centre and a semidetached house in a suburban area. In addition to the embodied impacts of buildings, they also considered energy consumed for occupants' transportation. The results indicated the significance of energy consumption for occupants' transportation, especially for the suburban building.

4.1.3. The extent of system boundary definition: calculating operational energy

Energy is consumed in the forms of thermal and non-thermal loads over a building's lifespan in order to maintain a habitable indoor environment [18,23,24]. Parameters influencing thermal loads include heating and cooling, whereas DHW, electrical appliances, ventilation, lighting, and cooking are the factors that determine non-thermal loads. Hence, whether the system boundary is set to account for the impacts of these parameters directly affects the calculation of operational energy.

The review showed that the studies had different levels of inclusion to account for the impacts of parameters that affect operational energy use (Fig. 2). It is found out that only 20% of the studies included all parameters [31–35,37,39,52], while the impacts of cooking were excluded by 68% of the studies, followed by cooling (53%), lighting (38%), ventilation (28%), electrical appliances (28%), DHW (28%), and heating (10%). Moreover, one study did not discuss its level of inclusion for the assessment of operational energy usage [58]. Eliminating each parameter from the system boundary affects LCEA results by changing the proportion of operational energy [59,60]. For example, Gustavsson and Joelsson [59] found that the share of embodied impacts in a building's total life-cycle energy usage decreased from 33% to 25% once the scope had been extended from space heating only to include ventilation, DHW, and household electricity.

It is also noted that the system boundary was commonly defined subjectively, without providing any contextual justification. Only four of the reviewed studies [7,38,42,61] gave reasons for excluding certain parameters. For instance, Crawford et al. [7] only considered heating and cooling loads as these are the only demands considered by the Building Codes of Australia. Pinky Devi and Palaniappan [38] also justified the exclusion of cooking since it was usually done using firewood in low-cost houses in India. The subjectivity in the definition of the system boundary underlines the lack of a framework or a standardized approach for calculating buildings' operational energy usage.

4.1.4. Building lifespan

The range of building lifespans assumed by the analysed studies falls between 30 and 100 years, with the most frequently used lifespan of 50 years (Table 5). This assumption is of utmost importance due to its direct effect on the proportion of embodied and operational energy in an LCEA. The share of embodied energy in a building's total life-cycle energy use can be affected by calculations of recurrent embodied energy, as assuming a long lifespan leads to frequent replacement of building materials, while assuming a short lifespan will induce the need to change the entire building [62,63]. Rauf and Crawford [63] studied the correlation between a building's lifespan and its embodied energy. They found that a building's embodied energy demands can be decreased by 29% by increasing the lifespan from 50 to 150 years. In addition, assumptions about a building's lifespan can affect operational energy, as prolonging the lifetime of a building results in an increase in energy consumption over its service life [64].

Determining a building's lifespan in an LCEA is challenging due to numerous variables involved in terminating a building's life such as urban redevelopment, deterioration of the building's physical condition, and damage from natural causes such as fire and flood. In an LCEA, the main concern in choosing a building's lifespan is that it is an arbitrary decision, as a number is simply assumed by referring to other research. In addition, there is an inconsistency in the choice of lifespan regarding the geographical region. This can be seen in Table 5, as the assumptions differ within one country, or region (e.g. the EU).

The ideal conditions for an accurate prediction of building lifespan are those in which the microclimate is well known, while the characteristics of all individual components and elements of the building can be determined using laboratory or real-life data [75]. However, this approach is impractical from an LCEA practitioner's point of view. It is therefore recommended to utilize a simpler "factor method" for such estimations, where the aim is to apply a "rough-and-ready" means of estimating rather than predicting buildings' service life [75]. The future direction in this particular area of LCEA may lie with developing performance-based estimation approaches in each region, combined with creating open-access databases containing information about the service lives of construction materials that can be accessible by all practitioners.

4.1.5. Assumptions

In an LCEA analysis, making assumptions is inevitable due to various uncertainties involved [23]. This paper identified various assumptions

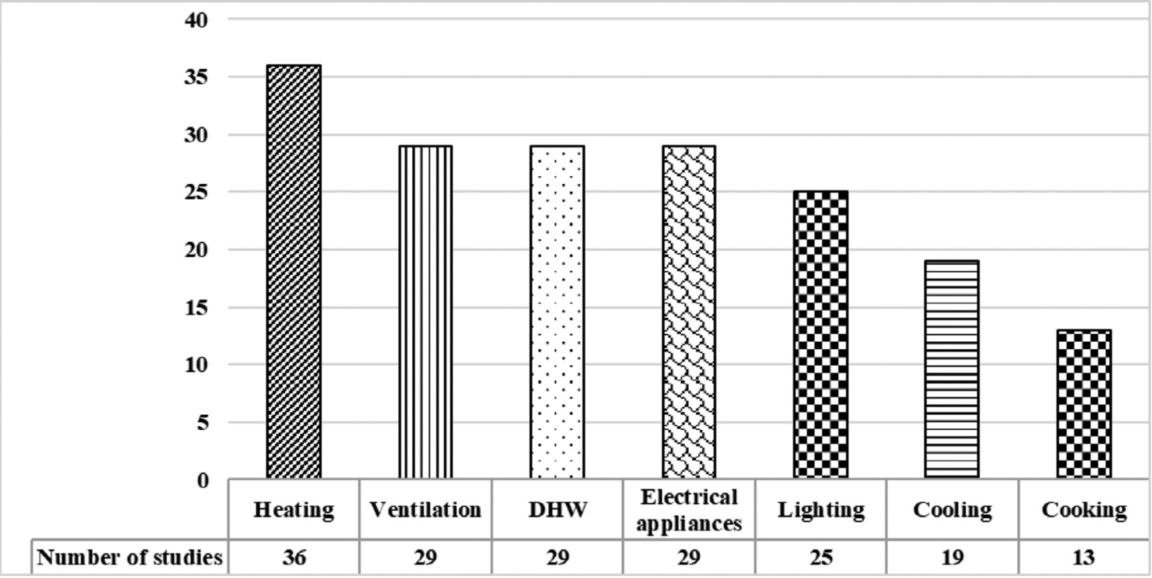

Fig. 2. Number of studies that considered the inclusion of parameters influencing operational energy

Table 5
Frequency of use of building lifespans

Country of case study	Building lifespan	Frequency of use	Reference
Australia	30 years	1	[44]
Canada	40 years	1	[65]
Australia, Sweden, Lebanon, Turkey, Belgium, Portugal, Norway, Finland, India, Thailand, China, Israel, Brazil	50 years	23	[7,29,32–34,37–39,43,46,50,53,57,59,61,66–72]
Ireland, Norway, Belgium	60 years	3	[40–42]
China, Italy	70 years	4	[52,55,56,73]
India, Portugal	75 years	3	[30,31,35]
Sweden	80 years	1	[54]
Belgium, Australia	100 years	4	[6,45,58,74]

made by the reviewed studies and grouped them with respect to their corresponding stage of the building life cycle (Table 6).

The first group refers to the assumptions that pertain to the calculation of embodied energy at the production stage. These assumptions are commonly made in response to the absence of a locally-driven database. For instance, Devi and Palaniappan [67] applied a European database to compute the embodied impacts of a building in India. Similarly, Stephan and Stephan [33], and Stephan et al. [6] employed 'Australian input–output-based hybrid embodied energy intensities' to calculate the embodied energy of buildings located in Lebanon and Belgium, respectively. However, geographic representativeness of the data is an important parameter that needs to be considered when measuring embodied energy since countries differ in their manufacturing processes, construction technologies, economic sectors, energy tariffs, and fuel supply structure [28]. As such, adopting data that is non-native to the location of the building under study may compromise the accuracy of calculations of embodied energy.

The second group of assumptions relates to the operation stage. A common trend in calculating the operational energy of buildings is to compute energy use for one year of the building's operation, then the calculated value is multiplied by the number of years assumed for the building's lifespan. As a result, the studies commonly assumed that operational energy consumption would stay constant throughout the entire life of the building. This assumes the occupancy profile of a building would remain unchanged (in terms of family size or the occupancy schedule), or there would be no depreciation of heating and cooling systems (a constant coefficient of performance). In addition, none of the reviewed studies considered the effects of climate change on buildings' energy consumption. The calculation of operational energy usage has been commonly carried out by considering present climatic conditions, while ignoring the possible future effects of climate change. This assumption was only declared by three studies [30,31,65]. Previous studies have shown that heating and cooling demands can be affected by climate change. For instance, Karimpour et al. [76] performed a parametric analysis using the Typical Meteorological Year for 2070 to design the building envelope of a residential building in Adelaide, Australia. They concluded that heating will become significantly less important as buildings would be better insulated while the climate would be warmer, and therefore more focus should be allocated toward mitigation of cooling loads in buildings. As such, considering the impacts of climate change on operational energy demands is recommended for future LCEA studies.

The maintenance and replacement stage has also been subject to several assumptions, as shown in Table 6. Although not discussed by most of the studies, it is commonly assumed that building materials are to be replaced with similar materials when they reach the end of their service lives; thus, they incur the same amounts of embodied energy as the original materials.

The final group attributes to the assumptions made in order to facilitate calculating embodied impacts of construction/installation and EOL stages. As previously mentioned, these stages were excluded by the majority of the reviewed studies. Amongst those accounting for their contributions, some assumed certain values as the impacts of these stages on the total building life-cycle energy consumption. For instance, Gustavsson et al. [50] assumed that the primary energy used for the on-site

Table 6

A summary of assumptions made by the reviewed studies

Targeted stage	Assumption	Reference
Production	• Use of databases containing embodied energy coefficients of building materials not originating in the country of the case studies; • Using input-output (I–O) data developed over a decade ago to represent energy intensities of construction materials; • Data for a similar material were used when more specific data were unavailable.	[6,33,39,43,57,74]
Assembly	• Assuming one location to carry out all the production processes; • Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use (e.g. 80 kWh/m^2, 160 kWh/m^2 or 4% of the material production primary energy).	[50,53,54]
Operation	• Unchanged occupancy profile (occupants' behaviors, family size, etc.); • Unchanged patterns of use for heating and cooling systems; unchanged coefficient of performance rates for all mechanical systems; • Unchanged resource mix supplying electricity to the buildings; • Using energy bills of another building with similar specifications to estimate the building's operational energy.	[29–31,35,37,51]
Maintenance and replacement	• The service life of the building's structural elements were assumed to be the same as the building itself; • Building materials were expected to be replaced with the same materials when they reached their end of service lives; • Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use; • Using the replacement lifetimes of U.S. construction materials for a case study in Australia; • Unchanged construction methods and materials during the entire building lifespan; • Replaced materials were assumed to have the same amount of embodied energy as the originals.	[41,44,46,57,66,74]
EOL	• Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use (e.g. 1% or 3% of the total life-cycle energy demand); • Assuming 10 and 20 kWh/m^2 of energy consumption for demolishing wood and concrete respectively; • Using only one type of fuel to transport construction wastage; • Assuming the recovery of 90% of the wood-based demolition materials, while decaying 10% into the atmosphere.	[39,50,51,53,54,57,67]

construction of an eight-story apartment equalled 80 kWh/m^2. Analogously, studies assumed different values in order to account for the impacts of the EOL stage [39,53,67]. For example, Devi and Palaniappan [67] assumed that this stage consumed 3% of the total initial embodied energy.

Overall, the assumptions made for different stages of a building's life cycle can have a significant effect on the final results of an LCEA. Thus, all the assumptions in an LCEA study need to be clearly stated for the sake of transparency while justifying their contextual applicability. The sensitivity of each assumption toward total building life-cycle energy use should be tested at the interpretation stage. Three methods are identified here that can potentially be used in order to assure the robustness of the LCEA results (See section Interpretation).

4.2. *Methods applied to calculate embodied energy*

The results of an LCEA can be influenced by the method applied to calculate embodied impacts. The review shows that three major methods have been utilized to compute the embodied impacts of buildings, namely the process-based, economic input-output (I-O), and input-output-based hybrid methods. The process-based method is most effective when the physical flow of the system under study is identifiable and can be easily traced. However, this approach becomes difficult to apply when the inputs and outputs of the system are numerous [57]. Also, errors can be induced by the subjective truncation of the upstream production system [68]. On the other hand, the economic I-O method takes a top-down approach and utilizes the entire economy as the theoretical boundary to arrive at clear definitions of the system boundary. This method aims to determine the quantity of energy consumed to produce a specific service or product by decoding the flow of materials in an economy's structure. Although using this method improves the incomplete system boundary definition in the process-based method, it still suffers from a lack of product-specific data. To address this issue, the I-O-based hybrid approach was proposed to incorporate the inputs from the entire upstream supply chain by amalgamating the two previous approaches [23,77]. The review revealed that 60% of the studies utilized the process-based approach; 23% used the I-O-based hybrid approach; only one study applied the economic I-O approach [44]. Furthermore, 15% of the studies did not discuss the methods they used to calculate embodied impacts [30,31,61,70,51,54].

To compute embodied impacts, it is necessary to select a background database that contains datasets representing the technical and economic contexts of the case study [23]. It is found out that the background data required for embodied energy calculations were retrieved from two primary sources: 'literature' (i.e. data published by other research) and databases that are available publicly or commercially (Table 7). Overall, 13% of the studies solely relied on the literature to calculate embodied impacts. Using this approach may potentially undermine the reliability of the achieved results for decision-making purposes since the adopted background databases might not represent the regional contexts of the

Table 7
Databases applied by the reviewed studies

Database	Developer	Data coverage	Boundary	LCI method	Ref.
SimaPro[1]	PRe´ Consultants, Netherlands	Industry data, U.S. LCI, Danish input-output database, Dutch input-output database, LCA food database, Ecoinvent	Cradle-to-grave	Process-based and I-O method	[29,52,74]
Ecoinvent	Ecoinvent centre, Swiss	Generic data on various products and processes including chemicals, waste management, agriculture, energy, washing agents, transport, paper & board, and building materials	Cradle-to-gate	I-O method	[34,40,41,46,53,56,71]
Inventory of Carbon and Energy	Bath University, UK	Specific-process data on over 200 construction materials, European, mainly UK data	Cradle-to-gate	Process-based method	[35,37, 38,42,57, 66,67]
AusLCI	Building Product Innovation Council, Australia	Process data on construction products and materials, Australian data	Cradle-to-grave	I-O method	[74]
Building for Environmental and Economic Sustainability	National Institute of Standards and Technology (U.S.)	Construction materials, mainly U.S. data	Cradle-to-grave	Process-based method	[66]
Database of Embodied Energy and Water Values for Materials	University of Melbourne	Construction materials, Australian data	Cradle-to-grave	I-O based hybrid method	[6,7,32,39]
Chinese Life Cycle Database	Sichuan University, China; IKE Environmental Technology Co., China	Waste management, energy carriers, transport, materials and chemicals; data coverage for China	Cradle-to-gate	Process-based method	[68]
Athena Institute Impact Estimator database	Athena Sustainable Materials Institute	Construction materials, North American	Cradle-to-grave	Process-based method	[65]

Note: (1) the exact database has not been reported.

buildings under study. In addition, 33% of the studies used generic international databases, namely Inventory of Carbon and Energy, Athena Institute Impact Estimator, Ecoinvent, and Building for Environmental and Economic Sustainability, while 15% of the studies combined process-specific data acquired from different sources such as local manufacturers [50,73], or databases developed nationally or regionally with generic international databases [53,54,71,74] in order to increase the geographical representativeness of the data.

The findings show that the studies have taken different approaches toward calculating the embodied energy demands of the analysed buildings. These differences of approach, coupled with the differing definitions of the system boundary, make the LCEA results highly variable across the reviewed studies.

4.3. Methods applied to calculate operational energy

This paper found that the studies applied five main methods to calculate operational energy usage:

- Building energy performance simulation (BEPS) tools. The review showed that 65% of the studies utilized BEPS tools to calculate operational energy. In recent years, this method has been widely applied to support the processes involved in building design, construction, operation, and retrofitting [78]. However, the main challenge of the BEPS approach attributes to incorporating assumptions about occupant behaviours into the simulated model and whether or how much they reflect real-world occupant behaviours. Previous studies indicated that relying solely on simulation software may induce significant deviations between predicted and actual building performances [79,80].
- Energy bills. Around 8% of the studies used the actual records of energy bills to calculate operational energy usage [37,39,57]. Employing this method enables researchers to comprehensively capture the effects of occupants' behaviours on energy usage. Nevertheless, using this method only provides an aggregate value for operational energy consumption, and does not provide a detailed breakdown of energy usage. This makes it difficult for decision-makers to identify the 'hot spots' of energy use in buildings and to provide solutions for energy reduction [23].
- Monitoring. 8% of the studies monitored buildings' energy consumption using sensors and actuators in order to calculate operational energy [52,67,73]. Using this method enables researchers to acquire detailed data on the actual energy use of buildings by continuously sensing instantaneous values of current and voltage, or gas usage to provide a measurement of energy used [81]. However, there are several challenges involved in using this method, in particular the issue of interoperability. This term refers to exchanging the data between components of building energy monitoring and metering systems in a standardized way so that they can properly communicate with each other irrespective of the manufacturing brands and physical medium [81]; thus, all the data corresponding to different types of energy use in buildings can be metered and recorded uninterruptedly. Furthermore, the high initial cost and the difficulty in managing and storing the high amounts of metering data can also be listed as potential challenges in using this method [81]
- National statistics. The review shows that 8% of studies utilized data representing national or regional statistics on energy consumption in the building sector in order to calculate operational energy use [34,35,38]. Using this method can potentially lead to a divergence between estimated and actual operational energy use since these data are developed based on the average energy consumption in the building sector. Moreover, the age of the data in this method can be a matter of concern. For instance, Bastos et al. [35] used data from 2002 related to the residential use of electricity and natural gas from the Lisbon Energy Matrix in order to calculate a building's operational energy usage.
- Others. Other methods were applied in 10% of the reviewed studies [6,32,33,55]. Stephan et al. [32] and Stephan et al. [6] used static equations in order to calculate heating and cooling loads, then non-thermal energy demands were estimated using regional per capita average energy consumption. In another study, Stephan and Stephan [33] utilized dynamic simulation software to calculate heating and cooling loads, while non-thermal energy demands were computed

using regional averages for energy consumption in Lebanon. Zhan et al. [55] also used static equations to calculate the amount of energy consumed for heating, ventilation, air conditioning, and lighting during a building's operation. Using static equations can assist researchers to produce an accurate estimation of a building's energy performance at the early stage of building design; however, it can be time-consuming when the aim is to optimize a building design through parametric analysis [23].

The review showed that the studies applied different methods to measure operational energy use. The majority employed BEPS tools, mainly without validating their results. Only two studies validated their simulated results against actual data [72,74]. The seldom reliance on this approach may lead to inaccurate results due to ignoring the impacts of occupants' behaviours on energy usage. For instance, Van Dronkelaar et al. [79] reported a discrepancy of 34% in total energy between design and actual building performance, with a 10–80% estimated effect of occupants' behaviours. Contrarily, the use of the energy bills [37,39,57] and monitoring [52,67,73] methods can address the aforementioned issue by taking into consideration the effects of occupants' behaviours on energy use over a building's lifespan. Using national or regional statistics on average energy consumption in the building sector was another method applied by the reviewed studies to calculate operational energy [34,35,38]; however, this approach can also lead to an inaccurate estimation of operational energy since it fails to account for the particular buildings' characteristics, occupants' behaviours, and the effects of microclimate on buildings' energy consumption.

In sum, LCEA results can also be affected by the method chosen to calculate operational energy. Quantifying the impacts of each method on the LCEA results is beyond the scope of this paper, though it is an important topic for future research.

4.4. Interpretation

Interpretation is the final stage of an LCEA in which the obtained results are discussed with regard to the scope and aim of the research and recommendations are made accordingly. In principle, the LCA standards recommend performing certain types of evaluation in order to assure the accuracy of the achieved results. For instance, ISO 14044 recommends three analyses: completeness check, sensitivity check, and consistency check [20]. Detailed explanations of these analyses can be found in [23]. EN 15978 also suggests undertaking result verification to formally confirm the achieved results [13]. In addition, EeBGuide recommends conducting an uncertainty analysis and states that, where possible, an alternative scenario should be modelled for each stage of the life cycle [47].

The findings showed that three methods have been applied by the analysed studies as a means of evaluation, namely sensitivity analysis, uncertainty analysis, and discussion of limitations. Uncertainty analysis measures the uncertainty in model outputs, which is derived from input uncertainty, while sensitivity analysis assesses the inputs' contributions to the total uncertainty in the analytical results [82]. Discussion of limitations refers to acknowledging the limitations of the LCEA and discussing their implications for the final results without undertaking any quantitative analysis. Regarding sensitivity analysis, 15% of the studies utilized only this method to examine the effect of inventory data parameters [34,37,53,59,67,69]. In these studies, the impacts of several variables on total building life-cycle energy use were analysed, namely climate and energy mix, the choice of insulation materials, the method of assessing embodied energy at the production stage, building lifespan, air infiltration rate, ventilation heat recovery efficiency, and the effects of building location. Also, 13% of the reviewed studies applied uncertainty analysis [6,32,50,54,56]. For instance, interval analysis was used by a number of studies to evaluate uncertainties concerned with embodied energy data [6,32]. Finally, 13% of the studies discussed limitations linked to their research [35,39,46,57,58]. Different limitations were discussed such as assuming a constant energy mix over 50 years, assuming the same service life for the building's structural components as for the building, and assumptions pertaining to building occupancy [57], using old I-O data [39], ignoring the EOL stage, using a database to calculate embodied energy that is derived from UK production processes [35], excluding the impacts of interior zoning of spaces (e.g. living room, bathroom, bedroom) on operational energy usage, and excluding the impacts of partition walls on embodied energy [46].

Furthermore, no study adopted all the three methods to evaluate the LCEA results, and only 18% of the studies included two of them, i.e. sensitivity analysis and discussion of limitations [7,38,40,66,74], uncertainty analysis and discussion of limitations [33], and sensitivity analysis and uncertainty analysis [41]. 42% of the studies also did not perform any evaluation.

5. Discussion

This section aims to offer responses to the first two research questions; 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; and 'what are the key parameters causing variations in LCEA results?'. Table 8 shows the overall methodological trends of the reviewed studies. In this table, 12 major parameters are identified that can lead to varying LCEA results. These parameters are further categorized into four main groups: i) system boundary definition, ii) calculation methods, iii) geographical context, and iv) interpretation of results.

The incomplete definition of the system boundary is a primary issue relating to the LCEAs carried out by the analysed studies. It is interesting to mention that, with one exception [39], no study had a complete definition of the system boundary, that is, a definition that included all stages of a building's life cycle, all parameters influencing operational energy usage, and the embodied energy of all building components. Even studies with a broad definition of the system boundary for assessing embodied energy [6,32–34,44] excluded the impacts of certain stages of a building's life cycle or some influential parameters in calculating operational and embodied energy. Another issue associated with the LCEAs conducted by the reviewed studies is the subjectivity in defining the system boundary since they barely gave justifications for truncating system boundaries. As a result, the incomplete definitions of the system boundaries compromise the accuracy of LCEAs in representing the total life-cycle energy performance of buildings. This can further reduce decision-makers' ability to rely on these results for purposes such as implementing environmental practices (e.g. eco-labelling).

The review also revealed different approaches employed by the studies to measure embodied energy and operating energy. Regarding embodied energy, studies with a wider approach, namely the I-O-based hybrid, were more likely to yield a higher value as it captures energy usage embedded in both the downstream and upstream stages of the supply chain [7,33,77]. Likewise, the analysed studies adopted different methods to calculate operational energy. A limited number of studies applied methods that capture occupants' behaviour regarding energy consumption, namely energy bills [37,39,57] and monitoring [52,67,73], whereas the majority employed simulation software. Moreover, regional or national averages for energy consumption in residential buildings were used by some studies [34,35,38] to calculate the operational energy of buildings. Another major difference amongst the studies is the geographical context, which leads to certain inherent differences such as climatic conditions, building regulations, quality of raw materials, production processes, economy structure, different processes involved in producing secondary energy, energy tariffs, fuel supply structure, and labour [28]. This emphasizes the necessity of considering the geographical representativeness of data when computing embodied impacts. Pullen [83] estimated a possible error of 2.6 percent in the results for embodied energy due to differing tariffs paid by different material suppliers at different locations when using the I-O method. The last major difference was the interpretation of the LCEA results. This

Table 8
Overall trends in the methodologies of the reviewed studies

Category	Methodological aspects	Overall trends in the LCEA studies
System boundary definition	Exclusion of building life-cycle stage.	58% excluded EOL; 35% replacement and maintenance; 27% excluded construction/installation; 22% excluded transport to construction site.
	Exclusion of reuse, recovery, and recycling.	65% of the reviewed studies.
	Building components considered for embodied energy assessment.	100% superstructure; 93% substructure; 75% finishings; 50% services; 30% RES; 18% built-in furniture/fixtures/appliances.
	Elements at the neighborhood scale considered for embodied energy calculation.	Occupants' transportation; urban infrastructure considered by 13%.
	Parameters considered for operational energy usage.	90% heating; 73% ventilation; 73% DHW; 73% electrical appliances; 63% lighting; 48% cooling; 33% cooking.
	Building lifespan.	58% assumed 50 years.
	Assumptions.	All stages are subject to assumptions.
Calculation methods	Methods used for calculating embodied energy.	60% process-based; 23% I-O-based hybrid; 3% economic I-O; 15% of the studies did not discuss their applied methods.
	Database employed for embodied energy calculation.	33% generic international databases; 13% literature; 15% combined generic international databases with national or regional databases.
	Methods used for calculating operational energy.	65% BEPS tools; 8% energy bills; 8% monitoring; 8% national statics; 10% other.
Geographical context	Distribution of countries.	58% Europe; 21% Asia; 16% Australia; 2.5% Brazil; 2.5% Canada.
Interpretation of results	Interpretation.	42% none; 15% sensitivity analysis; 13% uncertainty analysis; 13% discussion of limitations; 18% used two methods.

paper showed that a large percentage of studies (42%) eschewed any type of evaluation of their final results, despite the recommendations in the LCA standards.

Overall, it can be stated that the applicability of current LCEA results for decision-making purposes is limited due to incomplete definitions of the system boundary, with no possibility of conducting cross-comparison between LCEA studies. Cross-comparison is important when aiming to advance knowledge about LCEAs of residential buildings within a global context [23]. Previous studies endeavoured to plot the significance of operational energy against embodied energy (or vice versa) by juxtaposing various case studies [18,24,84–86]. For instance, Ramesh et al. [24] cross-compared 73 cases of residential and office buildings. It was concluded that operational energies constituted 80–90% of the total buildings' life cycle energy usage, while embodied energies made up 10–20%. It was further shown the total life cycle energy requirements of conventional residential buildings fell in the range of 150–400 kWh/m^2 per year and that of office buildings in the range of 250–550 kWh/m^2 per year. These comparisons are infeasible considering the significant variations existing among the studies. In one study, Yung et al. [87] attempted to compare residential and office buildings. They noted that some studies excluded the transportation and construction stages from their system boundaries. To account for the impacts of these excluded stages, 4% (for transportation) and 10% (for construction) of the initial embodied energy were added to the original values calculated by the researchers in order to make the cases comparable. To standardize operational energy, they considered energy usage for heating and cooling only, and then compared the embodied energy and operational energy of the cases. Despite the authors' great efforts, comparing LCEA studies with such unclear system boundary definitions and the variety of methodological choices can inherently increase the risk of misinterpretations if LCEA cases are utilized for inspiring particular design practices, or promoting indications for building regulations.

6. An evidence-based framework for LCEA research

This section aims to elaborate on the methodological bases of a conceptual framework that brings forward proposals for the standardization of LCEA use. The framework is developed based on the theoretical examination of the reviewed studies and the resultant reflections on the LCA methodology (Fig. 3). Thus, it addresses the third research question; '*how can the continued variations in the application of LCEA in residential buildings be overcome?*'. This framework primarily targets to simplify the interlocking processes involved in an LCEA by providing a clear description of the system boundary. It encourages incorporating embodied impacts of building components within a stepwise approach consisting of four levels in that each one represents a different degree of inclusion for assessing embodied and operational impacts.

6.1. Embodied energy

The importance of describing physical and temporal system boundaries has been widely emphasised by LCA standards to assure maintaining transparency and comparability. Description of physical system boundary refers to clearly stating which parts of the physical building components need to be included for assessment. Examples of these standards are ISO 21931-1 1 [11], and EN 15978:2011 [13], whereby building elements that should be considered for the analysis are recommended. These standards serve well in providing general guidance for practice, as well as providing a basis through which buildings' environmental impacts can be investigated. However, a more detailed framework is required when LCEA cases are to be horizontally compared e.g. for obtaining certification. The proposed framework recommends a stepwise approach by which buildings' embodied and operational impacts can be taken into consideration. Stepwise approach offers flexibility in assessing buildings' environmental impacts when dealing with data unavailability. Using this framework facilitates the possibility of comparing different versions of a similar building or cross comparing cases that are analysed by the LCEA approach.

The current study complements the description of physical system boundaries of current standards (i.e. EN 15978:2011 [13]) by recommending the inclusion of embodied impacts associated with renewable energy systems, and occupants' transport (Table 9). Considering the significant investment being made worldwide to support the concept of zero energy buildings, it is necessary to account for the embodied impacts of these components when the building is zero energy. The framework recommends including embodied impacts of renewable energy systems at level 1, where the inclusion of these components combined with superstructure, substructure, and finishings establishes the mini-

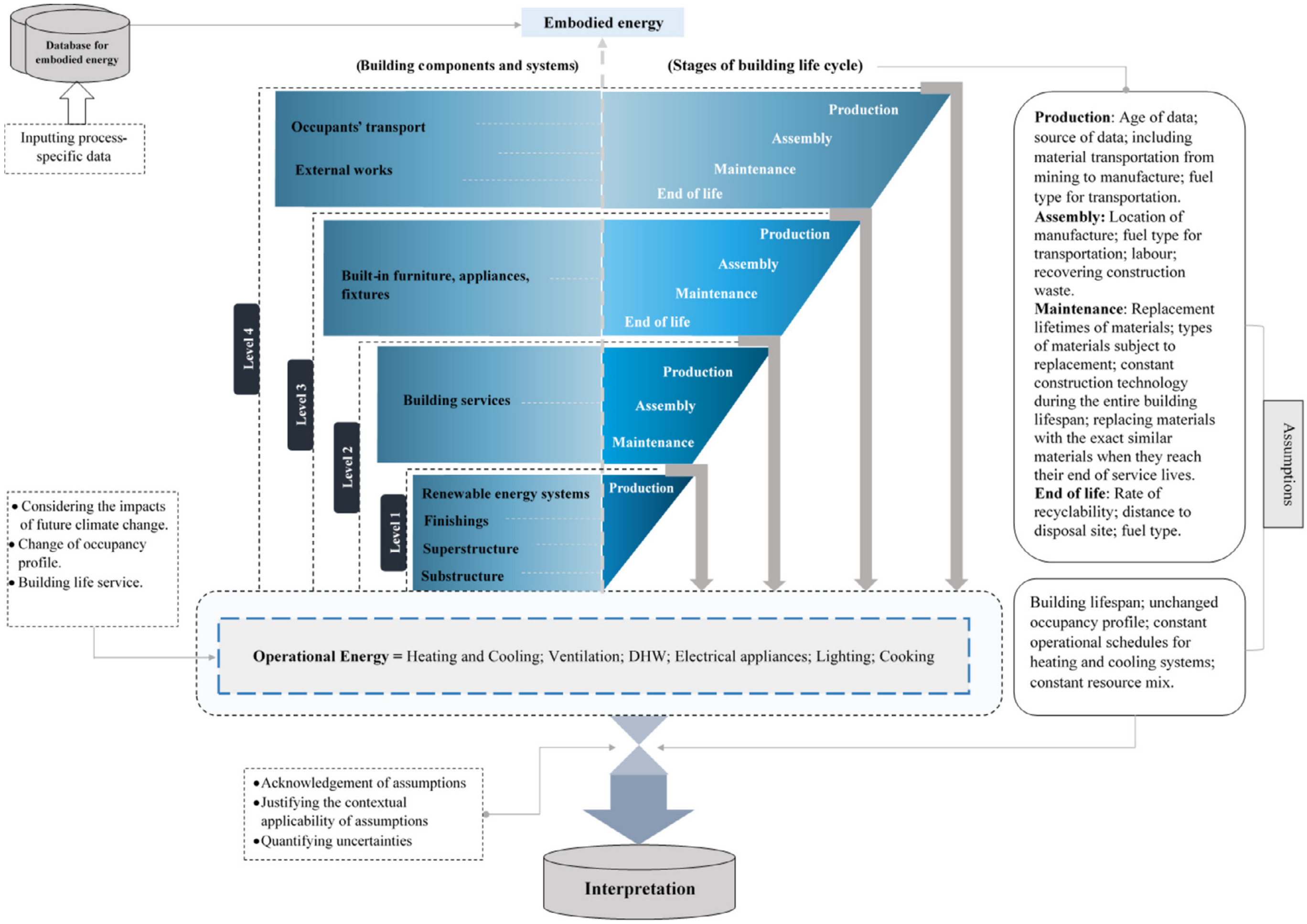

Fig. 3. An evidence-based conceptual framework for LCEA research

Table 9
Components suggested by international standards for inclusion within system boundary [13]

Main components	Sub-components
Substructure	Foundation; and basement.
Superstructure	Frame; upper floors; roof; stairs and ramps; external walls; windows and external doors; internal walls; and internal doors.
Internal finishes	Wall, floor and ceiling.
Fitting, furnishes and equipment	Fitting, furnishes and equipment
Services	Sanitary; water, and disposal installations; service equipment; heat source; ventilation and air conditioners; electrical and fuel installations; lift; and control system.
Prefabricated buildings	Complete buildings; building units; and pods.
Work to existing buildings	Minor demolition and alteration work; repairs to existing services; damp-proof course; façade retention; cleaning existing surfaces; and renovation work.
External works	Site preparation; roads, path, paving and surfaces; soft landscaping, planting and irritation systems; fencing, railing and walls; external fixtures, drainage, and services.
Renewable energy system	Photovoltaics panels and its supporting systems; solar collectors; and wind turbines.
Occupants' transport	Vehicles; access to public transport.

mum level of LCEA assessment at building scale. Levels 2 and 3 promote adding embodied impacts of building services and fittings, built-in-furniture, and appliances to the system boundary in order to capture a holistic understating of buildings' environmental performance.

The assessment of embodied impacts relating to external works has been recommended by EN 15978:2011 (see table 9) [13]. This study suggests adding embodied impacts of occupants' transport to the physical system boundary (i.e. level 4) along with external works in order to account for the impacts of elements that are beyond the building scale. The review also showed that a number of studies endeavoured to include embodied impacts of nearby infrastructure, and occupants' transportation within their system boundaries [6,32–34,44]. Level 4 represents the ambitious level for assessing the life cycle energy performance of buildings.

Regarding the temporal system boundary, this study recommends that the embodied impacts of production (initial embodied energy) stage should be a minimum assessment requirement at the building level. The initial embodied energy plays a significant role in emitting GHGs into the atmosphere since they are mainly produced by combusting fossil fuels [7]. It is also widely accepted that initial embodied energy constitutes a higher percentage of total embodied energy use compared to other stages of building life cycle [6,7,23,88,89]. Additionally, the majority of current databases contain initial embodied impacts of building materials that are calculated based on energy inputs from the entire structure of an economy; thus, the impacts of this stage can be taken into consideration regardless of buildings' locations. Level 2 recommends including the impacts of recurrent embodied energy and assembly (construction/installation), while levels 3 and 4 encourage including embodied impacts of all the building life cycle stages.

6.2. Operational energy

From the review, it became evident that only 20% of the studies accounted for all parameters with potential impacts on operational energy [31–35,37,39,52]. The proposed framework recommends that all parameters influencing operational energy use should be considered for assessment at all levels. Many jurisdictions across the world now aim to increase energy efficiency in the building sector by supporting the construction of energy-efficient buildings (e.g. NZEBs, and passive buildings). These dwellings are principally built to minimize operational energy consumption. The European Union's revised Energy Performance in Buildings Directive of 2010 is an exemplar of policy to support constructing buildings with high energy efficiency. It sets the nearly-zero energy building as the target for all new buildings from 2021 [90]. Similar examples can be found in other countries such as the U.S. [91], UK [92], Japan [93], and Australia [94]. Therefore, heating and cooling loads that are commonly considered by the vast majority of the studies for assessment, are likely to be minimized in the future while the shares of other parameters such as electrical appliances in consuming energy would be maximized.

The accuracy of measuring operational energy can be improved by future research. This review found out that the analysed studies commonly assumed an unchanged occupancy profile (e.g. family size, occupational settings and etc.) for the entire assessment period. To address this issue, the deterministic and stochastic statistical approaches can be employed in order to take the impacts of occupants' behaviours into consideration [23]. In the deterministic approach, different scenarios for users' behaviours on an hourly basis throughout a year should be defined, ranging from energy-saving to wasteful. Thereafter, the impacts of each scenario on building energy consumption can be measured and compared. Alternatively, a stochastic statistical model can be developed to predict occupants' presence throughout the year based on scholarly literature and national sociological investigations [47]. Despite the easier application of the first approach, using a stochastic statistical model may generate more accurate results. Moreover, considering the effects of future climate change on the heating and cooling demands can also be considered by future LCEA research when estimating operational energy usage. This consideration can potentially increase the accuracy of estimating operational energy consumption.

7. Conclusions

This paper approached the literature with the aim of addressing three key questions; 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, 40 LCEA studies representing 157 cases of residential buildings across 16 countries have been critically reviewed. The findings indicate that the current LCEA application in residential buildings suffers from an incomplete definition of the system boundary. This compromises the accuracy of LCEA results to be used for decision-making purposes. The key parameters leading to variations in LCEA results are the system boundary definitions, calculation methods, the geographical context, and interpretation of the results. The system boundary determines which building life-cycle stages are excluded from the assessment, including reuse, recovery, and recycling; which building components and systems are included in embodied energy calculations; whether elements beyond the building scale (e.g. urban infrastructure) are included in calculating embodied energy; the parameters of operational energy calculations; building lifespan; and assumptions. The calculation methods refer to the methods and background databases applied to calculate embodied energy, as well as the methods used to calculate operational energy. The geographical context refers to the different countries and/or regions in which LCEAs have been conducted. Finally, the interpretation of results refers to the studies' different methods of evaluating the accuracy of the LCEA results. Identifying the principal parameters with potential contributions to varying results in LCEAs can minimize the uncertainties accruing from LCEAs of residential buildings.

The findings also suggest that although the current LCA standards serve well in providing general guidance for practice as well as providing a basis for investigation of buildings' environmental impacts, they are still ineffective in harmonising the LCEA application. Thus, further research is needed for developing a more detailed framework when the aim is to horizontally compare cases (e.g. certification). This paper contributes to developing a conceptual framework for the standardization of LCEA use. The framework primarily targets to simplify various interlocking processes involved in an LCEA by providing a clear description of the system boundary. It encourages incorporating embodied impacts of building components within a stepwise approach consisting of four levels in that each one represents a different degree of inclusion for assessing embodied and operational energies. The framework offers the possibility of comparing different design strategies of a similar building or cross comparing cases that are analysed by the LCEA approach.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbenv.2020.09.005.

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