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EDITED BY
Saheed O. Ajayi,
Leeds Beckett University,
United Kingdom

REVIEWED BY
Graziano Salvalai,
Politecnico di Milano, Italy
Adekunle Oyegoke,
Leeds Beckett University,
United Kingdom

*CORRESPONDENCE
Ali Amiri,
ali.amiri@aalto.fi

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Life cycle energy analysis of residential wooden buildings versus concrete and steel buildings: A review

Daniela Schenk and Ali Amiri*

Built Environment Department, School of Engineering, Aalto University, Espoo, Finland

Around 40% of global energy consumption can be attributed to the construction sector. Consequently, the development of the construction industry towards more sustainable solutions and technologies plays a crucial role in the future of our planet. Various tools and methods have been developed to assess the energy consumption of buildings, one of which is life cycle energy analysis (LCEA). LCEA requires the energy consumption at each stage of the life cycle of a product to be assessed, enabling the comparison of the impact of construction materials on energy consumption. Findings from LCEAs of buildings suggest that timber framed constructions show promising results with respect to energy consumption and sustainability. In this study a critical analysis of 100 case studies from the literature of LCEAs conducted for residential buildings is presented. Based on the studied material, the embodied, operational, and demolition energies for timber, concrete and steel buildings are compared and the importance of sustainable material selection for buildings is highlighted. The results reveal that on average, the embodied energy of timber buildings is 28–47% lower than for concrete and steel buildings respectively. The mean and median values of embodied emissions are 2,92 and 2,97 for timber, 4.08 and 3,95 for concrete, and 5,55 and 5,53 GJ/m^2 for steel buildings. Moreover, the data suggests that the energy supply system of residential buildings plays a larger role in the operational energy consumption that the construction material. In addition, climate conditions, insulation detail, windows and building surfaces, and building direction are the other energy use role players. Finally, it was found that the demolition energy contributes only a small amount to the total life cycle energy consumption. This study demonstrates the significance of embodied energy when comparing the life cycle energy requirements of buildings and highlights the need for the development of a more standardised approach to LCEA case studies.

KEYWORDS

life cycle energy analysis, embodied energy, timber buildings, review, wooden buildings

1 Introduction

Rapid population growth and urbanisation are putting ever more pressure on natural resources and are increasingly burdening the environment (Junnila, 2004; Junnila, 2006). Simultaneously, the need for the construction of new buildings is growing, with urbanisation rates predicted to reach 68% by 2050 (United Nations, 2019). Currently, the construction sector accounts for about 36% of global energy consumption and around 40% of process-related emissions (International Energy Agency and United Nations Environment Programme, 2018), therefore, there is an urgent demand for the development of more sustainable and resource-friendly solutions within the sector (Hong et al., 2011; Poveda and Young, 2015; Schandl et al., 2018).

Life Cycle Assessment (LCA) is a methodology that has been developed to evaluate the environmental impacts of products and systems (Junnila, 2004; Junnila, 2006), (Junnila and Horvath, 2003; Cabeza et al., 2014). The comprehensive, qualitative approach to the evaluation of the environmental impacts associated with the production, use, disposal, and recycling of a product intrinsic to LCAs enables sustainability-conscious decision making in the development of products (Rossi et al., 2012a; United Nations Environment Programme (UNEP), 2009; Bartlett and Howard, 2000). In recent years, LCA has also been gaining traction within the construction industry (Ortiz et al., 2009; Buyle et al., 2013; Yang et al., 2017), as it allows stakeholders to make informed and sustainable decisions concerning the design, use and energy systems employed in buildings.

Buildings are complex, with many systems and materials contributing to the final product. Design decisions have to be considered carefully and should be well informed. Moreover, buildings, once in commission, are in use throughout their operational lifetime. Thus, outside factors such as user profiles, location, and climate can have an impact on the energy consumption of a building. It has therefore been recognised that life cycle energy analysis (LCEA) can be a valuable tool in evaluating the overall energy consumption of a building (Fay et al., 2000; Lippke et al., 2004).

LCEA focuses specifically on the energy requirements of a given product throughout its life cycle (Hendrickson et al., 1998; Bilec et al., 2006; Hu et al., 2017). For buildings, this can be broken down into embodied energy, operational energy, and demolition energy. Embodied energy refers to the energy that is consumed during the production stage of the building, covering the construction materials and construction energy involved. Operational energy encompasses the energy requirements during the use-phase of the building, including HVAC, domestic hot water (DHW), and daily electricity use. Finally, demolition energy describes the energy at the end-of-life stage of a building, required for its deconstruction. It therefore follows, that a comprehensive life cycle approach to the energy consumption of buildings could be instrumental in highlighting and uncovering specific areas and methods by which the global energy consumption of the construction sector could be reduced.

Additionally, the LCEA framework accounts for energy consumed by the transportation of building materials and waste. This, however, combined with the energy required for the physical construction and demolition of the building only amounts to around 1% of building lifecycle energy consumption, see Figure 1.

Previous studies have found that on average, the operational energy of a conventional building accounts for around 85% of its total energy requirement (Petrovic et al., 2019). For many years, the focus of improving the sustainability and efficiency of buildings has therefore been centred on the reduction of operational energy (Buchanan and Honey, 1994; Reddy and Jagadish, 2003; Dodoo et al., 2009). This has predominantly been achieved by increasing the amount of insulation (Çomaklı and Yüksel, 2004), (Papadopoulos and Giama, 2007), material choices (González and Navarro, 2006; Thormark, 2006), adopting more energy efficient energy delivery systems (Henze et al., 2004; Henze et al., 2005; Sozer, 2010; Sadineni et al., 2011) and in some cases, including local energy production (Morel et al., 2001), such as PV cells (Kibert, 2016), (Lin and Liu, 2012). For instance, the share of embodied emissions by nearly zero-energy buildings (NZEB) is roughly 50% of their total emissions (Foliente, 2007; Ferrante and Cascella, 2011; Dokka, 2013; Ren et al., 2013; Lützkendorf et al., 2015). For low-energy buildings the share is estimated to be 46% (Takano et al., 2014) while this figure is nearly 70% in case of passive buildings (Passer et al., 2012). Consequently, the reduced energy consumption during the operational phase of the building and higher material consumption due to insulation has prompted a focus shift towards the study of embodied energy (Amiri et al., 2019; Sicignano et al., 2019; Amiri et al., 2020a). As a result, an increasing number of studies are taking a wider, life cycle approach when examining the energy consumption of buildings, and a greater emphasis is being placed on the importance of material selection (Dodoo and Gustavsson, 2013).

Accordingly, there is a growing body of literature emerging, dedicated to examining the effects of construction material choices on the life cycle energy consumption and environmental impacts of buildings. Individual cases have concluded that wooden buildings require notably less primary energy than steel and concrete buildings in the production phase (Sicignano et al., 2019), (Börjesson and Gustavsson, 2000; Glover et al., 2002; Gustavsson and Anna, 2010; Gong et al., 2012; Buchanan et al., 2013; Tettey et al., 2019; Amiri, 2021). For instance, Glover et al. (Glover et al., 2002) compared the embodied energy of building materials required for steel, concrete, and wooden framed houses. The study concluded that the embodied energy for wooden framed houses was an average of 41% and 58% lower than that for concrete and steel

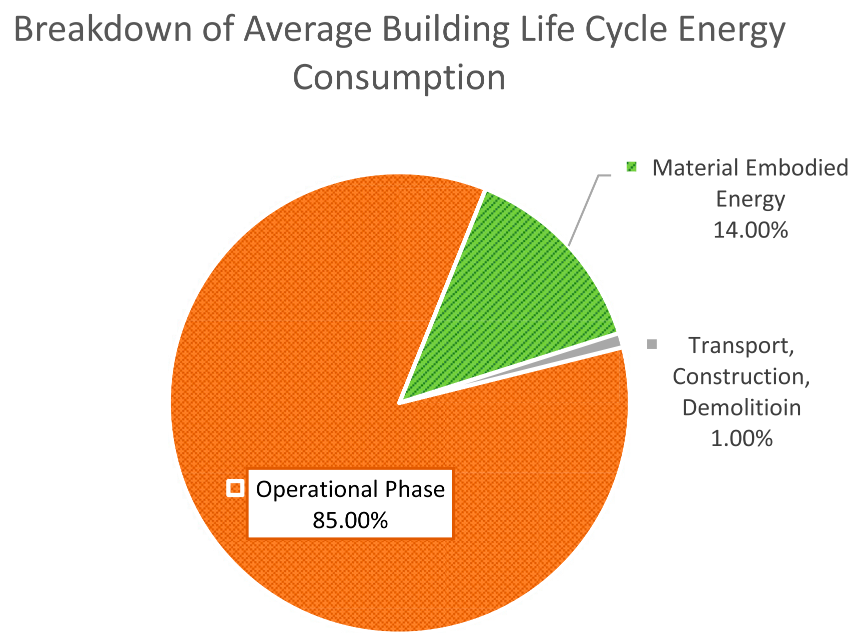

FIGURE 1
Breakdown of average building life cycle energy consumption .

framed houses respectively. However, it has been recognised that the primary energy required for the production of concrete could vary significantly based on the manufacturing methods employed (Josa et al., 2004). In response to this, Börjesson and Gustavsson (Börjesson and Gustavsson, 2000) discovered that even when considering various different manufacturing methods, the overall embodied energy for a concrete building would still be up to 60%–80% higher than its wooden equivalent.

In addition to the comparison of embodied energy for different construction materials, several studies have compared the effects of construction materials on the operational energy of buildings. Buchanan et al. (Buchanan et al., 2013) studied the life cycle energy consumption of a three-storey educational timber building in New Zealand, comparing the results to simulations of concrete, steel, and low energy timber versions. The results demonstrated that the only significant variation in operational energy consumption could be observed in the comparison of the low energy version of the building to the three standard models. It was therefore concluded that the operational energy of the building was almost independent of the construction materials in the case of well-designed conventional buildings. Further studies have highlighted the effects of climate and energy supply systems on the operational energy of a building, suggesting that these may have a larger impact than material from which they have been constructed (Tettey et al., 2019), (Gustavsson and Anna, 2010). In contrast, Khavari et al. (Khavari et al., 2016) concluded that energy savings of up to 12% could be achieved in the operational phase in cold climates when traditional concrete and steel buildings were replaced with timber equivalents.

With respect to the end-of-life phase of buildings, individual case studies comparing the embodied energy for different construction materials have discovered that the primary energy input of wooden framed buildings can be over 50% lower than that of concrete equivalents, when the energy recovered from wood waste is taken into consideration (Börjesson and Gustavsson, 2000), (Tettey et al., 2019). Furthermore, comparative life cycle energy assessments of steel, wood and concrete framed buildings have concluded that in particular cases, significant energy savings can be achieved throughout the entire life cycle of a building when it is constructed from wood instead of concrete or steel (Tettey et al., 2019), (Amiri et al., 2020b; Amiri et al., 2021; Ottelin et al., 2021).

While there is a wealth of literature on building LCEAs, the process of conducting LCEAs is generally complex. Moreover, the low level of standardisation in the practices involved make drawing direct comparisons between case studies challenging. Most LCEAs apply to individual cases and locations, consider only certain life cycle stages, or use varying functional units, which prevent general conclusions from being drawn without further processing of the presented data.

In order to combat this, several reviews of LCEA studies have been undertaken in an attempt to consolidate the available information in this field and draw more general conclusions about the life cycle energy use of buildings (Cabeza et al., 2014), (Feist, 1997; Petersen and Solberg, 2002; Zhong, 2005; Sharrard et al., 2008; Hafner et al., 2012; Al-Ghamdi and Bilec, 2015). For example, Yung et al. (Yung et al., 2013) conducted an audit of building LCEAs in order to compare the embodied and operational energy of office and residential buildings based on different classifications of floor areas. In 2014, Cabeza et al. (Cabeza et al., 2014) conducted a broad re-view of LCEAs in the construction sector, providing an overview of existing studies. In both instances, it was concluded that case studies from literature are often difficult to compare due to a number of parameters that can be independently defined in the individual studies.

However, none of these reviews has actively sought to compare the life cycle energy use for buildings constructed from different materials. This study therefore aims to compile a database from the existing LCEAs of timber, concrete, and steel buildings, and to consolidate the available information. Based on the results, this paper seeks to compare the embodied, operational and demolition energy of timber buildings with concrete and steel buildings from the literature. The goal is to identify whether it is possible to gain a deeper insight into the relationship between the construction materials and the life cycle energy consumption of buildings throughout the different life cycle stages.

2 Methodology

The study is done in several steps. First, the papers for literature review were selected using keywords based on the aim of the study. As the purpose of the study was to review the results for life cycle energy analysis (LCEA), the papers that had the targeted data were selected for detailed study (Sub-section 2.1). It was also possible to present the number of studies in each region and countries. Next, was the LCEA considerations. As the research articles use different methods, boundaries, included components and life cycle stages, it was needed to prepare the results in a way to make the comparison possible (Sub-section 2.2). Finally, some unit conversions and assumptions were made to have the same unit and format.

2.1 Selection of papers for review

The search was conducted in such a way that journal articles discussing the energy use during the whole life cycle of buildings could be targeted. Scopus was used as the search engine and the selection of reviewed papers was based on the PRISMA diagram (Attached as supplementary file). The search term was “building life cycle energy analysis” through the title of sources in November 2021. This resulted in 103 hits (See supplementary file). While keeping the journal articles, other materials, i.e., conference proceeding, meeting abstracts and letters were excluded so the remaining sources reduced to 78. In the next stage, through record screening 30 of the results were removed. Lastly, by omitting studies that were not related to the study 37 articles remained (Table 1). While the finding of this study is based on the final 37 articles, there is an in-detail assessment of 10 selected studies (See Sub-section 3.1) that include 100 case buildings for the purpose of review.

As shown in Figure 2, the majority of studies come from the US followed by China and Australia. In addition, the most studies were published in 2017 compared to other years considering that the year 2021 was not finished at the time of source searching. It seems that the focus on the topic is growing steadily from the year 2018 while the importance of LCEA is increasing.

2.2 Life cycle energy analysis (LCEA)

A building uses energy during its life cycle including pre-use (Construction), use (Operation) and end of life (Demolition) (Buyle et al., 2013), (Treloar et al., 2000; Adalberth et al., 2001; Verbeeck and Hens, 2007; Yung et al., 2013). Life cycle energy analysis (LCEA) is a tool to evaluate the energy use during whole life cycle of the building (Klopffer, 1997; Crawford, 2011; Fuller and Crawford, 2011; Stephan et al., 2019). There are three main methods of LCEA: process LCEA, input-output LCEA and hybrid LCEA. Process LCEA applies the data that is related to the defined location of the system, products and processes involved (Säynäjoki et al., 2011; Säynäjoki et al., 2017; Leskinen et al., 2020). Although there is certain limitation to this method because of dependency of the results to the defined system, process LCEA is one of the most common methods (Kalaniemi et al., 2020), (Ottelin et al., 2021). The other method, input-output, takes a broader approach to LCEA that is carried out by tracing energy use between different industries (Yang et al., 2017), (Goedkoop et al., 2009), (Majeau-Bettez et al., 2011). Input-output LCEA gathers data for energy use from different sources and combines them to account for each aspect that is related to the energy requirement of the building (Suh et al., 2004). Finally, hybrid LCEA combines both process and input-output LCEA to minimise the errors of each individual method (Suh et al., 2004), (Crawford et al., 2018).

For this study, the papers using process LCEA for their assessment were selected for two main reasons. The first reason was the larger number of papers using process LCEA that shows this method as mostly common method. The second reason was the noticeable difference in results of papers with different methods which makes the findings less trustable. Säynäjoki et al. (Säynäjoki et al., 2017) stated in their review article that the difference between the results by input-output and process LCEA is significant. Therefore, we selected one of the methods for the comparison, i.e., Process LCEA.

TABLE 1 Selection of material process.

No.	Selection base	Number of remaining sources
1	Search term “building life cycle energy analysis”	103
2	Adding two extra papers based on previous knowledge	105
3	Removing non-reviewed papers	78
4	Record screening	48
5	Full text assessing for eligibility	37

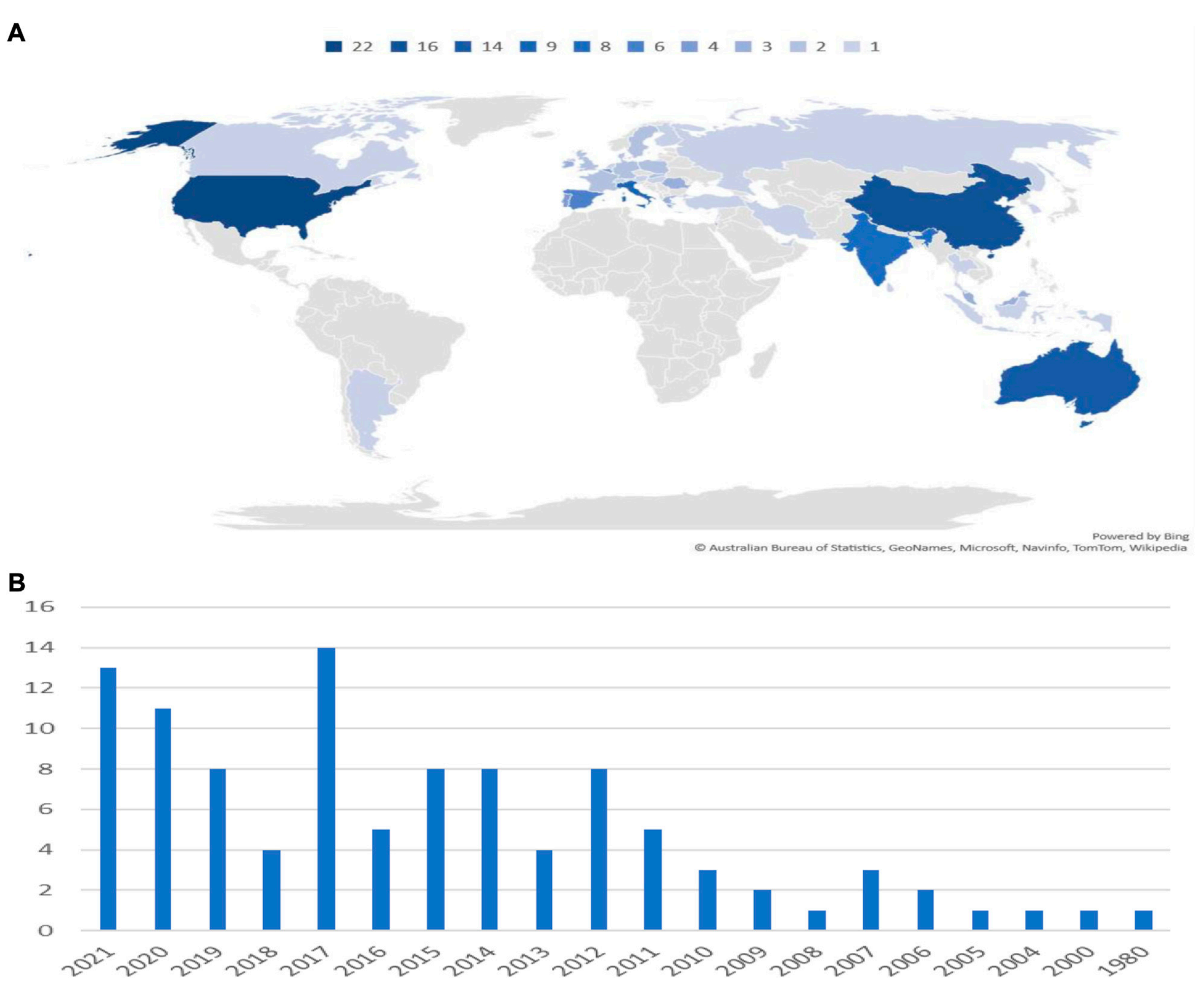

FIGURE 2
(A) Distribution of studies by location. **(B)** Distribution of studies by time.

2.3 Assumptions

Generally, most studies define the functional unit per m^2, however, the issue is that there is variation in the type of surface area considered. Two types of area have been used in the selected studies for review: useable floor area (UFA) also known as heated floor area (HeA) and gross floor area (GFA). UFA was selected for this study, it was therefore necessary to prepare a conversion

TABLE 2 Life Cycle Energy Analysis data gathered from reviewed literature.

Author	Frame mat.	Frame type	Type	Floors	Country	Life-time (yr)	Area UFA (m^2)	EE (GJ/m^2)	OE ($GJ/m^2/y$)	DE (GJ/m^2)
Li et al. (Li et al., 2021)	T	Wood	SD91	1	AUS	50	118	2,55	1,13	-
“	T	“	SD06	“	“	“	145	2,77	0,82	-
“	T	“	SD11	“	“	“	101	2,94	0,67	-
“	T	“	SD19	“	“	“	101	3,14	0,62	-
“	T	“	D91	“	“	“	175	2,34	0,88	-
“	T	“	D06	“	“	“	217	2,60	0,62	-
“	T	“	D11	“	“	“	244	2,82	0,51	-
“	T	“	D19	“	“	“	244	2,86	0,47	-
“	C	RC	HF91	“	“	“	97	4,49	1,25	-
“	C	PC	LF91	“	“	“	“	3,86	1,23	-
“	C	RC	HF06	“	“	“	122	4,24	0,90	-
“	C	PC	LF06	“	“	“	“	3,95	093	-
“	C	RC	HF11	“	“	“	108	4,55	0,87	-
“	C	PC	LF11	“	“	“	“	4,10	0,87	-
“	C	RC	HF19	“	“	“	“	4,80	0,81	-
“	C	PC	LF19	“	“	“	“	4,55	0,82	-
Dodoo et al. (Dodoo et al., 2014a)	T	CLT	L-E, HP	4	SWE	50	928	2,70	0,67	0,040
"	T	“	L-E, DH	"	"	"	"	2,70	0,63	0,040
"	T	B&C	L-E, HP	"	"	"	"	3,11	0,69	0,040
"	T	“	L-E, DH	"	"	"	"	3,11	0,65	0,040
"	T	Mod. prefab.	L-E, HP	"	"	"	935	2,87	0,69	0,040
"	T	“	L-E, DH	"	"	"	"	2,87	0,65	0,040
"	T	CLT	L-E, HP	"	SWE	"	928	2,70	0,72	0,040
"	T	“	L-E, DH	"	"	"	"	2,70	0,67	0,040
"	T	B&C	L-E, HP	"	"	"	"	3,11	0,74	0,040
"	T	“	L-E, DH	"	"	"	"	3,11	0,69	0,040
"	T	Mod. prefab.	L-E, HP	"	"	"	935	2,87	0,74	0,040
"	T	“	L-E, DH	"	"	"	"	2,87	0,68	0,040
"	T	CLT	L-E, HP	"	SWE	"	928	2,70	0,78	0,040
"	T	“	L-E, DH	"	"	"	"	2,70	0,71	0,040
"	T	B&C	L-E, HP	"	"	"	"	3,11	0,81	0,040
"	T	“	L-E, DH	"	"	"	"	3,11	0,73	0,040
"	T	Mod. prefab.	L-E, HP	"	"	"	935	2,87	0,81	0,040
"	T	“	L-E, DH	"	"	"	"	2,87	0,73	0,040
Tettey et al. (Tettey et al., 2019)	C	-	Std,CHP	6	SWE	80	1686	4,46	0,49	0,072
"	C	-	Std, HOB	"	"	"	"	4,46	0,62	0,072
"	C	-	Std, HP	"	"	"	"	4,46	0,55	0,072
"	C	-	Pas, CHP	“	“	“	“	4,67	0,26	0,076
"	C	-	Pas, HOB	"	"	"	"	4,67	0,33	0,076
"	C	-	Pas, HP	"	"	"	"	4,67	0,29	0,076
"	T	CLT	Std, CHP	"	"	"	"	3,14	0,49	0,036
"	T	“	Std, HOB	"	"	"	"	3,14	0,62	0,036
"	T	“	Std, HP	"	"	"	"	3,14	0,55	0,036
"	T		Std, CHP	"	"	"	"	2,72	0,49	0,036

(Continued on following page)

TABLE 2 (*Continued*) Life Cycle Energy Analysis data gathered from reviewed literature.

Author	Frame mat.	Frame type	Type	Floors	Country	Life-time (yr)	Area UFA (m^2)	EE (GJ/m^2)	OE ($GJ/m^2/y$)	DE (GJ/m^2)
		Mod. prefab.								
"	T	“	Std, HOB	"	"	"	"	2,72	0,43	0,036
"	T	“	Std, HP	"	"	"	"	2,72	0,55	0,036
"	T	CLT	Pas, CHP	"	"	"	"	3,35	0,26	0,040
"	T	“	Pas, HOB	"	"	"	"	3,35	0,33	0,040
"	T	“	Pas, HP	"	"	"	"	3,35	0,29	0,040
"	T	Mod. prefab.	Pas, CHP	"	"	"	"	3,03	0,26	0,040
"	T	“	Pas, HOB	"	"	"	"	3,03	0,33	0,040
"	T	“	Pas, HP	"	"	"	"	3,03	0,29	0,040
Petrovski et al. (Petrovski and Science, 2019)	T	Stud	Std	2	MKD	?	?	-	0,23	-
Evangelista et al. (Evangelista et al., 2018)	C	-	Std	5	BRA	50	40,370	3,40	0,32	-
Gustavsson and Joelsson (Gustavsson et al., 2010)	C	-	Std, RHC	4	SWE	50	1190	2,66	1,32	-
"	C	-	Std, HPC	"	"	"	"	2,66	0,77	-
"	C	-	Std, DHC	"	"	"	"	2,66	0,70	-
"	C	-	Std, DHB	"	"	"	"	2,66	0,60	-
"	C	-	Std, RHC	12	SWE	"	2802	3,67	1,24	-
"	C	-	Std, HPC	"	"	"	"	3,67	0,77	-
"	C	-	Std, DHC	"	"	"	"	3,67	0,71	-
"	C	-	Std, DHB	"	"	"	"	3,67	0,63	-
"	C	-	Pas, RHC	"	"	"	"	3,67	1,10	-
"	C	-	Pas, HPC	"	"	"	"	3,67	0,75	-
"	C	-	Pas, DHC	"	"	"	"	3,67	0,71	-
"	C	-	Pas, DHB	"	"	"	"	3,67	0,64	-
"	T	Wood	Std, RHC	"	"	"	"	2,20	1,32	-
"	T	“	Std, HPC	"	"	"	"	2,20	0,77	-
"	T	“	Std, DHC	"	"	"	"	2,20	0,70	-
"	T	“	Std, DHB	"	"	"	"	2,20	0,60	-
"	T	“	Ren. RH, C	"	"	"	"	2,20	1,21	-
"	T	“	Ren. HPC	"	"	"	"	2,20	0,73	-
"	T	“	Ren. RHC	"	"	"	"	2,20	0,67	-
"	T	“	Ren. DHB	"	"	"	"	2,20	0,58	-
"	T	“	Retro, RHC	"	"	"	"	2,20	1,07	-
"	T	“	Retro, HPC	"	"	"	"	2,20	0,71	-
"	T	“	Retro, DHC	"	"	"	"	2,20	0,66	-
"	T	“	Retro, DHB	"	"	"	"	2,20	0,60	-
Gustavsson et al. (Dodoo and Gustavsson, 2013)	T	“	CST, RH	8	SWE	50	3374	3,51	0,90	0,04
"	T	“	CST, HP	"	"	"	"	3,51	0,63	0,04
"	T	“	CST, DH	"	"	"	"	3,51	0,57	0,04
"	T	“		"	"	"	"	3,51	0,82	0,04

(Continued on following page)

TABLE 2 (*Continued*) Life Cycle Energy Analysis data gathered from reviewed literature.

Author	Frame mat.	Frame type	Type	Floors	Country	Life-time (yr)	Area UFA (m^2)	EE (GJ/m^2)	OE ($GJ/m^2/y$)	DE (GJ/m^2)
			NGCC, RH							
"	T	“	NGCC, HP	"	"	"	"	3,51	0,58	0,04
"	T	“	NGCC, DH	"	"	"	"	3,51	0,51	0,04
"	T	“	BST, RH	"	"	"	"	3,51	1,05	0,04
"	T	“	BST, DH	"	"	"	"	3,51	0,73	0,04
"	T	“	BST, DH	"	"	"	"	3,51	0,64	0,04
"	T	“	BIG/ CC, RH	"	"	"	"	3,51	0,90	0,04
"	T	“	BIG/ CC, HP	"	"	"	"	3,51	0,63	0,04
"	T	“	BIG/ CC, DH	"	"	"	"	3,51	0,53	0,04
Gong et al. (Gong et al., 2012)	C	-	Std	3	CHN	50	3913	7,36	0,36	0,16
"	S	-	Std	"	"	"	"	6,10		0,04
"	T		Std	"	"	"	"	2,59	0,34	0,04
Sicignano et al. (Sicignano et al., 2019)	C	-	Std	"	ITA	"	?	5,58	-	-
"	S	-	Std	"	"	"	"	5,33	-	-
Rossi et al. (Rossi et al., 2012a)	S	-	Std	2	BEL	50	192	8,16	0,92	-
"	S	-	Std	"	"	"	"	3,75	1,07	-
Rossi et al. (Rossi et al., 2012b)	S	-	Std	2	BEL	50	192	5,05	0,99	-
"	S	-	Std	"	PRT	"	"	5,05	0,63	-
"	S	-	Std	"	SWE	"	"	5,42	1,18	-

Frame Materials: T: timber, C: concrete, S: steel. Frame type: CLT: Cross Laminated Timber, B&C: Beam and column, Mod. prefab: modular, prefabricate, RC: Reinforced concrete, PC: Precast concrete. Type: Dxx: detached + year, SDxx: Semi-detached + year, HFxx: high flat + year, LFxx: low flat + year, L-E: low energy, Std: standard, Pas: passive, Ren: renovated, Retro: retrofit, CST: coal-based steam turbine, NGCC: natural gas-based combined cycle, BST: biomass-based steam turbine, BIG/CC: biomass-based integrated gasification combined cycle

factor for GFA to UFA. The conversion unit of 0.7 was applied, which is in line with several past studies (Passer et al., 2012), (Lylykangas et al., 2013).

3 Results and discussion

3.1 Data

The results of the examined case studies, which consisted of 100 different cases are presented in Table 2. The gathered data demonstrates the variation between individual life cycle analyses, with demolition energy being the least represented of the examined stages. The cases included 64 scenarios for timber buildings, 29 for concrete, and only seven for steel. In the table below, the “Type” refers to elements that characterise the building in question, this includes whether the building is designed to standard, low-energy or passive criteria, the heating system employed, as well as if the case in question is for a renovated or retrofitted building. These categories were assigned to the cases based on the information given in each of the individual studies.

Buildings use energy and material during their life cycle, i.e., pre-use (construction), use (operation) and end of life (demolition). There has been continuous research to reduce the operation energy which has resulted in zero energy buildings (ZEB), near zero energy buildings (nZEB), low energy buildings and passive houses. There might be more type of these buildings with different name that all focus on the energy efficiency of the buildings. On the other hand, there are standard buildings regarding their energy use in operation phase. All these buildings were found in the studied case buildings which are shown in Table 2 in Type column.

Regarding the energy supply, the case buildings in the reviewed studies has different sources including coal-based steam turbine (CST), natural gas-based combined cycle

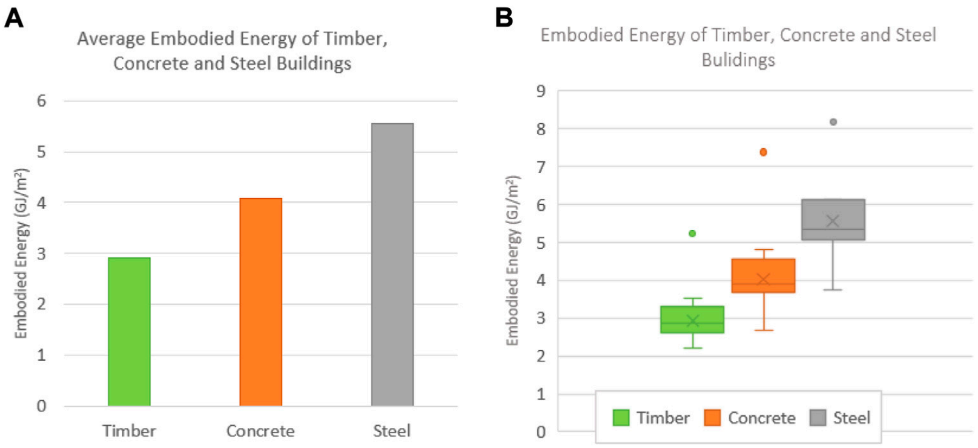

FIGURE 3
(A) Average embodied energy **(B)**Embodied energy.

TABLE 3 An overview of GJ/m² Embodied Energy of buildings.

Frame	N	Mean	Standard Dev	Min.	1st quartile	Median	3rd quartile	Max
Timber	64	2,92	0,53	2,20	2,62	2,87	3,30	5,23
Concrete	29	4,08	0,96	2,66	3,67	3,95	4,55	7,36
Steel	7	5,55	1,35	3,75	5,05	5,33	6,10	8,16

(NGCC), biomass-based steam turbine (BST), and biomass-based integrated gasification combined cycle (BIG/CC).

3.2 Embodied energy analysis

Figure 3 depicts a side-by-side comparison of the embodied energy for timber, concrete, and steel buildings. Of the 100 examined cases; timber buildings appear to require the lowest amount of embodied energy. On average, the embodied energy for timber buildings is 28% and 47% lower than for concrete and steel buildings respectively.

With respect to the consistency of the data, the means, and medians of each building type, presented in Table 3, are reasonably close to one another (Timber: 2,92 and 2,97; Concrete: 4,08 and 3,95; Steel 5,55 and 5,33), speaking for the overall consistency of the data. Furthermore, the standard deviations of all three building types are relatively small, suggesting that the average provides a good representative value of the gathered data. As a result, comparisons can be drawn between the average embodied energies with reasonable reliability. It should however be noted that the sample size for steel buildings was considerably smaller than for the other two building types which could impact the reliability of the results for these buildings.

There are outliers that can be observed for each of the building types with values considerably higher than the respective averages. For the embodied energy of the timber buildings, this value was presented by Sicignano et al. (Sicignano et al., 2019) in their 2019 study which aimed to reduce the amount of embodied energy in steel, concrete, and timber buildings. The specifications and construction methods for the timber building in question were taken from the Murray Grove Stadthaus in London and adapted for a hypothetical scenario in Italy. The study employed a method whereby the amounts of each required construction material were estimated and then converted to embodied energy by applying coefficients suggested by the University of Bath, England. While the method is described in some detail, there are inconsistencies in the presentation of the data and the method deviated from many of the other case studies included in this review. It could therefore be argued that the outlier for the timber buildings should not have strong bearing in the overall conclusions that can be drawn from the collected case studies.

While the range of embodied energy was larger for the concrete buildings than their timber counterparts, there is still

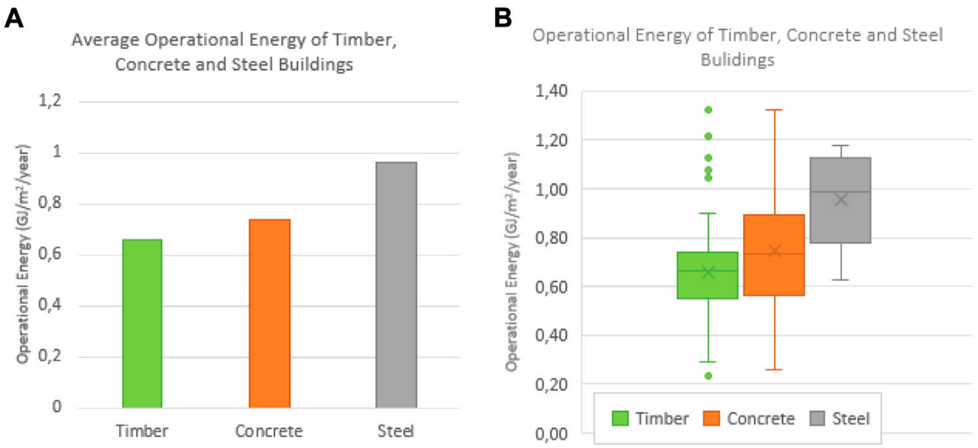

FIGURE 4
(A) Average operational energy **(B)** Operational energy

TABLE 4 An overview of GJ/m²/year operational energy of buildings.

Frame	N	Mean	Standard Dev	Min.	1st quartile	Median	3rd quartile	Max
Timber	64	0,66	0,22	0,23	0,55	0,67	0,74	1,32
Concrete	28	0,74	0,30	0,26	0,56	0,73	0,89	1,32
Steel	5	0,96	0,21	0,63	0,78	0,99	1,12	1,18

one outlier with a value of 7,36 GJ/m^2. The study in question, Gong et al. (Gong et al., 2012), is the only study from Beijing, which stated that its calculations were based on the concrete manufacturing process of large concrete companies in China. This data was applied instead of life cycle inventory information from already existing databases. It is therefore possible that there is a geographical factor underlying this outlier, as concrete manufacturing practices can vary between countries. This suggests that the local effects of building material production could influence the outcome of life cycle energy analyses.

Finally, as is apparent from Figure 3, the average embodied energy of steel buildings appears to be considerably larger than that of both timber and concrete buildings. Both the lowest and highest values for steel buildings originated from study Rossi et al. (Rossi et al., 2012a) in which an LCA tool was designed and compared to Equer, an existing verified LCA software. The authors argue that the sizeable difference between the values could be attributed to the databases upon which each of the tools is based, as each database employs different conversion factors for steel construction materials. This highlights the importance of consolidating the data, tools, and methods surrounding LCEAs if reliable comparisons are to be drawn between different case studies.

3.3 Operational energy analysis

The annualised operational energy of the three different building types is presented in Figure 4. The results suggest that the average operational energy of wooden buildings is only slightly lower than that of concrete buildings, see Table 4. On the other hand, steel buildings presented the highest values for operational energy, with even the lowest values falling well above the average for both timber and concrete buildings. Overall, the data indicates that the average operational energy for timber buildings is 12% and 31% less than that for concrete and steel buildings respectively. The similar results for timber and concrete buildings can be explained by the fact that several of the building designs presented in the case studies strove to attain the same level of insulation and U-values for the building envelopes. The difference between the operational energy of the concrete and timber buildings compared to the steel buildings is potentially due to variation in the types of buildings examined. The dataset for both concrete and timber buildings included cases with low-energy or passive buildings, whereas the five cases examining the steel buildings only covered cases with standard buildings. This supports the literature and suggests that the operational energy depends

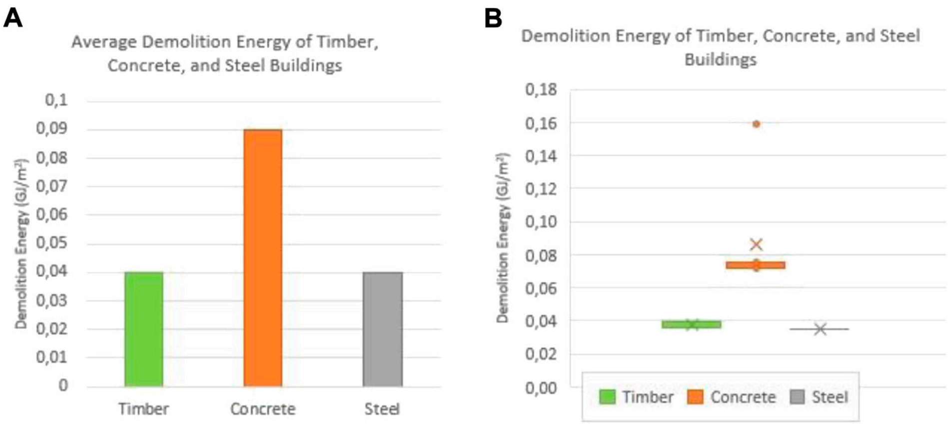

FIGURE 5
(A) Average demolition energy **(B)** Demolition energy.

more greatly on the efficiency and type of energy supply system as well as the energy design of the building than on the frame material from which the building is constructed.

The major energy consumption areas in the operation of buildings are heating, ventilation, air conditioning, lighting, major applinces including refrigerators, water heating and dryers in addition to miscellaneous areas like electronics. While the selection of insulation material and its thickness can play a role on the energy consumption, it is possible to reduce energy consumption by one- building surfaces and windows with tunable optical properties, two- innovative insulating material, three- high-efficiency heat pumps, four- optimized building design and operation, five- high-efficiency lighting devices, six- energy harvesting sensors and controls, and seven- optimized control strtegies (U. Department of Energy, 2015; Wei et al., 2022; Iijima et al., 2022; Li and Mahalec, 2022; Mor et al., 2021).

With respect to outliers, the highest values for both wooden and concrete buildings were 1,32 GJ/m^2/year and around 1,23 GJ/m^2/year. These values all originated from the same study, Gustavsson and Joelsson (Gustavsson and Anna, 2010), where in addition to the effect of different building materials on the overall life cycle energy consumption of buildings, the authors also examined the effect of different heating systems. The higher values of operational energy for these outliers can therefore be traced back to the use of resistance heaters in those particular cases. This highlights one of the many challenges in comparing the operational energy consumption of buildings from various as it can be observed that there are a number of factors beyond the construction materials of the buildings affecting their operational energy consumption.

3.4 Demolition energy analysis

Figure 5 presents the demolition energy for timber, concrete, and steel buildings. On the whole, there were only a few studies that gave values for the demolition energy or even the total end-of-life energy. Demolition energy was the least represented in the results, with only 51 of the 100 case studies reporting values for the demolition energy. The reasoning behind this in many cases was the fact that the demolition energy is considerably lower than the energy required in the other life cycle phases of a building and was therefore frequently omitted. The lower significance of demolition energy in the life cycle of a building could also explain the lack of developed methodologies for the calculation of demolition energy as well as the low availability of relevant data. Consequently, a number of studies also stated that they had estimated the demolition energy based on available literature (Adalberth et al., 2001), (Dodoo et al., 2014a).

For wooden buildings, the demolition energy per square meter had a notably small range and focused around 0,04 GJ/m^2, see Table 5, which is the same as the value obtained from the literature. There were only seven cases that included the demolition energy for concrete presenting a range of values between 0,07 GJ/m^2 and 0,16 GJ/m^2. Only one of the case studies of steel buildings presented a value for demolition energy.

The examined literature delivered one outlier for the demolition energy of the concrete buildings. This value was obtained from the study by Gong et al. (Gong et al., 2012), where once again, the geographical location and different construction methods could be behind the large disparity in the values. In the study itself, the other two presented values for the demolition energy of the timber and steel buildings were around 0,040 GJ/m^2, giving the only value for the demolition energy of steel buildings form the cases considered in this study. As this is the only value of demolition energy that had been presented in the examined case studies for steel buildings, the

TABLE 5 An overview of GJ/m² demolition energy of buildings.

Frame	N	Mean	Standard Dev	Min.	1st quartile	Median	3rd quartile	Max
Timber	43	0,04	0,00	0,04	0,04	0,04	0,04	0,04
Concrete	7	0,09	0,03	0,07	0,07	0,08	0,08	0,16
Steel	1	0,04	-	0,04	-	0,04	-	0,04

data is insufficient to draw any conclusions at this stage, especially given that the study in questions provided a number of outliers. Similarly, with the small sample size of 7 cases for the concrete buildings, it is suggested that further studies should be conducted into the demolition energy required for buildings before being able to draw reliable conclusions.

The results of this study highlight the growing importance of embodied energy and material selection in the construction and maintenance of residential buildings. The case studies examined in this paper suggest that it is possible to reduce the embodied energy per square meter by an average of 28% when constructing from wood rather than concrete. Furthermore, the results indicate that it is possible to achieve similar operational energy consumptions in both timber and concrete framed buildings. Policymakers could take these findings into consideration and encourage the adoption of higher levels of timber framing materials in construction where efforts to reduce building life cycle energy are concerned.

The value of lower emissions differs largely which makes the comparison hard and less trustworthy. This is the result of different parameters like the amount of wood used in the building, type of wood, used technology, number of stories, and applied LCA method. For example, if a wooden building has used the maximum potential wood in its structural and non-structural components, the GHG emissions difference reaches to its highest level. Therefore, there is an urgent need for the decision-makers to prepare a unique format of LCA study for the world. It is necessary to do the studies in a unified way that makes the comparison possible in all locations of the world. Otherwise, the case building studies are just useful inside the same study.

Generally, there are two main solutions for the climate change mitigation, one is the lower production of GHG emissions and the other is capturing carbon. Wooden buildings can store carbon while they produce less GHG emissions. For example, Amiri et al. (Amiri et al., 2020b) conducted a study on Europe level and estimated the carbon storage by wooden buildings. They found that wooden buildings can capture 1 to 55 Mt of CO2 annually if the future building construction in Europe switches to wooden, this is equal to CO2 emissions by cement production in Europe (Perilli, 2018).

It might be assumed that wood as a building construction material can be considered as a renewable material in the countries that have forest or access to large amount of wood while the transportation of wood through sea produces low amount of emissions. Therefore, wood can be an option for the future of design and building construction if it is supplied form sustainable sources.

The benefits of wooden building construction can be a useful solution if the forests are managed efficiently and sustainably. There has been continues argument that it is better to leave the forest untouched which can be considered as natural carbon sinks. The issue arises when production of CO2 equals its capture of CO2 by forests. Meanwhile, there is surplus of wood available in the forests (Gustavsson et al., 2006), (Robertson et al., 2012) which can be used for the construction of wooden buildings without any extra cost (Lippke et al., 2004), (Dodoo et al., 2014b).

This study has three main limitations. Firstly, the lack of standardised system boundaries and definitions for life cycle energy analyses complicate the comparison of data between studies. Several conversions were carried out and several studies had to be omitted. Consequently, the interpretation of the data could have had an effect on its accuracy. It is suggested that further studies are conducted in order to develop standardised definitions and methods for LCEAs. For example, Omrany et al. (Omrany et al., 2021) have developed a framework for the definition of system boundaries of LCEAs to enable the comparison of results between studies. Assumptions, included components of a case study building, included life cycle phases, and defined boundaries affect the results of LCA studies significantly. The review study by Säynäjoki et al. (Säynäjoki et al., 2017) is a good source for readers.

Secondly, this study classified all studies that examined wooden-framed buildings as timber buildings, regardless of the detailed construction method and materials. Therefore, the results present the values for timber buildings on a general level and some detail is inevitably lost. Future studies could therefore strive to examine the LCEAs of timber buildings with respect to their construction methods (i.e., CLT, beam and column, log).

Finally, this study highlights a lack of available data concerning the demolition stage of residential buildings in LCEA studies. This is emphasised by the lower number of studies which included data about the demolition stage of the building, as well as the fact that many referred to values from the current literature rather than calculating the demolition energy on a case-by-case basis. This may be due to the fact that overall; the demolition energy contributes only a small percentage to the life cycle energy consumption of buildings and has therefore received little attention. Consequently, in addition to including energy required in the demolition stage of buildings, future studies could aim to focus on factors related to the building materials, such as speed of demolition, economic factors, and recycling or energy recovery. Additionally, common frameworks to aid the calculation of this life cycle stage could be further developed and implemented in order to extend our understanding of the link between demolition energy requirements and the selected building materials.

4 Conclusion

Buildings use energy in their life cycle including pre-use (Embodied energy), use (Operational energy) and end of life (Demolition energy). As a large amount of energy is being used by buildings worldwide, it is necessary to do research and evaluate the energy use in different stages of buildings' life cycle. Life cycle energy analysis (LCEA) is a tool for this kind of assessment. Using LCEA, this study went through literature and reviewed 100 case buildings with different material, i.e., wood, concrete or steel, from the world.

In the pre-use stage, wooden buildings have 28% and 47% lower embodied energy on average compared to concrete and steel buildings respectively. Although the number of reviewed steel case buildings were limited in this study, the embodied energy difference between wooden and non-wooden buildings is noteworthy making wooden buildings as a potential solution for climate change. Compared to use stage, the energy use in pre-use stage occurs in a very short time so any plan for the reduction of energy use is helpful for the current environmental situation of the world.

The operational energy use is mainly related to the efficiency and energy supply system of the buildings but not the building frame material, this is true while keeping the U-values the same in the buildings. In addition to energy supply systems, insulation detail, windows and building surfaces, building direction, and climate conditions are the other energy use role players. The demolition phase uses the least energy compared to other building' life cycle stages but there is need to do more research on the evaluation methods of this stage, and design more energy efficient end of life scenarios.

Author contributions

As the primary author, DS initiated the study, performed the majority of the analysis, and wrote the main body of this paper. AA supervised the study, contributed to process of data collection and provided advice on the research scope and methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2022.975071/full#supplementary-material

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