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Life cycle assessment of mass timber construction: A review

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ABSTRACT

Life cycle assessment (LCA) has been widely used to determine the environmental impact of mass timber construction (MTC) as a substitute for conventional construction. This article presents a systematic review of MTC from a life cycle assessment perspective. The goal and scope definition, life cycle inventory analysis, impact assessment and interpretation are examined and analyzed in 62 peer-reviewed articles. The results show the variety in scope, lifespan, system boundary, data sources and indicators. Studies on MTC have been conducted at the building material, component, structure, and entire building levels, as well as at the urban level. The majority of studies compare the LCA of reinforced concrete (RC) and cross laminated timber (CLT) buildings. The global warming potential (GWP) and life cycle energy are the most frequently evaluated category indicators among the articles. It is found that the average embodied energy of mass timber buildings is 23.00% higher than that of RC alternatives, while the average embodied greenhouse gas (GHG) emissions of RC buildings are 42.68% higher than that of mass timber alternatives. There is a clear general trend that mass timber buildings generally have lower GWP and life cycle primary energy (LCPE) than RC and steel buildings. Eventually, sensitivity analysis, carbon storage and outlook of the mass timber are also reviewed and discussed in the literature.

1. Introduction

Current environmental challenges have attracted great attention throughout the world to promote initiatives aimed at reducing the impact of human activities on the environment. The Paris Agreement, adopted in December 2015, reinforced the targets and measures to reduce greenhouse gas (GHG) emissions [1], limiting the rise of the global average temperature to 1.5 °C above the pre-industrial level.

The building sector has become a prominent target for environmental impact reduction as it accounts for one-third of the globe's final energy and contributes around 15% of the direct carbon dioxide emissions [2]. With trends such as population increase and urban migration, the construction industry's energy demand and associated emissions continue to rise, particularly in developing countries [3]. It is predicted that about 70% of the population in the world will live in urban regions by 2050 [4], resulting in an expansion in housing and infrastructure. To reach carbon neutrality by 2050, all the new buildings and 20% of the current building stock are expected to be zero-carbon by 2030 [2].

The construction of buildings and infrastructure was reported to emit 7 $GtCO_{2e}$ in 2015, of which 4 $GtCO_{2e}$ were attributed to material usage in construction [5]. As buildings become more energy-efficient, attention has shifted to the environmental impact of construction materials [6]. By substituting wood, bamboo, and other plant fibers for energy-intensive materials such as concrete and steel in building construction, GHG emissions from material manufacturing can be greatly reduced [7]. A 17% increase in wood usage resulted in a 20% reduction in carbon emissions from building materials [8], promoting the development of the wood industry to mitigate global warming.

Over the last two decades, a new class of structural wood products has been developed that uses manufacturing waste and low-grade and smaller diameter trees as raw materials [9]. These exceptionally strong and versatile products are known as mass timber. Initially developed in Austria and Germany in the 1990s, demand for mass timber continues to grow globally. Mass timber (Fig. 1 [10]) is increasingly used in building applications [11], as people begin to recognize and take advantage of its benefits [12,13]. Cross laminated timber (CLT), sometimes termed X-Lam or Cross-Lam [14], is the most extensively used mass timber, and is regarded as a suitable alternative to conventional building materials such as reinforced concrete (RC). CLT is commonly constructed utilizing an uneven number of layers of timber boards (typically three, five, or seven), with adjacent layers glued to each other in orthogonal orientations [15]. Recently, the environmental impact of CLT products and related construction has received increasing attention globally.

Life cycle assessment (LCA) is a technique for assessing the environmental impact of a product throughout its complete life cycle, which

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Abbreviations

LCA	Life cycle assessment
MTC	Mass timber construction
RC	Reinforced concrete
CLT	Cross laminated timber
GWP	Global warming potential
GHG	Greenhouse gas
LCPE	Life cycle primary energy
P&C	Product and construction
EoL	End of life
LCC	Life cycle cost
BIM	Building Information Modelling
LVL	Laminated veneer timber
LWT	Light weight timber
PE	Primary energy
MHM	Massiv-Holz-Mauer
SCC	Steel-concrete composite
BoQ	Bill of quantities
LCI	Life cycle inventory
EPD	Environmental product declaration
USLCI	U.S. Life Cycle Inventory Database
AP	Acidification potential
EP	Eutrophication potential
LCE	Life cycle energy
ODP	Ozone depletion potential
SFP	Smog formation potential
SA	Sensitivity analysis
PF	Phenol formaldehyde

has been adopted in the context of building since the early 1990s [16]. The standard methodological framework for LCA entails goal and scope definitions, life cycle inventory analysis, impact assessment and interpretation [17]. Building phases can be classified into several stages (Fig. 2) based on the process involved, including the product and construction (P&C) stage, operational stage, End of life (EoL) stage and supplementary information beyond building life cycle (Benefits) stages. The majority of research complied with EN 15978 and ISO 14044 as guidelines. According to the National Institute of Standards and Technology Handbook, life cycle cost (LCC) evaluates all costs associated with owning, operating, maintaining, and ultimately disposing of a project [18], and is classified as static or dynamic [19].

With the growing interest in building LCAs, the number of studies is increasing each year [20,21]. Nwodo et al. [21] presented an overview of the current focus in building LCA within the last decade, including life cycle energy assessment, life cycle greenhouse gas emissions assessment, building refurbishments, dynamic LCA, uncertainty analysis, integration of LCA in rate systems, integration of LCA with LCC and Building Information Modelling (BIM)-based LCA. However, limited information is available on the review of mass timber construction (MTC) LCA. Cadorel et al. [22] evaluated the environmental performance of CLT construction in medium-density residential buildings with 9 samples in 2018. Himes et al. [23] compared the GHG emissions between 18 comparisons of mass timber and conventional materials in the construction phase (A1-A5). Rasmussen et al. [24] examined 81 environmental product declarations (EPD) of structural wood products. From the literature research, no comprehensive review has been identified on the comprehensive life cycle assessment of mass timber construction.

The study aims at delivering a systematic review of MTC from the perspective of life cycle assessment to fill the existing gaps in the research field. This review examines recent advances in the application of LCA to mass timber and summarizes key findings from the existing literature. The review also compares the environmental impact of mass timber construction with that of conventional construction and explores the factors that contribute to the differences. Additionally, it contains specifics about the method, such as the scope, system boundary, functional unit, data source and databases. Eventually, the development and outlook of mass timber are explored and summarized.

The following sections outline the structure of this study. Section 1 presents the introduction of life cycle assessment, mass timber and the existing research gap. Section 2 describes the research method for conducting a systematic literature review. Section 3 provides an overview analysis of the available literature. Section 4 discusses the findings of the existing LCA research on mass timber, including the goal and scope definition, life cycle inventory analysis, impact assessment and interpretation. Finally, sensitivity analysis, carbon sequestration and outlook are addressed as references for further research.

2. Method

This section describes the method for searching and scrutinizing existing literature. Systematic literature reviews are regarded as a thorough, complete, transparent, and reproducible way to identify, select, and critically appraise relevant research that is also able to gather

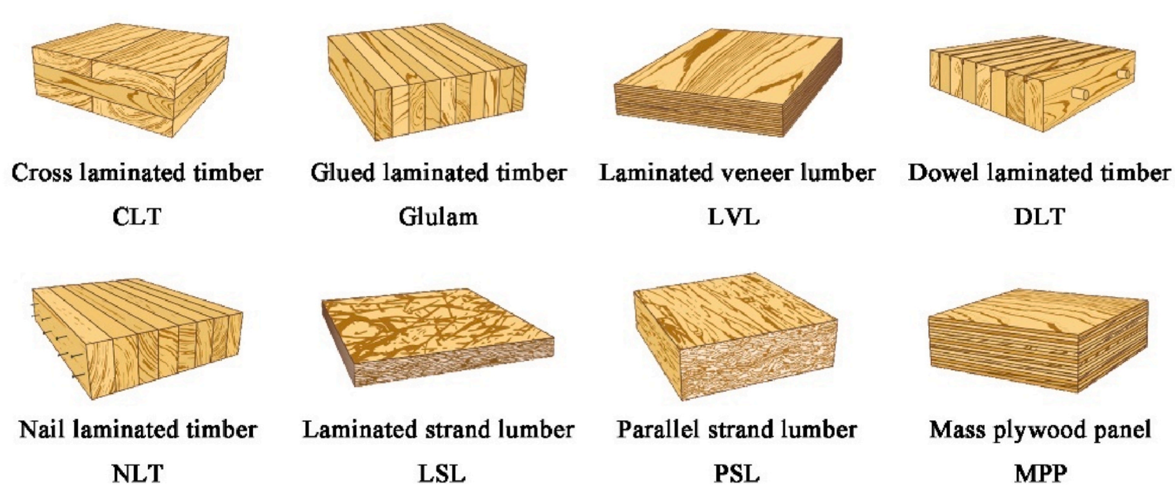

Fig. 1. Mass timber [10].

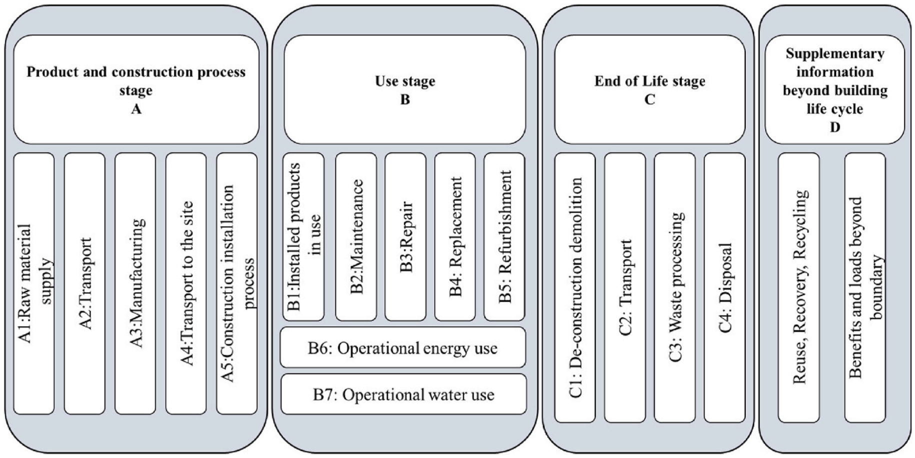

Fig. 2. LCA stages of the building sector.

and analyze data from the studies included in the review [25–27]. By adopting specific and systematic methods for analyzing papers and all relevant material, bias can be eliminated, thereby generating accurate findings from which conclusions can be derived and decisions taken [28]. Fig. 3 illustrates the review procedure. The publications were searched through the databases of Scopus and Web of Science. Web of Science comprises of numerous database platform, including Science Citation Index Expanded, Social Science Citation Index, and Arts & Humanities Citation Index. Containing more than 12,000 high-impact international journals, Web of Science is widely utilized by scholars throughout the world [29]. Introduced by Elsevier in 2004, Scopus covers more than 49 million records, including trade publications, open-access journals, and book series. It contains 20,500 peer-reviewed journals from 5000 publishers, together with 1200 open access journals, over 600 trade publications, 500 conference proceedings and 360 book series from all areas of science [30]. The keywords 1 (life cycle assessment/life cycle analysis/environmental impact/LCA) and keywords 2 (mass timber/cross laminated timber/CLT) were combined and used in

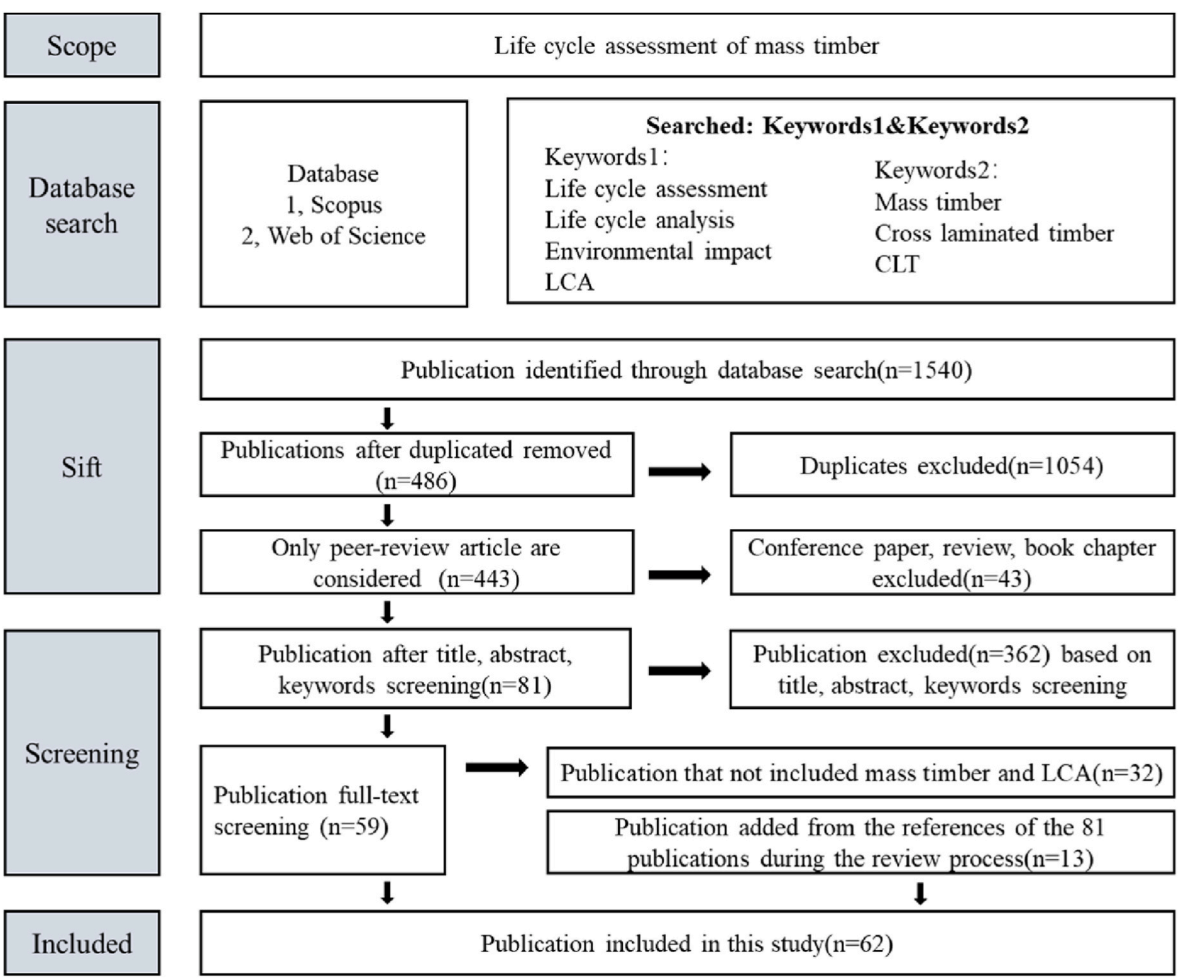

Fig. 3. Review process of this study.

search engines for title, abstract and keyword searches. The search was carried out in March of 2022 with a total of 1540 returns. It is worth noting that this review is limited to peer-reviewed articles on mass timber life cycle assessment. Therefore, the conference paper, book chapter and reviews were excluded from this study. After further screening of the title, abstract and keywords of the retrieved articles, only 81 publications were left for full-text screening. The following step excluded 32 articles that either did not conduct LCA or were not explicitly labeled as mass timber. In addition, 13 related papers were manually added to the study, which were obtained from the references of 81 publications during the review process. These 13 papers were not in the 81 papers but were highly relevant to the scope and were therefore added manually to the literature body. The 62 peer-reviewed papers were extensively examined and researched to identify deficiencies and propose future directions for LCA development in mass timber construction to promote sustainable construction.

3. Literature result overview

For systematic analysis, we classified articles according to publication year, publishing journal, building type and scope. As illustrated in Fig. 4, the number of publications on mass timber LCA has increased steadily over the last two decades. Petersen et al. [31] conducted the first life cycle study of mass timber construction in 2002, evaluating the GHG emissions associated with utilizing glulam to replace steel beams at the airport. Recent years have seen an increase in the number of LCA studies analyzing mass timber construction since several countries have altered their rules to promote mass timber sustainable construction [32, 33].

The distribution of journals among the retrieved papers is depicted in Fig. 5. The top four journals account for more than 60% of the selected publications. *Sustainability* (22.6%) is the most influential publisher, with 14 LCA articles on mass timber published, followed by *Energy and Buildings* (11 articles), *Building and Environment* (7 articles) and the *Journal of Cleaner Production* (6 articles).

Fig. 6 shows the number of mass timber LCA studies published by countries. As can be observed, the majority are carried out in developed countries. Over half of the LCA case studies (32 articles) on mass timber have been conducted in Europe, particularly in northern Europe (i.e., Sweden, Finland, Norway). This may be due to the mass timber initially developed in Europe, where forest resources are abundant. In addition, there are 12 papers reported in the United States, ranking first among all countries. In Asia, only China (6 articles), Japan (2 articles) and Malaysia (1 article) contribute to mass timber LCA. No mass timber LCAs have been conducted in Africa, and only one article (Chile) has been published in South America.

4. Results

As defined by EN ISO 14040 and EN ISO 14044, LCA comprises the following phases: goal and scope definition, life cycle inventory analysis, impact assessment and interpretation.

4.1. Goal and scope definition

When performing the LCA, the goal and scope of the study should be stated, including the studied scope, functional unit, system boundary and assumptions.

4.1.1. Studied scope

Among the 62 publications, 44 papers focused on the environmental impact of mass timber buildings. The majority of studies compared the life cycle assessment of reinforced concrete and cross laminated timber buildings [34]. Along with CLT buildings, mass timber construction, which is composed of glulam or laminated veneer timber (LVL) columns and beams as well as CLT floors and slabs [35–39], was also compared to other conventional structural buildings composed of light weight timber (LWT), brick, masonry and steel alternatives as reference comparison objects [40–43]. For instance, Pal et al. [40] examined the life cycle energy-cost optimal building in RC, CLT and steel buildings. In addition to comparing mass timber buildings to conventional buildings, there are LCA comparisons among different mass timber buildings, such as CLT buildings versus beam and column buildings (LVL and glulam) [37,44], and CLT buildings versus glulam buildings [45]. Balasbaneh et al. [45] revealed that CLT buildings had lower embodied energy and global warming potential (GWP) than glulam buildings, while glulam buildings cost approximately 7% less than the CLT alternative.

Among the selected literature, building typologies assessed were residences, offices, stadiums, garages, airports, [31,41,46,47]. For residential buildings, 46.77% of the papers emphasized residential MTC (see Table 1), ranging from single houses to high-rise apartments. Dong et al. [46] compared the life cycle energy and GWP of RC and CLT stadiums in five climate zones in China. Zeitz et al. [41] developed LCA on 4 real parking garages (pre-cast concrete, post-tensioned concrete, cellular steel and mass timber). Peterson et al. [31] compared the GHG emissions by using glulam beams versus steel alternatives at the airport, determining that utilizing glulam instead of steel results in a 0.24–0.34t reduction in GHG emissions per m^3.

The number of storeys in the studies varied significantly, ranging from 1 to 43-storey. Among them, the majority involved 7 ~ 9-storey buildings. The highest mass timber building studied in the literature was a hypothetical 43-storey commercial building by Li et al. [48], concentrating on the embodied environmental impact of three buildings (RC, RC and timber non-structural element, CLT with RC core). Guo et al. [49] investigated the energy consumption of RC and CLT buildings

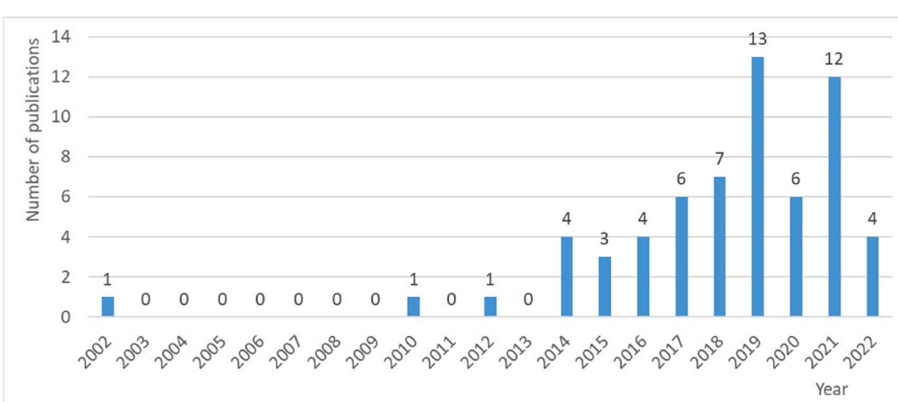

Fig. 4. Number of publications of LCA for mass timber by year.

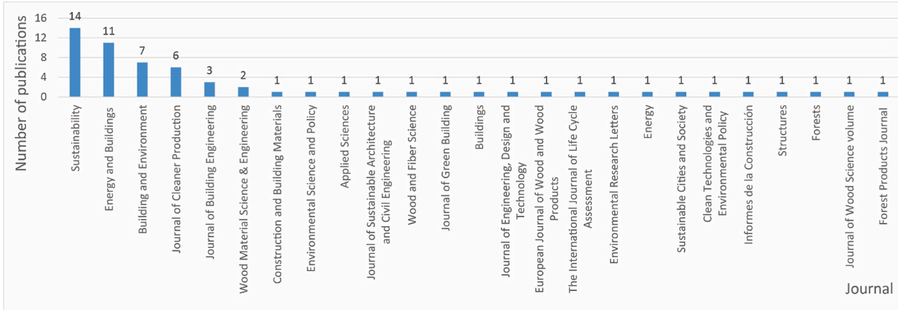

Fig. 5. Number of publications of LCA for mass timber by journals.

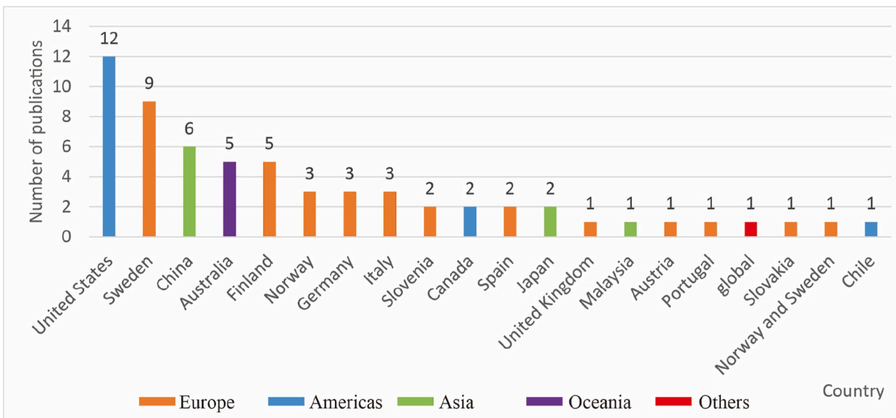

Fig. 6. Number of publications of LCA for mass timber by countries.

with varying storeys.

Furthermore, passive standards and energy-efficient cases were assessed in the LCA of MTC. Dodoo et al. [36] developed LCA on the life cycle carbon footprint of conventional and low-energy versions of CLT, beam and column, and light frame module timber buildings, revealing that low-energy version of CLT building offered the lowest carbon emissions. Tetty et al. [50] evaluated the life cycle primary energy (LCPE) of precast concrete, CLT and modular timber buildings designed to meet the standards of the Swedish building code and passive criteria. It demonstrated that CLT and modular buildings resulted in lower primary energy (PE) and greater biomass residue than concrete equivalents. In comparison to Swedish building code alternatives, passive standard buildings consumed a greater proportion of primary energy during the P&C phase and had a significantly lower life cycle energy balance.

Several studies performed LCA of hybrid structures of mass timber construction, where mass timber is combined with additional structures such as steel or RC [35,48,51]. Robertson et al. [35] compared the environmental impact of a reinforced concrete building to that of a hybrid mass timber building constructed of glulam columns, CLT floors and a concrete core. Li et al. [48] explored the embodied energy of hybrid CLT with an RC core. Takano et al. [52] investigated the effects of combining RC, light weight timber (LWT), and CLT structures in a building on life cycle primary energy.

Along with the entire building, others emphasized the LCA of mass timber components or elements that comprise buildings, such as walls and floors. For instance, Larivière-Lajoie et al. [53] conducted an LCA analysis on light-frame construction, lightweight steel framing, CLT and glulam wall assemblies, reporting that embodied impact represented 40–66% of all environmental impact in the life cycle assessment of wall assemblies. Kovacic et al. [54] developed a tool for evaluating the LCC and LCA of façade systems and tested three distinct façade systems (steel liner tray, steel sandwich panels, CLT). The environmental performance of the Massiv-Holz-Mauer (MHM) wall, part of the CLT system patented in 2005 with no adhesives used, was evaluated in a classroom in Italy by Ref. [55]. It was also compared with a conventional brick wall system by Santi et al. [14]. Chiniforush et al. [56] explored the life cycle energy of adoption of steel-timber composite (Steel and CLT) and steel-concrete composite (SCC) floors in steel and concrete structures. Another study compared CLT slabs to concrete alternatives in terms of CO_2 emissions, economics, and structural design [57]. Vanova et al. [58] compared the impacts of construction components in a CLT building, reporting that the foundation contributed the most to photochemical oxidation and the depletion of fossil fuels, while the exterior wall accounted for the largest share of acidification, eutrophication, depletion of elements and water scarcity.

Apart from highlighting MTC, several research provided specific data for mass timber materials. Bowers et al. [59] concentrated on glulam cradle to gate data in the northwest and southeast Pacific areas of the United States. Lan et al. [60] developed a dynamic cradle to grave life cycle assessment of CLT manufacturing in the Southeast United States over a 100-year period. Furthermore, LCA studies have been carried out and expanded to the urban level. D'Amico et al. [6] investigated the possibility of replacing steel-concrete floor slabs in steel structures with CLT slabs, saving an average of 50 Mt of CO_2 by 2050.

4.1.2. System boundary

The definition of the system boundary plays an essential part in the environmental assessment of MTC [67]. One of the difficulties inherent in comparing LCA results is caused by various system boundaries [94]. Cradle to gate, cradle to site, and cradle to grave were the most commonly used system boundaries in literature studies [54,95]. In this study, reuse, recovery, recycling, and benefits beyond boundary were considered in cradle to grave.

Table 1
Definition and scope of the reviewed paper.

	Area	Country	Year	City	Scope	System boundary	Reference
The entire building	Europe	Norway/ Sweden	2019	Trondheim and Växjö	CLT/glulam	P&C and operational stage	[11]
	Europe	Spain	2021	Madrid	CLT	Cradle to grave	[61]
	Europe	Sweden	2016	Stockholm	concrete/CLT/increased bio-CLT	Cradle to grave	[62]
	Europe	Finland	2014	Otaniemi	precast concrete/CLT/light weight timber	Cradle to gate	[63]
	Europe	Norway	2022	Trondheim	CLT/concrete	Cradle to grave	[64]
	Europe	Sweden	2014	Växjö	(conventional/low-energy) CLT/beam-and-column (glulam and LVL)/prefabricated light-frame volume	Cradle to grave	[36]
	Europe	Sweden	2010	Växjö	wood-framed (glulam)	Cradle to grave	[65]
	Europe	Sweden	2019	Växjö	(Swedish building code/passive criteria) precast concrete/CLT/modular timber	Cradle to grave	[50]
	Europe	Germany	2015	Mietraching	LVL with CLT elevator shaft	Cradle to grave	[66]
	Europe	Finland	2017	Helsinki	RC/CLT/steel	P&C and operational stage	[40]
	Europe	Finland	2015	Helsinki	light weight timber/CLT/RC/autoclaved aerated concrete/brick/steel/combination 1&2(LWT-RC)/ combination 3(CLT-RC)	Cradle to grave	[52]
	Europe	Norway	2019	Oslo	RC/light frame timber/massive timber frame (CLT)/beam & column timber frame (LVL&glulam)/modular timber frame	Cradle to grave	[44]
	Europe	Sweden	2014	Växjö/Östersund/Kiruna	CLT/beam -and-column/modular buildings	Cradle to grave	[37]
	Europe	UK	2018	Cambridge	concrete/masonry/CLT/steel	P&C and EoL stages	[67]
	Europe	Germany	2017	–	Single House: timber frame + mineral wool/CLT + mineral wool/perforated brick + ETICS/perforated brick, single-leaf Multi-storey: CLT + mineral wool/porous concrete/ perforated brick + insulating plaster/perforated brick + mineral wool	Cradle to grave	[68]
	Europe	Italy	2018	Milan	CLT with rock wool/CLT with wood fiber/RC with cellular concrete blocks/RC with rectified bricks/steel with rock wool/steel with wood fiber	Cradle to grave	[69]
	Europe	Spain	2019	Granada	CLT	Cradle to grave	[70]
	Europe	Slovenia	2019	Maribor	Detached/Semi-detached/Terraced/2-storey/3-storey CLT houses	Cradle to grave	[71]
	Europe	Sweden	2021	–	Concrete/CLT/Modular timber	P&C, EoL and benefits stages	[72]
	Europe	Slovakia	2021	–	CLT	Cradle to gate	[58]
	Europe	Sweden	2021	Växjö	CLT	Cradle to grave	[73]
	Europe	Austria	2021	Vienna	RC/CLT	Cradle to grave	[74]
	Europe	Finland	2015	Helsinki	Detached house/Row house/Townhouse/Apartment block of light weight timber/CLT/RC/Steel	Cradle to grave	[75]
	Europe	Finland	2014	Helsinki	Light weight timber/CLT/RC/Autoclaved aerated concrete/Brick/Steel	Cradle to gate	[76]
	North America	U.S.	2019	Seattle	hybrid CLT (fireproofing& charring design)/RC	Cradle to site	[77]
	North America	U.S.	2020	Oregon	RC/CLT	Cradle to grave	[47]
	North America	Canada	2012	Burnaby	RC/hybrid mass timber (glulam beam and column frame with CLT floor, CLT slab and concrete core)	Cradle to gate	[35]
	North America	U.S.	2019	Oregon	pre-cast concrete/post-tensioned concrete/cellular steel/ Mass timber	Cradle to gate	[41]
	North America	U.S.	2021	–	mass timber (glulam frame and CLT floor)/Steel	P&C, EoL and benefits stages	[38]
	North America	U.S.	2021	Oregon	concrete/mass timber (glulam frame and CLT wall and slab)	Cradle to grave	[39]
	North America	U.S.	2021	Washington/ Massachusetts/Georgia.	concrete/mass timber	Cradle to site	[78]
	South America	Chile	2022	Santiago	concrete/mass timber	P&C and operational stage	[79]
	Asia	China	2016	Xian/Harbin	RC/CLT	Cradle to grave	[80]
	Asia	China	2017	Harbin	RC/CLT	Cradle to grave	[49]
	Asia	China	2019	Harbin/Beijing/ Shanghai/Shenzhen/ Kunming	RC/CLT	Operational stage	[81]
	Asia	China	2017	31 Cities	RC/CLT	Operational stage	[82]
	Asia	China	2020	Harbin/Beijing/ Shanghai/Guangzhou/ Kunming	RC/timber (CLT)	Cradle to grave	[46]
	Asia	Malaysia	2021	–	hardwood CLT/softwood CLT/hardwood glulam/ softwood glulam	Cradle to grave	[45]
	Asia	China	2022	Chongqing	concrete/CLT	Cradle to site	[83]
	Asia	Japan	2020	Kyushu	CLT	Cradle to site	[84]
	Oceania	Australia	2020	Melbourne/Sydney/ Brisbane	RC/CLT	Cradle to grave	[34]

(continued on next page)

Table 1 (*continued*)

	Area	Country	Year	City	Scope	System boundary	Reference
	Oceania	Australia	2017	Brisbane	three types of LVL/concrete/steel	Cradle to grave	[85]
	Oceania	Australia	2018	Sydney	STC slab with RC wall/SCC slab with RC wall/STC slab with CLT shear walls/RC	Cradle to grave	[56]
	Oceania	Australia	2018	Melbourne	concrete/CLT	Cradle to site	[86]
	Oceania	Australia	2019	Melbourne	RC/RC and timber non-structural element/mass timber with RC core	Cradle to gate	[48]
Mass timber product	Europe	Portugal	2021	Coimbra	cross-insulated timber panel	P&C and EoL stages	[87]
	North America	U.S.	2020	–	CLT production	Cradle to grave	[60]
	North America	U.S.	2017	Pacific Northwest and the Southeast	glulam	Cradle to gate	[59]
	North America	U.S.	2019	Washington	CLT products	Cradle to gate	[88]
	North America	U.S.	2019	Oregon	CLT products	Cradle to gate	[89]
	North America	U.S.	2021	Fayetteville	CLT transport	Transportation to the site	[90]
	Asia	Japan	2020	–	CLT	Cradle to gate	[91]
Floor	–	global	2021	–	steel-concrete slab/CLT slab	–	[6]
façade	Europe	Germany	2016	–	steel liner tray/steel sandwich panel/CLT	Cradle to grave	[54]
Wall	North America	Canada	2022	Quebec	light-frame construction (3)/lightweight steel framing (1)/CLT (2)/glulam (2)	Cradle to grave	[53]
Wall	Europe	Italy	2019	Sant'Ulderico	MHM	Cradle to grave	[55]
Wall	Europe	Italy	2016	–	MHM/brick wall	Cradle to gate	[14]
Wall and Roof	Europe	Slovenia	2018	–	RC/Brick/CLT/timber-frame panel	Cradle to gate	[43]
Floor	Europe	Sweden	2019	–	concrete slab/CLT slab	Cradle to gate	[57]
Floor	North America	U.S.	2018	Oregon	concrete-CLT/cork tile-CLT floor	Cradle to gate	[92]
Beam	Europe	Norway	2002	Oslo	glulam/steel	P&C, EoL and benefits stages	[31]
Beam	Europe	Sweden	2018	–	glulam/steel beam	Cradle to gate	[93]

"-" means the unavailability of the data.

The cradle to gate system boundary is defined as the extraction of raw materials to the production gate [14,35]. Several studies referred to the complete production phase, including transportation and on-site erection, as cradle to gate [77,78,83,86], alternatively referred to as cradle to site (A1-A5, shown in Fig. 2) [95]. To distinguish between these two stages, the cradle to site was considered to identify the A1-A5 in this review. The cradle to grave approach encompasses all the stages in the buildings, from the materials extraction to the EoL stage. Cradle to grave was the most frequently adopted system boundary in the retrieved research (see Table 1). For instance, Jayalath et al. [34] employed LCA to evaluate the cradle to grave impact of RC and CLT in 3 Australian cities. Liu et al. [80] compared cradle to grave LCA on a 7-storey residential RC and CLT buildings in China. Chen et al. [47] adopted Athena Impact Estimator for Building software to compare the cradle to grave LCA for a 12-storey building constructed from CLT and RC in the United States. Dodoo et al. [36] explored the cradle to grave LCA of conventional and low-energy versions of three timber multi-storey buildings in Sweden.

Certain stages were separated and evaluated in various research. Guo et al. [82] presented the operational energy and carbon emissions of CLT and RC residential buildings in 31 Chinese cities. Dong et al. [81] evaluated the operational energy of a 15-storey office in RC and CLT buildings in 5 climate zones of China, observing that CLT buildings consumed much less heating energy in cold and severe cold regions. Moncaster et al. [67] considered the carbon footprint of various structures (concrete, masonry, CLT, steel) in a Cambridge residential college during the P&C and EoL stages. Furthermore, some researchers investigated forest biogenic carbon sequestration and the system boundary included managed forestry, forest growth, and biogenic carbon emissions during the EoL phase [62].

4.1.3. Functional unit

The functional unit ensures the comparability of the results by defining the quantification of the identified function of the product based on ISO 14040:2006 [96]. The retrieved literature contained a range of functional units (Table 2). Among the 62 mass timber LCAs, 54.84% of the total references employed the most common functional unit of 1 m^2 of the building area, allowing for comparisons of environmental impact based on the equivalent functional performance of different buildings [97]. Likewise, a few studies reflected the 1 m^2 of the net heated area [52,71,73,75,76]. Moreover, several research studies utilized the entire building as the functional unit [45,80,98], which meant that comparisons could be made only if the buildings were comparable in size and function. When studies on energy consumption were conducted, 1 m^2 of total floor area per year was also used as a functional unit [81,82]. In studies that examined the LCA of mass timber components and elements, 1 m^2 of façade area [54], 1 m^2 of roof or wall component [43,55], 1 m^2 of panel [87] were adopted as functional units. 1 m^3 of CLT manufacturing was also a frequently utilized functional unit when analyzing the environmental impact of mass timber production [59,91]. Hemmati et al. [90] carried out LCA of mass timber transportation, using 1 ton of transported CLT as a functional unit. Due to the variety of functional units adopted in LCA studies, some argued that the definition of functional units was inadequate and recommended that functional units should include building type, lifespan and pattern of use [21].

4.1.4. Lifespan

The lifespan of a building has a significant impact on overall energy consumption and material replacement during the use phase. It is universally acknowledged that the operational phase dominates the life cycle impact. 66.13% of the references (41 papers) included the operational stage. The lifespan varies considerably, ranging from 35 to 100 years (Table 2). The majority of the referred researchers preferred a 50-year life cycle of buildings in LCA, accounting for 43.55% of the retrieved papers. A few studies performed dynamic LCA. Peñaloza et al. [62] argued that the total duration of the building dynamic LCA should be at least 230 years, including the forest harvesting (80 years), building

Table 2
Functional units and lifespan in the reviewed papers.

Storey	Lifespan	Building typology	Functional unit	Reference
9(CLT)/8 (glulam)	50	Residential	1 m^2 of heated floor area per year/1 m^2 of either external wall or internal floor area per year	[11]
2	50	Residential	1m^2 of net floor area per year	[61]
–	0-300/-80-220[a]	Residential	1 m^2 of living area for fifty years	[62]
1	–	Box building	1 m^2 of building area	[63]
5(concrete)/8 (CLT)	100	Residential	1 m^2 of total area for 100 years	[64]
4	50	Residential	1 m^2 of living area	[36]
8	50/100	Residential	1 m^2 of total floor area	[65]
6	80	Residential	1 m^2 of heated floor area	[50]
4	50	Residential	1 m^2 of living floor area	[66]
3	50	Residential	1 m^2 of area per year	[40]
2	50	Residential	1 m^2 of net heated floor area	[52]
4	50	Residential	1 m^2 of heating floor area	[44]
4	50	Residential	1 m^2 of living area	[37]
4	–	Residential	The entire building	[67]
1/7	50	Residential	1 m^2 of gross external area	[68]
9	100	Residential	The entire building	[69]
4	50	Residential	1 m^2 of gross floor area	[70]
1/2/3	50/100	Residential	1 m^2 of building net heated floor area	[71]
6	–	Residential	The entire building	[72]
1	–	Residential	The entire building	[58]
8	50	Residential	1 m^2 of heated floor area	[73]
8	100	Mix-used (offices, commercial residential)	1 m^2 net floor area	[74]
2/3/4	50	Residential	1 m^2 of net heated floor area	[75]
3	–	Residential	1 m^2 of net heated floor area	[76]
8	–	Office	1 m^2 of total floor area	[77]
12	60	Mixed-use (retail, public exhibition, office, residential)	The entire building	[47]
5	50	Office	The entire building	[35]
–	–	Parking garages	1 m^2 of total parking area	[41]
5/12	60	Office(5F)/Residential(12F)	The entire building	[38]
12	60	Mixed-use (commercial and residential)	1 m^2 of total floor area	[39]
8/12/18	–	Mixed-use (commercial and residential)	1 m^2 of total floor area	[78]
5	50	Residential	1 m^2 of total floor area.	[79]
7	50	Residential	1 m^2 of floor area	[80]
4/7/11/17	50	Residential	1 m^2 of total floor area	[49]
15	–	Office	1 m^2 of total floor area per year	[81]
7	50	Residential	1 m^2 per year	[82]
/	50	Stadium	1 m^2 of total floor area	[46]
1	50	Residential	The entire building	[45]
8	80	Residential	1 m^2 of total floor area	[83]
2	–	Institute/laboratory	The entire building	[84]
8	50	Residential	1 m^2 of building area	[34]
4	60	Residential	The entire structural frame of building	[85]
5/10/15	50	Office	1 m^2 of total floor area	[56]
15(concrete) /11(CLT)	–	Commercial (Concrete)/Mixed (CLT)	1 m^2 of total floor area	[86]
43	–	Commercial	The entire building	[48]
–	50	–	1 m^2 of panel	[87]
–	100	–	1 m^3	[60]
–	–	–	1 m^3 of final product packaged for shipment	[59]
–	–	–	1 m^3 of CLT	[88]
–	–	–	1 m^3	[89]
5	–	Mix-used	1 ton of transported CLT	[90]
–	–	–	1 m^3 of CLT production	[91]
–	30	–	–	[6]
–	35/40	–	1 m^2 of facade area	[54]
3	50	Office	1 m^2 of load-bearing wall	[53]
1	50	Classroom	1 m^2 of wall element	[55]
–	100	–	1 m^2 of exterior wall	[14]
–	–	–	1 m^2 of roof or wall component	[43]
–	–	–	1 m of span length	[57]
–	–	–	11 m^2 section of floor system	[92]
–	50	Airport	1 m^2 of roof area	[31]
–	–	–	The entire beam	[93]

[a] Indicates the time span of the study.

service life (50 years) and capturing the effects after pulsed emissions or storage have occurred (100 years). As a result, carbon emissions from concrete, CLT, and increasing bio-CLT buildings were investigated between the years 0–300 and −80–220 using dynamic life cycle assessments.

On the other hand, Grant et al. [99] advocated that rather than making generalizations regarding building lifespan, realistic and thoughtful assumptions based on the science of case studies should be addressed. According to an Athena survey, 60–80% of demolished concrete and steel buildings were demolished within 50 years, whereas

65% of demolished wooden buildings were demolished after more than 75 years [39]. However, mass timber is an emerging material, making it difficult to predict its lifespan.

4.1.5. Definitions and assumptions

Definitions and assumptions based on system boundaries and EoL also lead to significant inconsistencies in results. The demolition stage is still a process that has not yet occurred and can only be estimated on the basis of assumptions. For instance, the life cycle assessment of landfill wood versus biomass recovery from wood in the EoL stage demonstrated a clear difference [62]. The global warming potential of a dynamic LCA on a CLT building for 300 years was 218 kg CO_2 eq/m^2 under the baseline scenario (90% of biomass materials were incinerated), while the value was 196 kg CO_2 eq/m^2 if 70% of biomass materials were landfilled and 30% were incinerated. The results differed significantly depending on whether carbon sequestration in forests occurred before or after the manufacture of materials [62]. The baseline scenario was based on the assumption that forest growth occurred after manufacturing. With regard to the forest growth before product manufacturing, the value for CLT building was 79 kg CO_2 eq/m^2. According to Peterson et al. [31], the way steel and glulam beams were handled during demolition had a major effect on the variations in life cycle energy usage. Three scenarios for glulam waste disposal were considered: energy from burning of glulam substituted oil; energy from burning of glulam replaced existing energy source; and landfilled. The findings indicated that if the wood was burnt, it generated more than 150 kWh/m^2, and if the wood was landfilled, it required 12 kWh/m^2 owing to the treatment at the landfill. Two waste disposal options for steel were considered: alternative scrap and alternative ore. It revealed that if steel replaced other scrap steel, the energy consumption for waste handling was nearly negligible, while if the steel substituted ore, the energy consumption utilized in the manufacture was offset.

4.2. Life cycle inventory analysis

Life cycle inventory analysis (LCIA) is the most complex and time-consuming process in LCA, which entails data collection and quantification of relevant inputs and outputs throughout the product life cycle [96,100]. Due to the diverse data sources used in the retrieved reference papers, a wide variety of data was identified. This section covered the following topics: 1) building material preparation, 2) the building process, and 3) operational consumption.

4.2.1. Building material preparation

4.2.1.1. Bill of quantities. Building material preparation encompasses the entire process from cradle to grave for the materials and services used in buildings. The bill of quantities (BoQ) of MTC LCA was identified mainly from BIM models, architectural drawings, construction site data or development firms.

The material and component quantities can be exported from the Revit model to Excel to form the bill of quantities in MTC LCA [38]. Additionally, the combination of LCA and BIM is growing in popularity. Tally, an Autodesk Revit (BIM) plugin, assesses the environmental impact of building materials using the LCA approach [101]. Some researchers defined the BoQ based on the construction drawings of architects and structural engineers [41,66]. Gustavsson et al. [65] estimated the quantities of building materials according to drawings and personal communication with the staff involved in the construction. Lechón et al. [61] defined material quantities by referring to the project's technical measurements and budget information. Additionally, some investigations were conducted using data from on-site construction and daily material receiving logs [84,86]. Some adopted data from development firms. For instance, The BoQ of CLT and concrete buildings was provided by Veidekke Company, combined with an analysis of the BIM model in Revit [64]. Another study analyzed data supplied by building systems companies [37].

It's worth noting that some studies considered material waste and revised the quantity of building materials. According to some research, concrete (1.5%), insulation (7%), plasterboard (10%), wood (10%) and steel reinforcement (15%) and other materials waste(5%) except crushed stone and porcelain were added in the material quantities [65,72]. Some estimated a mass increment of 5% for construction waste [45]. However, Andersen et al. [64] argued that prefabricated elements such as CLT elements and bathrooms should not be included in waste share calculations, as these components are delivered as complete modules.

4.2.1.2. Mainstream life cycle inventory database. According to the reviewed literature, the life cycle inventory (LCI) database was adopted to evaluate the environmental impact of MTC (Table 3). There are many LCI databases such as Gabi, USLCI and Athena, but the most widely used is Ecoinvent, one of the most completely generic databases in the world. Most of the mass timber cases (31 articles) adopted the Ecoinvent database, followed by environmental product declaration (EPD), U.S. Life Cycle Inventory Database (USLCI), and Athena databases. According to Ref. [69], the use of the different databases may influence the LCA results of mass timber, RC and steel buildings by 30%. Takano et al. [63] compared five databases for the GHG emissions in the material production phase of LWT, CLT and precast concrete box buildings. Though the trends in GHG emission values across all databases were consistent (the concrete case has the highest value while the LWT case has the lowest value). The study showed that the GHG emission values of different building materials are different, especially wood fiberboard and cellulose fiber insulation materials. Therefore, the adoption of a correct and appropriate database is an essential part of the

Table 3
LCI databases used in mass timber construction.

Country	Source of LCI database	Reference
Globe	Ecoinvent	[14,36,37,40,44,45,52,53,55,58,61–63,66,69,70,72–79,83,85,87,88,90,92]
	Inventory of Carbon & Energy (ICE)	[41,56,69]
	Environmental product declaration (EPD)	[11,36,54,63,64,69–71]
Germany	Gabi	[63,90,92]
	Ökobau.dat	[43,54,68]
Europe	European reference Life Cycle Database	[77,92]
Australia	Environmental Performance in Construction database	[34]
	Australian National Life Cycle Inventory Database	[48,85]
	Australian national greenhouse gas accounts	[34,86]
North America	U.S. Life Cycle Inventory Database (USLCI)	[35,47,59,77,78,88,92]
	ATHENA	[35,38,39,47,49,77,80]
	Building for Environmental and Economic Sustainability (BEES)	[35]
	Committee on Renewable Resources for Industrial Materials (CORRIM)	[77–79]
	DATASMART	[39,78,83]
China	Chinese Life Cycle Database	[49,80]
Japan	Inventory Database for Environmental Analysis (IDEA)	[84,91]
	Carbon Footprint of Products	[63]
UK	Bath/BSRIA(ICE)	[67]
Austria	Austrian Institute for Building Biology and Ecology (IBO)	[63,71,74]
Malaysia	Malaysian Life Cycle Inventory Database	[45]
Finland	Synergia	[63]

implementation of LCA.

Furthermore, the generic database or secondary data from literature or reports may not precisely reflect time, geography and technology correctly, thus increasing uncertainty [102]. However, in some developing countries, the LCA data of building materials may not be available due to the infancy stage of the LCI database, particularly with the recent emergence of mass timber. For instance, Liu et al. [80] used North American data on CLT in the LCA of MTC in China. In studies that took data localization into account, modifications to the general database were made based on local electricity and traffic conditions to get an accurate local result [45,62]. Felmer et al. [79] adjusted data on mass timber by incorporating Chilean forestry operations and energy sources. Furthermore, a few studies gathered and provided specific data on mass timber. Pierobon et al. [77] used regionally specific data for the production of CLT and glulam in the U.S. Pacific Northwest.

4.2.2. Building process

The building process involves activities in transportation, construction, maintenance, replacement, demolition and waste processing. This section outlines the calculation and method used to quantify the environmental impact of mass timber LCA.

Numerous studies employed a variety of methods to ascertain transportation and construction data. Transportation and on-site erection were occasionally simplified or omitted due to a lack of data in these stages, as they accounted for a small portion of the LCA. Puettmann et al. [78] reported that transportation accounted for 5–11% of the P&C stage in mass timber buildings, while construction made 3–4%. In the LCA conducted by Nakano et al. [78], the values were 4% and 2%, respectively [84]. When evaluating the environmental impact of transportation based on assumptions, building materials were typically delivered via truck [34,70,77,78], rail [78,85] or sea freight [56] during the P&C and EoL stages. Dolezal et al. [74] quantified the environmental impact of the A4 (shown in Fig. 2) using the default trucks in Eco2Soft based on Ecoinvent. According to the circumstances and interviews in China, Chen et al. [83] assumed that CLT was imported from Europe. Moreover, Hemmati et al. [79] compared the environmental impact of CLT transportation (an overseas transportation route and two local lines) using two life cycle tools: SimaPro with Ecoinvent database and Tally with GaBi database.

Energy consumption during the construction stage was hard to define and was frequently overlooked. A few studies quantified A5 (shown in Fig. 2) by specified ratios. It was reported that on-site construction and demolition accounted for 3% of primary energy use by Gustavsson et al. [65], and 4% of the material production primary energy in other studies [37,44]. Some studies identified the A5 by estimation. The energy consumption of A5 was set at 20 MJ/m^2 for CLT buildings [49,80], 80 kWh/m^2 for primary energy use [65], 15 MJ/m^2 of diesel and 2 kWh/m^2 of electricity [45], 11.6 MJ/m^2 and 29.3 MJ/m^2 for CLT and concrete buildings [64], respectively. The values set varied considerably at this stage. For instance, it was considered that 80 kWh/m^2 was set for wood frames and 160 kWh/m^2 for concrete [50]. Moreover, some studies were dependent on the various types of construction equipment and machinery used [56,86]. Jayalath et al. [34] assumed that CLT buildings took 30% less construction time than RC buildings. Furthermore, a few research identified A5 utilizing Athena software [47,77] and Athena data [39,74] to identify A5. Some quantified the A5 module based on the diesel fuel consumption for lifting the building materials by crane [83] or by checking the installed power meter weekly to define the electricity consumed [84].

Only a few studies considered maintenance and repair in the use phase, frequently relying on prior literature or assumptions. Lechón et al. [61] calculated these stages based on the maintenance manual of the building provided to the owner, assuming that the interior was painted every 5 years and the exterior every 20 years. The replacement stage was commonly based on literature references and reports such as *Study of Life Expectancy of Home Components* by the National Association of Home Builders [34]. Andersen et al. [64] assessed material replacements according to the Estimated Service Lifetime by the Danish Building Research Institute. Takano et al. [52] assumed the expected service life of building materials and components using *the single-family house service book* by the Finnish Ministry of the Environment.

As for the demolition module, the approach for determining the environmental impact of the deconstruction module is relatively similar to that used during the construction phase. For example, some investigations assumed that the energy of demolished buildings was 90% of the energy required in the construction stage [49,80]. Invidiate et al. [69] reported that the demolition module accounted for less than 2% of the total energy demand. The primary energy required for demolition was assumed to be 10 kWh/m^2 [65,70], 10 kWh/m^2 and 20 kWh/m^2 for wood-frame and concrete buildings, respectively [50]. Furthermore, Lechón et al. [61] assumed that demolition energy was estimated based on the mass of each material to be demolished and the energy consumed per unit mass. Jayalath et al. [34] estimated the demolition time for CLT and RC buildings to be 4 and 6 weeks, respectively, based on the operation of machines such as excavators and wheel loaders.

The scenario for the EoL of building materials is based on references or assumptions. Steel, concrete and mass timber materials are all frequently regarded as recyclable, recoverable, and reusable materials. In several studies, the material was considered to be recycled with a 10% mass loss [52,75].

The assumptions made in EoL vary significantly and will have a strong relationship with the results. CLT, glulam and LVL [85] were extensively investigated for landfills, biomass recovery, and reuse. CLT was assumed to be 50% incinerated and 50% used for biomass energy [45], 55% recycled with 45% used for biomass energy in another study [80], 91% recycled in a subsequent system, 7% used for energy and 2% for landfilling (based on https://ec.europa.eu/eurostat/data/database) by Lechón et al. [61], and 30% for landfill and the remainder for recycled or biomass energy recovered in the LCA conducted by Liang et al. [39].

While Europe prohibits landfilling wood [36,62], the timber of North American houses is commonly dismantled and buried in landfills at the end of its life cycle [103]. Methane emissions from landfill wood due to lack of oxygen were reported to have a greater effect on global warming than burning all wood, as methane is a much stronger GHG than CO_2 [31]. However, some sources claimed that landfill gases were being captured and used as fuel [103]. While the US Environmental Protection Agency estimated that capture technology could capture up to 75% of landfill gas, an empirical study found that this technology captured only 35% of landfill gas [104,105]. It was reported that biomass recovery rather than landfilling resulted in lower carbon emissions and fossil fuel use outcomes for the EoL recycling phase [103]. Santos et al. [87] suggested that incineration with energy recovery was the best option at present as wood degradation in landfills was uncertain. Concerning the recovery of mass timber materials, mass timber is always burned to make fossil fuel substitutes. The avoided GHG emissions and energy recovery from biomass residues are usually calculated via *Equation (1)* and *Equation (2)*, respectively, based on the approach proposed by Sathre et al. [106] and Gustavsson et al. [107].

$$\mathbf{Cav} = \sum_{j} (M_j H_j) \times C_f \varphi_f - (C_{diesel} D_{diesel}) \tag{1}$$

$$\mathbf{Eav} = \sum_{j} \{ M_j H_j [1 - \beta_j (1 + \alpha_{diesel})] \} \tag{2}$$

where C_{av} (kg CO_2 -eq) is net reduced GHG emissions, j is the type of biomass residues, M(kg) presents the mass of recovered residue (oven dry tones), H (GJ/t) is the lower heating value of the residue, C_f (kg CO_2 -eq/GJ) is the carbon intensity of the reference fossil fuel, φ_f is the relative conversion efficiency of biofuel versus reference fossil fuel; C_{diesel} (kg CO_2 -eq/GJ) and D_{diesel}(GJ) are the carbon intensity and quantity of diesel fuel used for recovering and transporting the biomass. where E_{av} is the net energy from recovered biomass residues (GJ); β is the diesel fuel energy required to recover and transport the residue; α is the fuel cycle energy requirement of the diesel fuel.

In addition, the disassembly design of MTC may promote the benefit of mass timber as a re-use material at the EoL stage before it is burned for biogenic energy recovery [65], hence deferring biocarbon emissions in the mass timber.

Concrete is routinely crushed into aggregate to replace natural gravel in concrete production or to fill other applications such as road construction [64,66]. Steel is regarded to be recovered and recycled, replaced into feedstock, which replaces ore-based steel for the new steel products, with a rate of 85% in reference [85], and 90% in another study [52]. Additionally, some research referred to regulation and baseline for assessing the EoL stage. For example, the Danish waste statistics for the waste treatment share of building materials were adopted in the LCA performed by Andersen et al. [64].

4.2.3. Operational consumption

Energy simulation tools are widely applied in research to determine the B6 module in the operation phase, such as Passive House Planning Package (PHPP) [61,71], ENORM software [65], VIP + simulation [37], VIP-Energy program [44,50], IDA ICE [40,52,75], EnergyPlus [53,69], IES (Integrated Environmental Solution) [39,46,49,81,82], TAS [79], Transient System Simulation Tool (TRNSYS) [34], Calener VyP [70], Designbuilder [56].

Energy use in buildings is highly related to activities and processes, including heating, domestic hot water supply, air conditioning (cooling humidification/de-humidification), ventilation and lighting. Table 4 presents the B6 energy activities considered in the literature. Space heating and cooling were the most extensively considered in the B6 module. Almost all the studies included heating in B6, whereas just a small portion considered ventilation.

Throughout the simulation of the energy consumption, the parameter settings varied significantly and had a great impact on the simulation energy consumption, such as heating recovery rate, air tightness. For instance, heating recovery efficiency, which directly influences energy consumption, was set at 60% [40,52,75], 80% [37], 85% [11], 0% in conventional buildings and 80% in low-energy buildings [36], respectively. Air tightness was set at 2/h (50pa: N50) [52,75], 0.1 and 0.35 (1/s m^2 @ 50pa) for unoccupied and occupied buildings, respectively [50], 025 ach [46,81], 0.3 (1/s m2 @ 50pa) [44], 0.2–0.4 (1/s m^2 @50pa) for low-energy buildings and 0.4–0.55(1/s m^2 @ 50pa) for conventional buildings [36].

Apart from focusing on simulation, a few studies utilized data from the development firm and national statistics. Andersen et al. [64] analyzed annual electricity and heat consumption data from construction and real estate development firm (Veidekke). Lolli et al. [11] collected operational energy from a building management system in 2017. Takano et al. [66] used the basic calculated energy of 31.83 kWh/m^2/a for heating and 31.31 kWh/m^2/a for electricity in accordance with German norms. Peñaloza et al. [62] calculated the operating energy consumption to be 55 kWh/m^2, which was consistent with the Swedish Passive House standard.

4.3. Impact assessment

Life cycle impact assessment aims to interpret the environmental burdens from the inventory into environmental impact, which entails associating data with specific category indicators. Several environmental impact indicators were reported in the life cycle assessment of MTC (shown in Table 5). Global warming potential and life cycle energy were the most generally evaluated category indicators, which accounted for 87.10% and 54.84% of the entire literature body, respectively. In this review, both life cycle GHG emissions and life cycle carbon emissions are considered GWP. Indicators like acidification potential (AP) and eutrophication potential (EP) were also identified in several mass timber studies, as indicated in Table 5. Indicators such as human health, photochemical oxidants, land use and water use were incorporated into other indicators, as they were not usually highlighted. Several research took life cycle cost into account to combine the economic value and environmental impact of MTC [34,40].

4.4. Interpretation

4.4.1. Analysis of the life cycle stages

Table 6 summarizes the modules of the inventory during mass timber LCA. It was found that none of the LCAs of mass timber contained all the modules. Takano et al. [66] conducted the most comprehensive LCA on a mass timber building (LVL with CLT elevator shaft), excluding installed products in use (B1) and operational water used (B7).

From 62 case studies, 46.77% of the papers included all stages: P&C, operational, EoL and benefits stages. The majority of the case studies (93.55%) covered the product stage (A1-A3), proving that data in the product stage was more accessible than in other stages [108]. The use, EoL and benefits stages were omitted, included or separated in studies depending on the aim of the studies. In conventional buildings, the operational stage accounts for more than 50% of the GHG and up to a maximum of 70% of the energy [75,109]. 46.77% of the studies considered B6: operational energy use, which mainly relied on the energy simulation tools described in section 4.2.3. However, the energy consumption associated with installed products (1.61%), repair (6.45%), refurbishment (1.61%) and operational water use (1.61%) was rarely included. 43.55% of the research omitted the EoL stage, as well as the benefits and loads beyond the system boundary. The demolition stage is still a process that has not yet occurred and can only be estimated based on assumptions. As Pierobon et al. [77] stated, the hypothetical scenarios for the EoL stage presented large variability and were

Table 4
Energy activities considered in operational energy use.

Space heating	Space cooling	Domestic hot water supply	Ventilation	Lighting	Household electricity (appliance)	Reference
•	•					[53,79]
•		•	•		•	[75]
•	•			•	•	[39]
•						[55]
•					•	[62,64]
•	•	•		•		[71]
	•		•			[70]
•	•					[69]
•		•			•	[36,37,44,50,52,65]
•		•	•	•	•	[40]
•	•	•		•	•	[61]
•	•	•	•	•	•	[46,81]
•	•				•	[49,82]
•	•			•		[34,80]

Table 5
Impact categories assessed in the reviewed papers.

GWP	LCE	EP	AP	ODP	SFP	Others	Reference
•							[11]
•	•	•	•	•	•	•	[61]
•							[62]
•							[63]
•		•	•	•		•	[64]
							[36]
•	•						[65]
	•						[50]
•	•						[66]
	•						[40]
	•						[52]
•	•						[44]
	•						[37]
•							[67]
•							[68]
•	•						[69]
•	•	•	•	•		•	[70]
•	•		•				[71]
•	•						[72]
•		•	•			•	[58]
•							[73]
•	•						[74]
	•						[75]
•	•						[76]
•		•	•	•	•		[77]
•		•	•	•	•	•	[47]
•	•	•	•	•	•	•	[35]
•	•						[41]
•		•	•	•	•	•	[38]
•	•	•	•	•	•		[39]
•	•						[78]
•	•						[79]
•	•						[80]
•	•						[49]
	•						[81]
•	•						[82]
•	•						[46]
•				•		•	[45]
•	•	•	•	•	•	•	[83]
•		•	•	•		•	[84]
•	•						[34]
•		•	•			•	[85]
	•						[56]
•							[86]
•	•						[48]
•		•	•	•		•	[87]
•	•						[60]
•	•	•	•	•	•	•	[59]
•		•	•	•		•	[88]
•	•	•	•	•	•	•	[89]
•							[90]
•		•	•	•		•	[91]
•							[6]
•	•		•				[54]
•		•	•	•			[53]
•		•	•	•		•	[55]
•				•		•	[14]
•	•		•				[43]
•							[57]
•							[92]
•							[31]
•							[93]

GWP: Global warming potential, LCE: Life cycle energy, EP: Eutrophication potential, AP: Acidification potential, ODP: Ozone depletion potential, SFP: Smog formation potential.

omitted, with mass timber being a relatively new material in the U.S. Benefits stage was provided in 40.32% of the literature body. In a review conducted by Bahramian et al. [20], only 11% of case studies analyzed reuse, recovery, recycling, and benefits and loads beyond boundary. One possible explanation could be that mass timber presents advantages in the reuse, recovery and recycling aspects, which are constantly considered and compared to other conventional alternatives.

Furthermore, Takano et al. [66] challenged that further classification of life cycle stages defined in EN 15978 should be discussed. The study argued that the prefabrication process should be considered. Computer numerical control technology is used to precisely shape mass timber products according to customized designs [110]. Takano et al. [66] advocated subdividing the construction stage into $A_{4-5}P$ for the prefabrication process and $A_{4-5}O$ for the on-site construction process. $A_{4-5}P$ covered the transportation of building materials from the production factory to the prefabrication factory, as well as all prefabrication activities performed at the factory. The study quantified the energy consumption associated with the prefabrication of wood elements using electricity meter monitoring. However, the product stage includes manufacturing, construction assembly of pre-fabricated products or any combination thereof according to EN 15978. Due to the untransparent nature of mass timber data, it was hard to determine whether the prefabrication part was taken into consideration. Therefore, in order to increase the accuracy of the LCA results for the prefabrication component of mass timber construction, the data should be explicated and transparent in further LCA studies.

4.4.2. LCA tools

Various LCA tools have been applied to evaluate the environmental impact of different indicators in the MTC, including SimaPro, Gabi, Athena, with 23 cases applying LCA tools in the assessment. Gabi and SimaPro are both professional LCA tools for evaluating the environmental impact of products and technologies [111]. SimaPro is the most frequently used life cycle assessment tool in mass timber construction, accounting for 22.58% (14 articles) of the body of literature. The Athena Eco Calculator and Athena Impact Estimator for Buildings, with an American database focusing on the whole building assemblies, have been designed and are being utilized in evaluating the environmental impact of buildings in North America.

4.4.3. Life cycle cost

According to the literature, several studies evaluated the cost analysis of mass timber from the perspective of life cycle cost analysis [31,34,39,40,45,54,57,61,69,76,85,93]. For example, Takano et al. [76] reported the material cost of six frame materials in a 3-storey townhouse, concluding that CLT had the highest cost (385€/m2) and embodied energy among six alternatives: LWT (252 €/m2)/CLT (385 €/m2)/RC (381 €/m2)/Aircrete (335 €/m2)/Brick (313 €/m2)/Steel (271 €/m2). Another study observed that the initial cost of the RC buildings was about 8–10% higher than that of CLT alternatives in three Australian cities, while the overall operational and maintenance cost of the CLT buildings was approximately 13–16% higher than that of the RC buildings due to more frequent replacement of wall and floor finishes and termite proofing [34]. The total LCC of the RC building was similar (1% higher) to that of the CLT alternative. Liang et al. [39] presented that the mass timber building had a 26% higher construction cost than the concrete alternative in a 12-storey mixed-use building in the U.S., and the total LCC of the mass timber building was 9.6% greater than the concrete building. It also conducted a sensitivity analysis to determine the effect of CLT prices on LCC, revealing that ±50% of the CLT price resulted in ±2.8% of the total LCC of MTC, 6.5–12.8% higher than the concrete building. In terms of the cost of a building frame for a 4-storey residential apartment in Brisbane, the most expensive option was the concrete frame ($477102), followed by the steel frame ($219216), and LVL frames ($119939–143983). This is due to the large quantity of material used, resulting in a higher cost of labor, demolition. Among the LVL structures, the LVL produced from early to mid-rotation hardwood plantation logs had 10% and 20% lower LCC than LVL from mature softwood and hardwood, respectively [85]. A few studies considered optimization of LCA and LCC. Pal et al. [40] proposed a life cycle energy cost optimized building design solution and discovered that thicker insulation did not always result in the lowest life cycle energy (operational energy and embodied energy), since it lowered operational energy

Table 6
Building life cycle modules of the existing literature.

A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	Reference
•								•							[11]
•				•	•			•		•	•		•	•	[61]
•	•	•						•		•	•	•	•		[62]
•															[63]
•	•	•				•		•				•	•	•	[64]
•		•						•		•				•	[36]
•		•						•		•				•	[65]
•	•	•						•		•	•	•	•	•	[50]
•	•	•		•	•	•	•	•		•	•	•	•	•	[66]
•	•	•		•		•		•							[40]
•				•		•		•		•	•	•	•	•	[52]
•		•						•		•	•	•		•	[44]
•		•						•		•				•	[37]
•	•	•								•	•	•	•		[67]
•				•		•						•	•		[68]
•	•	•		•				•		•	•				[69]
•	•	•						•		•					[70]
•						•		•					•		[71]
•										•	•	•	•	•	[72]
•															[58]
•	•	•		•	•	•				•	•	•		•	[73]
•	•	•				•		•		•	•	•	•	•	[74]
•				•		•		•		•	•	•	•	•	[75]
•															[76]
•	•	•													[77]
•	•	•		•		•		•		•	•	•	•	•	[47]
•															[35]
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•	•	•		•	•	•		•	•		•		•		[39]
•	•	•													[78]
•	•	•						•							[79]
•	•	•						•		•				•	[80]
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•	•	•													[83]
•	•	•													[84]
•	•	•				•		•		•	•			•	[34]
•	•	•		•						•				•	[85]
•	•	•						•		•	•			•	[56]
•	•	•													[86]
•															[48]
•	•										•	•	•		[87]
•	•	•								•	•			•	[60]
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	•														[90]
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while increasing embodied energy. Furthermore, it demonstrated that CLT appeared to be a suitable alternative to RC in Finland, with almost the same energy performance but less LCC.

Additionally, some research described the adoption of mass timber as overall cost neutral, owing to the innovative nature of mass timber, which enables project savings, faster construction, and lower construction and labor costs [112]. The LCC of MTC is largely reliant on forest resources, regions, system boundaries, local mass timber development, and the maturity of the CLT market in terms of structural wood supply. The construction cost will increase in MTC if mass timber is imported and transported over a long distance.

5. Discussion

5.1. Sensitivity analysis

Sensitivity analysis (SA) was utilized to examine the effects of parameter impacts in both the LCA and the LCC. In terms of data uncertainty, the following parameters were performed to assess the influence on LCA: insulation [36,37,43,61], material substitute [61], use of phenol formaldehyde (PF) resin [85], transportation distance [36,53,70,85,86,91], energy supply [36,53,61,91], energy efficiency [70], air infiltration rate [36,37], ventilation heat recovery efficiency [36,37,61], mass timber reclaim ratios [80], material recycling [36], biomass residues [36], life span [34,36,37,50,53,54]. Moreover, resale prices [34,39], discount rate [34,54,85] and inflation rate [85] were investigated in SA for LCC.

Lechón et al. [61] explored the effect of increased insulation thickness in the sensitivity analysis, and reported that increasing the thickness of the insulation reduced the overall effect by 2%. It also found that replacing PVC windows with aluminum or wood windows resulted in an 11–14% reduction in the heating demand. MHM panels were chosen over CLT panels, and stone wool was chosen over light density fiberboard in the SA performed by Vanova et al. [58]. Lu et al. [85] discovered that a 20% decrease in PF use resulted in a 20% reduction in GWP and fossil depletion potential, a 9% reduction in AP and a 7% reduction in EP. Due to the scarcity of mass timber production in several countries, CLT needs to be transported over long distances to the construction site. SA is applied to determine the impact of material localization on the environment. For instance, Vidal et al. [70] reported that improvements in local transportation led to a 7.1% reduction in GWP and a 3.7% decrease in cumulative energy demand. The energy supply system had a substantial impact on the life cycle energy balance of the building and was also evaluated in SA. Piccardo et al. [72] performed LCA on concrete, CLT and modular timber buildings considering three distinct electricity mix scenarios (standalone production, 100% fossil gas, 70% wind and 30% biomass). The overall primary energy balance of fossil gas and wind biomass scenarios dropped by up to 9% and 44%, respectively, as compared to the baseline scenario. The values increased by up to 45% and dropped to 76%, respectively, for the total carbon dioxide balance. A study by Dodoo et al. [36] reported that switching from biomass-based steam turbines to coal-based steam turbines increased operational carbon emissions by approximately tenfold, greatly affecting the results of the LCA. Dodoo et al. [37] conducted SA to assess the impact of parameter variations such as infiltration rate and heat recovery rate, insulation material and lifespan in three timber buildings, discovering that enhanced airtightness significantly reduced the primary energy. By changing the insulation material from glass wool to stone wool, the primary energy was reduced by 4% and 9% in beam-and-column and modular buildings, respectively. Several parameter variations, such as energy supply, biomass residues and insulation were also carried out in SA to determine their effect on carbon emissions [36].

When it comes to SA in LCC, Jayalath et al. [34] reported that the initial cost was not sensitive to CLT price fluctuations as a 10% change in CLT price led to a 2% change in total initial cost. The study also pointed out that increasing the discount rate to 10% lowered the operation and maintenance costs of CLT and RC buildings by 33%, while reducing the discount rate to 4% increased the cost of two buildings by 68%. In the SA performed by Lu et al. [85], a 2% decrease in the discount rate increased the LCC of the LVL structure by 8–11%, while a 2% increase in the discount rate resulted in a 3–4% decrease in the LCC. Moreover, the study also conducted SA on the inflation rate, demonstrating that an increase of 2% in the inflation rate resulted in a decrease of 3–4% in LCC, while a decrease of 2% in the inflation rate led to an increase of 8–13% in LCC.

5.2. Carbon storage

The removal of carbon dioxide from the atmosphere through photosynthesis makes wood a carbon sink, also known as biological carbon emissions. However, there is no consensus on how biogenic carbon should be modeled, strongly influencing the GWP in the LCA of MTC. Certain studies regarded carbon sequestered in wood as a net sink of carbon and considered negative emissions. Li et al. [48] reported that the embodied carbon emissions of a 43-storey commercial building, constructed with a glulam frame, CLT slabs and an RC core, is −9463.36 tC, compared to 5933.97 tC in the RC alternative. This difference was attributable to the consideration of carbon storage in glulam and CLT. Takano et al. [76] showed that the CLT frame had the larger carbon storage (−348 $kgCO_2$ e/m^2) to RC, steel, aircrete, brick frames(-52∼-53 $kgCO_2$ e/m^2). Allan et al. [38] showed that the mass timber building resulted in a lower GWP than the steel alternative if benefits stage was counted together with biogenic carbon. The study reported that a 5-storey mass timber building emitted −141 tCO_2 eq for P&C, EoL and benefits stages, while the value was 1280 tCO_2 eq for the steel alternative.

On the other hand, wood is considered a source of carbon sink and is considered carbon neutral over its life cycle assessment. Takano et al. [76] argued that carbon storage or sequestered CO_2 in mass timber would be eventually released into the environment if the wood decayed or was incinerated. According to Hafner et al. [68], the biogenic GWP left the system in the EoL stage (positive value) with the same value as carbon in P&C stage (negative value). Therefore, some analyses excluded carbon sequestered in wood and biomass emissions released into the atmosphere at the EoL stage [61].

EoL management of wood-based products brings significant primary energy and GHG benefits compared to steel and concrete [44]. The reuse of wood extends the time period of biogenic carbon sequestered and delays the release of GHG into the atmosphere [113]. It was discovered that trees aged 20–80 years showed an advantage in terms of CO_2 absorption [57]. Carbon storage will have a positive impact on the climate under a sustainable forest scenario in which trees harvested for mass timber production are considered replanted. As a result of forest regeneration, the forest biomass will be restored to the previous level, guaranteeing that replanted wood resources will remain available for subsequent harvesting [77].

5.3. Study comparison

It is difficult to compare the research cases, as building type, climate, system boundary, database, local regulation, location and functional unit are quite different in research. This section compares primary energy and GHG emissions in the retrieved literature. The embodied energy and GHG emissions are compared side by side, as this stage is generally discussed and data is readily available. Since assumptions and settings varied significantly in studies, the comparison of GWP and LCPE of buildings was carried out in the same study, where the buildings were likely to have the same functional units, system boundaries, life span. In articles that did not express the values of embodied energy, embodied GHG emissions, life cycle energy and life cycle GHG emissions but were shown in the figure or could be calculated, the values were read from figures or calculated based on the information in the paper, which diminished the accuracy of the comparison. Embodied energy has been defined by several studies, including the production of the material (A1-A3), the total energy of manufacturing and construction and assembly processes (A1-A5), and a more comprehensive definition [114,115]. In this review, embodied energy and GHG emissions refer to the production stage (A1-A3), as the construction and transportation stages vary greatly.

Fig. 7 summarizes the embodied energy and embodied GHG emissions in the retrieved literature. As illustrated in Fig. 7, some research reported negative embodied GHG emissions in mass timber buildings, which was due to carbon storage considered in the product stage. Results showed that the average embodied energy of mass timber construction was 3993.85 MJ/m^2, 23.00% higher than that of the RC alternative (3075.09 MJ/m^2). In terms of embodied GHG emissions, RC buildings had an average of 303.63 kg CO_2 eq/m^2, 42.68% higher than the mass timber alternatives (174.03 kg CO_2 eq/m^2).

According to Zeitz et al. [41], the mass timber garage had the lowest embodied GHG emissions (52 kg CO_2/m^2) compared to precast concrete, post-tension concrete and steel garages. The mass timber garage had the

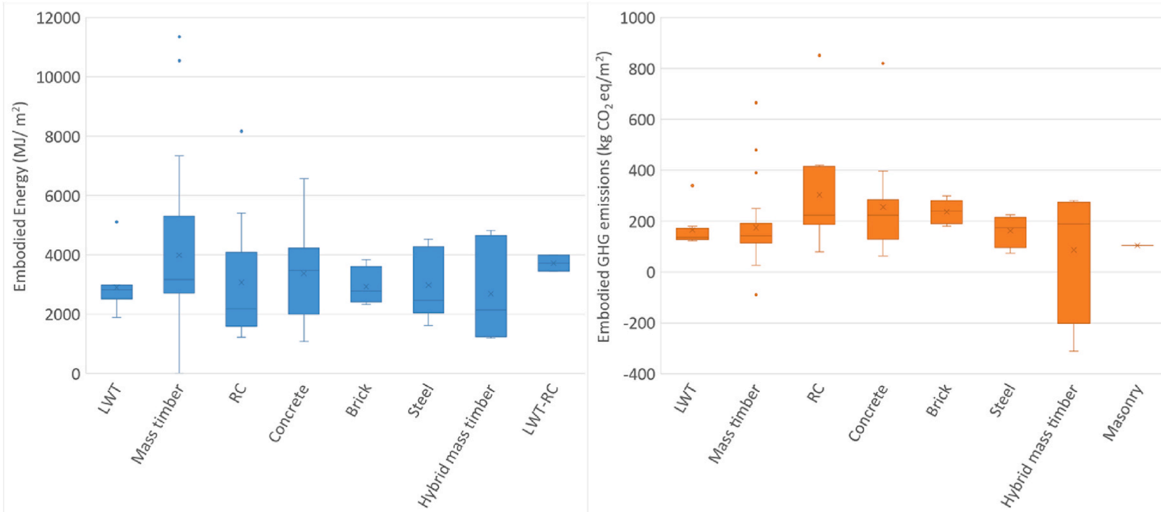

Fig. 7. Embodied energy and embodied GHG emissions comparison.

second-highest embodied energy (1311 MJ/m^2), lower than the steel garage (1625 MJ/m^2) and higher than concrete alternatives. Another study found that the mass timber building was 44% lower in embodied carbon and 37% higher in embodied primary energy than that of the RC building [79]. Takano et al. [52] revealed that the CLT building had the highest embodied primary energy (5311 MJ/m^2) compared to other alternatives (RC, Autoclaved aerated concrete, Brick, Steel), but still had the lowest LCPE (45949 MJ/m^2). However, some studies argued that timber-based buildings (LFT/CLT/beam & column timber frame/-modular timber frame) presented 4–18% lower primary energy for building production than the RC alternative in Norway [44].

Moreover, Puettmann et al. [78] indicated that embodied carbon emissions increased with the building height in mass timber buildings, with mass timber buildings emitting 22–50% less embodied carbon emissions than concrete alternatives. However, Leskovar et al. [71] showed that the detached house had the highest embodied GHG, followed by semi-detached, terraced, 2-storey and 3-storey houses for CLT structures. And Guo et al. [49] demonstrated that both RC and CLT high-rise buildings had lower energy consumption per square meter than low-rise and mid-rise buildings.

According to Hafner et al. [68], the carbon footprint of single-family and two-family timber buildings (containing CLT and timber frame) was 77 and 207 kg CO_2 eq/m^2, respectively, 35–56% lower than that of mineral alternatives in P&C and EoL stages, considering the biogenic GHG as a zero net balance. In terms of multistorey buildings, the values were 18 and 178 kg CO_2 eq/m^2, respectively, 9–48% lower than their mineral counterparts. Another study showed that steel had 31–41% higher GHG emissions than its mass timber counterparts for P&C and EoL stages [38].

As for construction materials and components, CLT accounted for 18% of the material carbon footprint, whereas steel and concrete contributed 38% of the embodied GHG emissions in a CLT building [73]. Dodoo et al. [37] reported that exterior and interior walls accounted for the largest share (38–40%) of the total primary energy for material production. Furthermore, mass timber is much lighter than concrete. For example, CLT weighs one-sixth the weight of concrete [57]. This makes the MTC mass much lighter than RC alternatives, resulting in cheaper and lighter foundations. For example, the total mass of the CLT building was 33.2% lower than that of the RC building [47]. In addition, MTC speeds up production times as concrete needs to be formed, reinforced and cast-in-situ, while mass timber elements can be installed quickly and efficiently, resulting in lower energy consumption in the construction stage. It strengthens the advantages of mass timber construction over conventional alternatives during the P&C stage.

Fig. 8 and Fig. 9 present the life cycle primary energy and life cycle greenhouse gas emissions of the studies. There is a clear general trend that mass timber buildings generally have lower GWP and LCPE than RC and steel buildings in the same paper, though the values vary greatly across all studies. For instance, in an 80-year lifespan of LCA, the CLT building gave a 20% lower LCPE than the concrete alternative, and a 37% lower LCPE if constructed as a passive house [50]. In comparison to RC-frame buildings, CLT buildings saved an average of 9.9% energy and 13.2% carbon emissions [49]. Takano et al. [75] found that the LCPE of the row house, townhouse and apartment block was approximately 20%, 30% and 45% lower than that of the detached house in four building frames: LWT, CLT, RC and steel.

The benefits stage have a great impact on the LCA results. In a study conducted by Dodoo et al. [73], the life cycle carbon balance of a CLT building was 92.1 kg CO_2/m^2 when the reuse, recovery and recycling phases were considered, while the value was 280.5 kg CO_2/m^2 if benefits stage was excluded. RC buildings benefit more from the recycling of steel to MTC, while MTC shows greater benefits from biomass residues. The net EoL benefits of MTC for primary energy were reported to be 49–51% higher than concrete alternatives [50]. Another study reported that energy recovery in the EoL phase reduced the GWP of the LVL frame by more than 30% and the AP and EP by more than 20% [85].

Consistent with previous research [23], the review confirms that using mass timber helps to mitigate environmental impact from the perspective of LCA, particularly in terms of global warming potential and primary energy.

5.4. Development and outlook

Non-wood materials such as resins used in mass timber are a major source of environmental impact. According to Lu et al. [85], the use of PF resin contributed to 20% GWP and AP of the LVL structure of a four-residential apartment. Another study reported that adhesives and manufacturing processes accounted for 46–52% of the GWP in CLT and glulam buildings [45]. In terms of cradle to gate CLT LCA, the resin accounted for 30% of the total GWP [88]. Lower resin usage will reduce the environmental impact of CLT. In order to limit the use of toxic adhesives in the production of mass timber, the European Commission has promoted the development of adhesive-free laminated wood beams and cross-laminates as an alternative to glulam beams and CLT boards [116]. Furthermore, MHW, patented in 2005 with no adhesive used, has the potential to reverse the environmental impact of the resin.

The geographical location of a building has a significant effect on the energy load. Recently, it has been shown that climate change has a

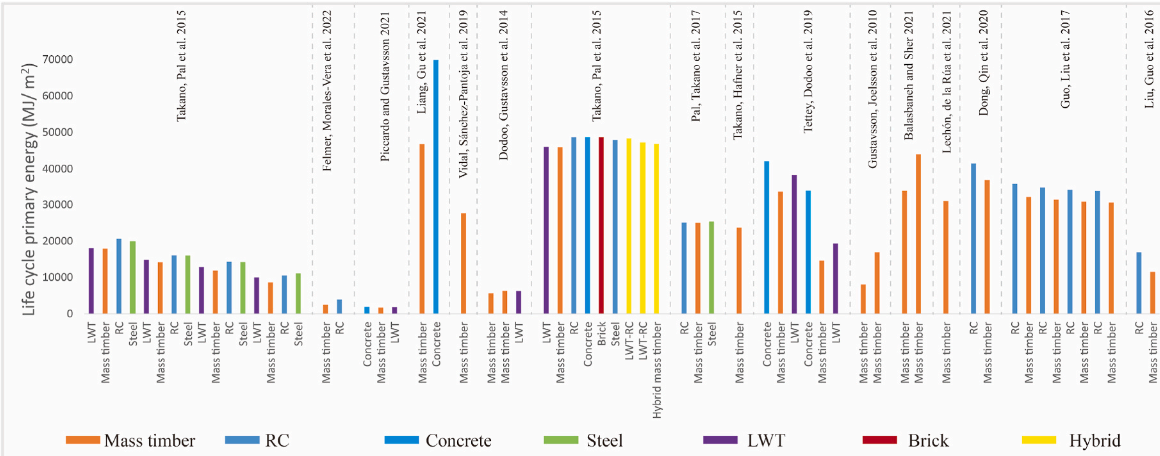

Fig. 8. Life cycle primary energy comparison.

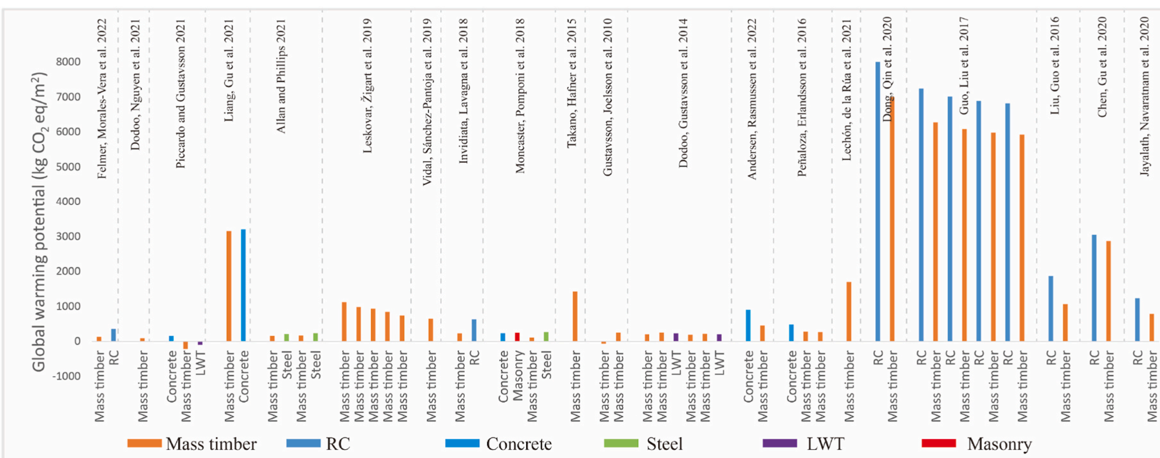

Fig. 9. Global warming potential comparison.

strong impact on the heating and cooling energy consumption of buildings [117,118]. In the LCA of MTC, the effect of climate change was also paid attention to Refs. [34,69]. Several previous investigations documented the overheating of mass timber in the summer [69,81,119,120]. Invidiata et al. [69] compared the carbon footprints of RC, CLT and steel buildings for the current climate (2017) and three future time slices (the 2020s, 2050s and 2080s). The results showed that the average energy demand of all cases in 2080 would increase by 13% compared to the current scenario. Due to climate warming in the future, the demand for cooling energy would increase significantly, while the demand for heating energy would decline by 50% on average.

Hassan et al. [57] revealed that the use of wood in construction may not always be justified in countries where forests and wood resources are not as rich as in northern Europe. With the application of mass timber in building construction, a growing amount of raw materials is required to manufacture mass timber, which is one of the potential barriers to mass timber adoption [121]. Consequently, Santos et al. [87] explored the LCA of cross insulated timber, a sandwich wall panel with a low-density core designed to improve insulation, reduce weight and rationalize wood volume. Bamboo-wood composite CLT has been proposed as a way to effectively utilize bamboo resources in China to alleviate the current contradiction between wood supply and demand [122].

6. Conclusion

The amount of LCA research applied to buildings has steadily increased since the early 1990s. When the building is designed as a low-energy or passive house, the environmental impact in the operational stage will decrease significantly, magnifying the impact of the P&C stage as well as the EoL stage. This promoted the introduction of new materials in buildings, such as mass timber. The amount of LCA research on mass timber has expanded significantly during the last decade. This study provided a systematic review of mass timber construction from the perspective of life cycle assessment. The review analyzed, compared, and summarized the goal and scope definition, life cycle inventory analysis, impact assessment and interpretation of the LCA phases in MTC.

The retrieved LCA mass timber research consisted of analyses at different levels, including building, component, structure and urban levels, most of which focused on the cradle to gate and cradle to grave boundaries. As for functional units, the entire building and 1 m^2 of total floor area were most widely applied in the MTC LCA. The disparity in the goal and scope definition makes it difficult to compare the outcomes. Consequently, it is argued that the scope, system boundary, functional unit and lifespan should be stated clearly.

This study analyzed and summarized the data collection and quantification methods of relevant inputs and outputs in the MTC LCA. Among the multiple databases used in the LCA of mass timber, Ecoinvent was one of the most completely generic databases and was commonly adopted in the retrieved research. The LCA of MTC was mostly conducted in developed countries, where the databases were more detailed and easily accessible. Data quality and transparency are other essential issues in LCA, especially for mass timber LCA. In developing countries, it is critical to establish local databases as a general database may be inapplicable due to local electricity and transportation. In addition, it is argued that the prefabrication process in the mass timber LCA should be considered and added in the P&C stage. However, some argued that the prefabrication was included in the cradle to gate boundary. To conduct a more comprehensive assessment, open data and open software are proposed to address transparency, repeatability and uncertainty, as well as improve the accuracy of LCA.

Global warming potential and life cycle energy were the most frequently evaluated category indicators in mass timber construction. Indicators like acidification potential and eutrophication potential were also identified in several mass timber investigations. Furthermore, some studies took LCC into account to balance the economic value and environmental impact of mass timber construction.

This review attempts to interpret the outcomes of the LCA studies. It is hard to include all the modules within a study of mass timber construction. Almost all case studies included A1-A3. A significant difference between mass timber buildings and conventional buildings lies in the EoL stage. Recovered mass timber in the EoL stage has various uses, including the recovery of biomass energy from combustion to replace fossil fuels, reuse as lumber, and reprocessing into particleboard or pulp. In addition, there is no consensus on the inclusion of biogenic carbon in MTC LCA. As trees are replanted and regrown, their absorption of carbon dioxide from the atmosphere through photosynthesis offsets the carbon stocks in the harvested trees. Sustainable forest management has a significant impact on the GHG emissions of MTC. SimaPro was the most extensively used LCA tool in MTC LCA. As for uncertainty in the data, SA is adopted to ascertain the effect of parameters such as transportation distance, energy supply, air infiltration rate, ventilation heat recovery efficiency and life span.

The review finds that mass timber cases are hard to compare due to variances in building type, location, functional unit and system boundary, consistent with a previous study [123]. However, this study tries to compare the embodied energy and GHG emissions (A1-A3) between mass timber buildings and other conventional alternatives. The average embodied energy of MTC is 23.00% higher than that of RC alternatives, while the average embodied GHG emissions of RC buildings are 42.68% higher than that of mass timber alternatives. In addition, mass timber buildings generally have lower GWP and life cycle primary energy than RC and steel buildings, indicating that the use of mass timber to substitute conventional materials could help mitigate climate change and promote sustainable construction.

This article attempts to ensure a comprehensive understanding of the benefits of the mass timer in the building sector and provides information to assist experts, practitioners, and designers in implementing the LCA of MTC. The LCA results will also be used to support government policies to promote mass timber construction and a more sustainable building industry.

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CRediT authorship contribution statement

Zhuocheng Duan: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Qiong Huang:** Writing – review & editing, Supervision, Resources, Conceptualization. **Qi Zhang:** Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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