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Complementing emergy evaluation and life cycle assessment for enlightening the environmental benefits of using engineered timber in the building sector

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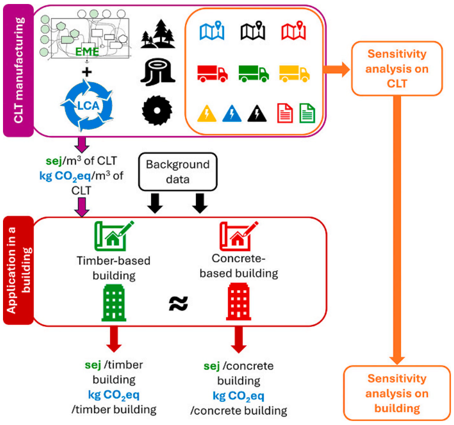
HIGHLIGHTS

- Emergy evaluation complements LCA by expanding the assessment scope.
- Emergy highlights the renewability of engineered timber often overlooked in LCA.
- Comparison of LCA and Emergy shows environmental benefits of engineered timber
- Sensitivity analysis confirms robust results across geographic and energy use scenarios

GRAPHICAL ABSTRACT



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ABSTRACT

Engineered timber can represent a great opportunity to mitigate the large impacts due to the global building sector. However, the most applied environmental assessment methodologies such a life cycle assessment (LCA) might show limited advantages when comparing the impact on climate change of buildings made of traditional materials, such as concrete and steel, and building based on engineered timber. This work proposes emergy evaluation (EME) as a complementary environmental assessment methodology. By expanding the boundaries of the assessment, EME captures input flows and related features, especially in terms of renewability, that are overlooked in LCA. LCA and EME were applied to two identically modeled buildings composed of either only traditional materials or engineered timber as their replacement. EME reveals the higher sustainability level of engineered timber compared to traditional materials in the building sector, capturing larger environmental benefits compared to LCA. Ultimately, the robustness of the results is tested through a comparative sensitivity

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analysis performed for three geographic scenarios, different energy use scenarios, and different transport distances.

1. Introduction

Building sector accounts for 21 % of the global GHG emissions, corresponding to 12 Gt CO_2eq, of which 18 % were related to cement and steel implied in the construction and refurbishment phases (Cabeza et al., 2022). Over the last two decades the GHG emissions from residential buildings increased by about 50 %, being population growth a major driver (Cabeza et al., 2022). Construction sector also accounts for 40 % of the GHG emissions associated with global materials use (Hertwich et al., 2020). Furthermore, global material use for construction sector projected to double between 2017 and 2060, reaching about 84 Gt of construction materials per year, driven by population growth (OECD, 2019). While the GHG emissions associated with operational energy consumption (e.g., heating, ventilation, and air conditioning and cooling – HVAC) are expected to decrease thanks to efficiency improvements, the emissions embodied in the construction materials – i.e., the emission required for manufacturing the building materials – are expected to assume a major role (Röck et al., 2020). Moreover, construction and demolition waste account for a large part of the total waste, reaching about one third of the total waste generated in the EU (European Commission, 2023).

The most traditional building materials are based on concrete and steel, which not only are among the most resource- and energy-intensive materials, but they derive from hard-to-abate industrial sectors too (Davis et al., 2018). Accordingly, during the last period alternative materials gained the attention of researchers (Abu-Jdayil et al., 2019; Bumanis et al., 2020; Campbell, 2019; Crini et al., 2020; Liang et al., 2020; Liu et al., 2016; Singh and Middendorf, 2020; Soni et al., 2022), policymakers (European Economic and Social Committee, 2023), and industry (KLH Massivholz GmbH, 2019; Södra Building Systems, 2020; Stora Enso, 2023).

Bio-based materials generated from renewable resources, such as biomass, received most attention thanks to their capacity to store biogenic carbon deriving from the carbon dioxide (CO_2) captured and removed from the atmosphere (Churkina et al., 2020; Le et al., 2023). This peculiarity grants such materials an environmental advantage with respect to, for instance, cement or steel whose manufacturing implies, conversely, the release of large amounts of CO_2 in the atmosphere (Younis and Dodoo, 2022).

Among the bio-based solutions, there are various products characterized by specific features that allow their usage as substitutes for traditional materials (Churkina et al., 2020). Engineered timber products (also referred to as "mass timber") are a class of wood-based solutions that include, for instance, glued laminated timber (glulam), laminated veneer lumber (LVL), and cross-laminated timber (CLT or XLT) – materials that have various applications in the building sector (United Nations and FAO, 2021). In particular, engineered timber can substitute concrete and steel in structural applications (United Nations and FAO, 2021). Considering these peculiarities, wood-based construction materials could play a pivotal role in the achievement of sustainable development (Omer and Noguchi, 2020; Pomponi et al., 2020). Although a total substitution is not always attainable, their usage can substitute a significant part of the traditional materials (Teh et al., 2017). While the technical feasibility of the use of engineered timber as building material in substitution of traditional materials (e.g., concrete and steel) is currently ascertained, the sustainability of such substitution must be comprehensively and properly assessed.

Life Cycle Assessment (LCA) is a widespread methodology capable of providing a quantitative assessment of the environmental impacts throughout the whole life cycle (from the raw material extraction phase to the end-of-life phase) of a product or system (Bruno et al., 2022). The existence of an international standard (International Organization for Standardization, 2006), and guidelines (European Commission, 2010) allow not only accurate estimations, but also horizontal comparisons among different products providing helpful indications to decision-makers. LCA provides results from a "user" perspective since the goal of the methodology is to identify, quantify and link all the natural (geosphere, atmosphere, and biosphere) and anthropogenic (technosphere) inputs to the single targeted product or system as well as the output to the environment (e.g., emissions) to the technosphere (goods or services) (Edelen et al., 2018). However, the role of ecosystems is usually overlooked as they are not accounted for, or considered since they are provided to the human society (or technosphere) for free, and (presumably) without limitations (D'Amato et al., 2020).

Emergy evaluation is a methodology to estimate not only the contribution of renewable resources generated by the ecosystems but also the contribution of anthropogenic commodities to the technosphere (Patrizi et al., 2020). It was originally proposed by H. T. Odum (Odum, 1988) with the objective of accounting for the ecosystem goods and services through a common physical term: Emergy is defined as the available energy of one kind (and the accounting is usually referred to the solar energy) used up directly and indirectly to generate resources and products (Odum, 1996a). Emergy evaluation (hereafter EME) can provide helpful information for the design of strategies for the consumption of resources compatible with the time required to generate them (Keena et al., 2018; Raugei, 2011; Rugani et al., 2011). The spatial boundaries of EME are set to include the whole planet while the temporal ones account for the past environmental work required to provide resources used in the present (Neri et al., 2014). EME is capable of estimating the effort required by the environment to replace the resources used as input to the technosphere in terms of solar energy that drives – directly or indirectly – all geobiospheric processes (Patrizi et al., 2018; Raugei et al., 2014). As such, EME is complementary with respect to LCA by adopting a "donor" perspective, going beyond the technocentric perspective of LCA by adopting a systemic eco-centric approach. However, even EME is affected by flaws, especially in terms of accuracy, which limited its usage in various fields such as economics, physics, and engineering (Brown et al., 2016; Cleveland et al., 2000; Månsson and McGlade, 1993).

It is clear that the two methodologies can be applied for the sustainability assessment of products, services, and systems from two different, complementary approaches. It has already been proven that the joint application of the two methodologies provides insightful results with higher informativeness compared to the individual application of the single methodologies (Dong et al., 2014; Kerdlap et al., 2020). In general, life cycle inventories and the LCA matrix framework can benefit EME by refining the resource input quantifications, offering process-specific details that increase the accuracy of emergy flows, and supporting system boundary consistency (Rugani and Benetto, 2012). In turn, EME can contribute by quantifying the renewability of a process/system, a unique EME feature that goes beyond LCA ability (Ulgiati et al., 2006; Wang et al., 2020). Furthermore, by expanding the system boundaries EME allows encompassing the ecological dynamics (and ecosystem services) that underpin all upstream processes, whereas LCA boundaries are necessarily truncated (Park et al., 2016; Rugani et al., 2019; Santagata et al., 2020; Wang et al., 2020). As a further expansion, EME incorporates human labor into the calculation framework, which is an input that is overlooked in LCA (Santagata et al., 2020). While EME relies on a single metric, facilitating the immediate and unequivocal identification of critical issues, especially in terms of the long-term sustainability of resource use, LCA normally generates a list of metrics focusing on specific impacts or damages (i.e., categories) that facilitate the identification of trade-offs across different environmental issues (Cano-Londoño et al., 2022). EME may serve as a weighting factor in LCA (Ingwersen, 2011) but can also support the solution of potential trade-offs across categories or different scenarios (Reza et al., 2014). These are the key aspects that allow the joint application of EME and LCA to provide synergic benefits in environmental assessments. However, the joint application requires particular attention due to several remarkable differences between the two approaches (Raugei et al., 2014).

LCA of CLT use in buildings has been implemented in some cases, highlighting the large potential for reducing the carbon footprint through the substitution of traditional materials such as reinforced concrete and steel (Younis and Dodoo, 2022). However, other environmental indicators reveal the existence of trade-offs (Liang et al., 2021; Liang et al., 2020).

EME has been applied in environmental assessments for buildings (Pulselli et al., 2009, Pulselli et al., 2007; Pulselli et al., 2008a, 2008b; Srinivasan et al., 2012; Thomas and Praveen, 2020; Yi et al., 2017; Yi and Braham, 2015), even focusing on the related waste (Yuan et al., 2011). Cabezas et al. (2010) focused on the EME of a comprehensive number of products, including engineered timber. However, the effect of substituting traditional building material with engineered timber has not been investigated from an emergy viewpoint.

The main objectives of this paper are to assess the sustainability level of CLT production and to investigate the consequences of its use as a replacement for traditional concrete-based building materials by means of joint implementation of emergy evaluation and Life Cycle Assessment. The novelty of the approach consists of the joint application of two complementary methodologies on two functionally equivalent buildings rather than a simple assessment of a stand-alone building based on either traditional material or timber. Only in this way, it is possible to compare the different materials in a scientifically sound way in their application – thus accounting for their technical features and their consequences on the building design. Thereby, we investigate if and how the joint application of the two methodologies can provide more comprehensive results for bio-based solutions. The results are contextualized within the field of environmental sustainability assessment of buildings. A critical knowledge and research gap is identified particularly for the application of sustainability assessment in the construction sector, and the necessity to complement the mainstream LCA approach with EME is discussed. The integrated use of EME and LCA is suggested as a fundamental requirement to provide an informative and comprehensive sustainability assessment for a construction sector that is bound to a shift from fossil to renewable resources.

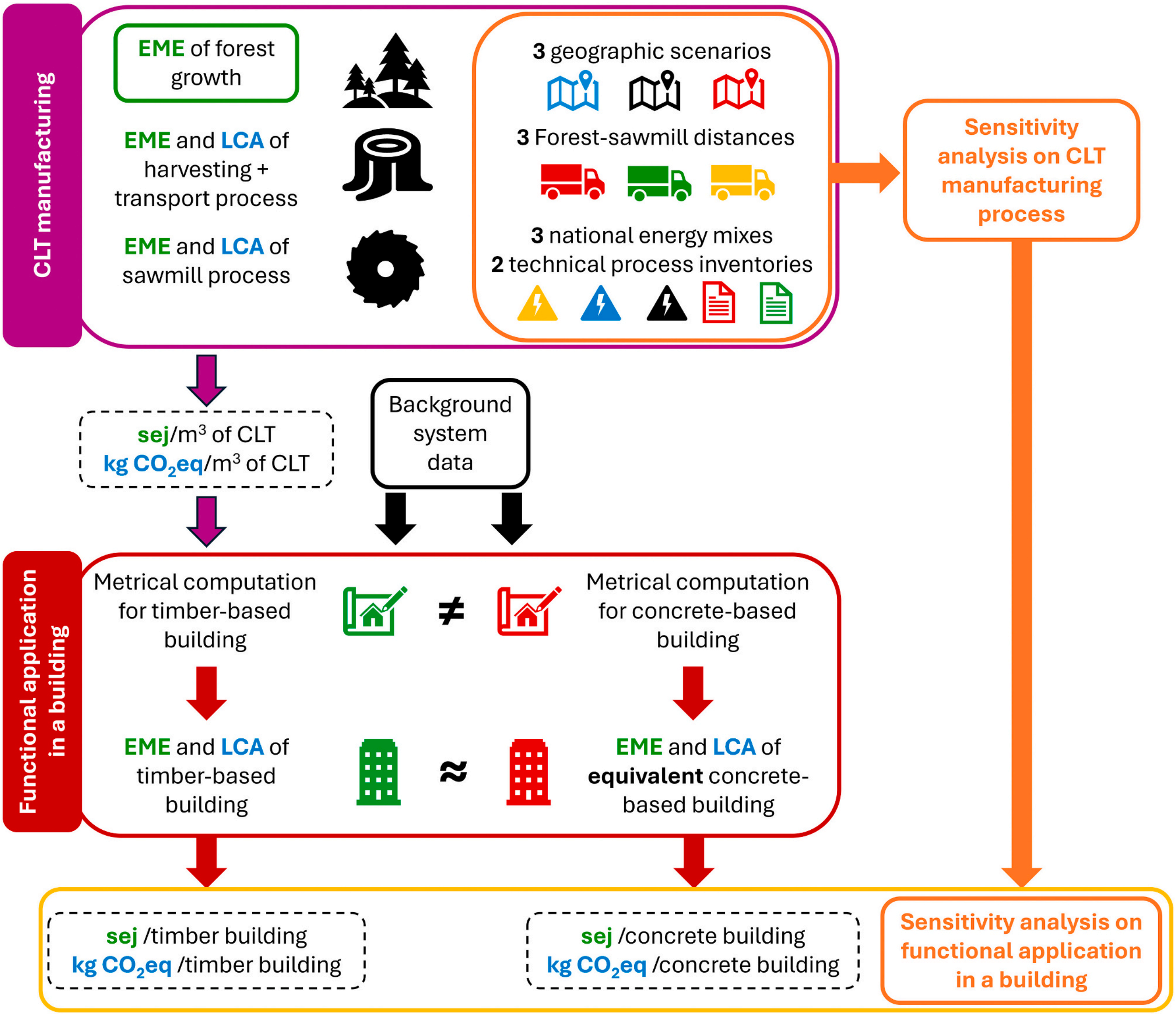

Fig. 1. Schematic representation of the methodological workflow. The green edges indicate the procedure exclusively pertaining to EME. The dashed line indicates the results for the two phases of the evaluation.

2. Materials and methods

The study is divided into two phases. The first phase focuses on the manufacturing of CLT. The second phase focuses on CLT and other engineered timber products used for structural and non-structural applications in residential buildings. The methodological workflow is schematically represented in Fig. 1.

Below we provide all methodological details for both EME (Section 2.1) and LCA (Section 2.2), and for the CLT manufacturing process (Section 2.3) and the residential building application (Section 2.4).

2.1. Emergy evaluation

Emergy is a thermodynamic metric defined as "the available solar energy used up directly and indirectly to make a service or product" (Odum, 1996b). The flows entering, leaving, and circulating within the analyzed system are expressed in terms of solar energy – which represents the source for the development of every biospheric system – using solar emergy Joule (sej) as the unit of measurement (Odum, 1988). Each flow can be expressed in intensive terms by means of the Unit Emergy Value (UEV), which represents the solar energy required directly or indirectly to make a unit of product or service (e.g., 1 g, 1 J, or 1 m^3) (Patrizi et al., 2018). UEVs are useful to qualitatively compare similar products that have been manufactured via different pathways. As EME can backtrack all the various flows of different kinds that characterize the studied system, it provides a variety of qualitative information helpful to describe the system from both an ecological and technological viewpoint. This kind of information is deployed by using a set of specific indicators calculated based on the distinction between renewable, (local) non-renewable, and purchased resources, goods, and services, such as the Emergy Yield Ratio (EYR), the Environmental Loading Ratio (ELR), the Renewability (%R), and the Emergy Investment Ratio (EIR) (Odum, 1996a). As in the present work, two non-directly comparable manufacturing processes are studied, and the focus will be on Renewability. The latter is the ratio between the renewable emergy flows over the total emergy flow – which includes renewable, purchased, and local non-renewable emergy flows.

2.2. Life cycle assessment

The LCA has been implemented according to the ISO standards 14,040:2006 (International Organization for Standardization, 2006) and 14,044:2020 (International Organization for Standardization, 2020) and the requirements set in EN 15804:2012 + A2:2019 (CEN, 2019). The Ecoinvent v. 3.6 (Wernet et al., 2016) database has been used to integrate the background data in the inventory. The SimaPro v. 9.0 software (PRé Consultants, 2021) has been used to perform the Life Cycle Impact Assessment, and EN 15804 + A2 is the impact assessment method used. Particularly, climate change is the impact category selected to estimate the GHG emissions. EN 15804:2012 + A2:2019 imposes consider timber as climate-neutral material, meaning that any biogenic emission linked with its incineration is not accounted for, as well as the related carbon absorption from the atmosphere.

The focus on the impact on climate change – global warming potential, GWP – is strictly linked to the essential difference between traditional materials (e.g., concrete and steel) and timber, the latter being capable of acting as carbon storage after the process of removing carbon from the atmosphere. In essence, the two types of materials substantially differ in terms of both upstream (carbon absorption or not), use (carbon storage or not), and disposal (carbon release or not) processes, making it necessary to apply both a methodology that well captures the biological processes – EME – and a methodology that well captures all technological processes and especially estimates the physical output flows that might affect ecosystems, resources, and human lives, i.e., LCA. The two methodologies have complementary scopes and are called to answer the same question on sustainability but from different standpoints. Therefore, the joint application ensures that the underlying existing ecosystem dynamics and efforts supporting the studied production system (in sej) and that the potential negative feedback flow – GWP – are both captured, ensuring a much more comprehensive, solid, and broad scientific information upon which decision-makers can draw more effective actions towards climate neutrality in the building and construction sector, avoiding unintended negative consequences.

2.3. CLT manufacturing phase

The CLT manufacturing phase includes the forest growth, the lumber harvest, the transport to the sawmill, and the CLT manufacturing as processes, with a cradle-to-gate approach. The lumber is assumed to be sourced from a forest located around 200 km from the sawmill. The CLT manufacturing is modeled for the year 2021. The definition of temporal boundary is fundamental since it allows to capture the significance of the time-specific national electricity grid composition – namely, the use of renewable or fossil resources for electricity generation. The functional unit is set to 1 m^3 of CLT (average data for 3, 5, and 7 layers CLT). The operations in the mill include the selection and linear cutting of the roundwood, the assembly and gluing of the boards, layers, and panels, all the intermediate drying, and the final cutting to obtain the CLT modules (see details in Fig. S1).

The flows considered for the EME of CLT manufacturing are schematically summarized in the diagram shown in Fig. 2.

In order to test the robustness of the study of the CLT manufacturing phase we used two different inventories, i.e., one provided by a CLT manufacturing company (Personal communication) – hereafter referred to as "Inventory 1" – and one retrieved from literature (Rüter and Diederichs, 2012) – hereafter referred to as "Inventory 2". To further test the robustness of our study, we performed the analysis considering three different geographic systems, based on different latitudes, in three different countries: Italy (ITA), Germany (DEU), and Norway (NOR). More details on the inventories and geographic scenarios can be found in the supplementary material (Table S1 – S3). Results will be presented as averages of the considered geographic scenarios, while they will be kept separated for the two different inventories. Fixed capital, such as infrastructures and machineries are usually overlooked in existing engineered timber environmental evaluations, or they are explicitly excluded due to their marginal relevance (Chen et al., 2019; Puettmann et al., 2018). Following the prevailing approach, fixed capital is excluded from the system boundaries.

The flows considered for the LCA only include part of the flows considered in EME. Details can be found in the schematic representation provided in the supplementary material (Fig. S1, S2).

2.4. Residential building application phase

Engineered timber cannot replace concrete and steel *ex aequo*: its specific technical features impose the use of engineered timber elements that can differ from the homologue elements made of concrete or steel, typically in terms of dimensions, and according to the building function (Hafner and Özdemir, 2023). Therefore, in order to perform a meaningful comparison, it is fundamental to compare the two materials (traditional and wood-based) from a practical application point of view, where the alternative materials have the same functions, but differ in quantities, shape, and dimensions. This can be done by modeling an application to a building with a determined function (e.g., residential, commercial, agricultural, industrial, etc.) and capacity (e.g., surface or volume). This approach is consistent with the related literature – see for instance Churkina et al. (2020).

The practical application example is conducted on a multistorey building for residential use with an engineered timber structure with a total gross internal area of 2881 m^2, which is taken as the functional unit for the second phase. It is composed of two building blocks (one of 4

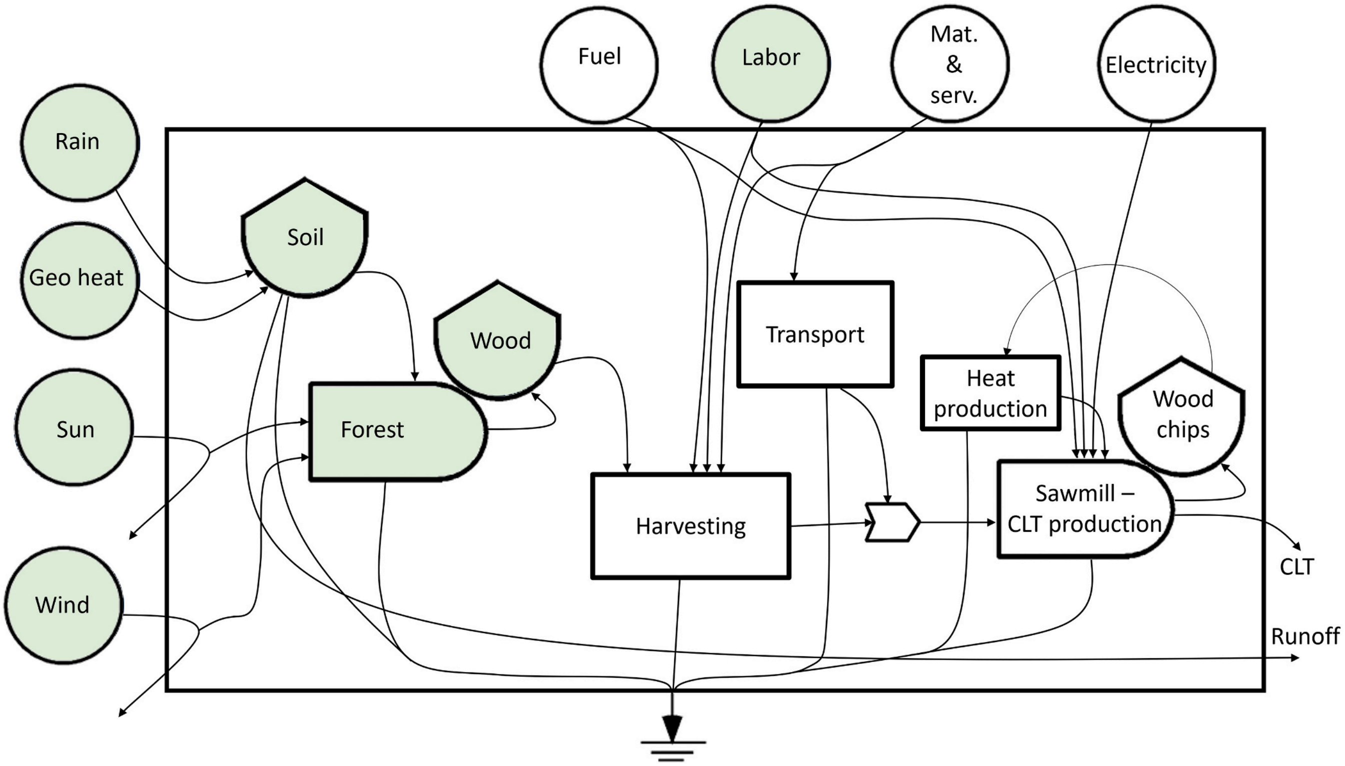

Fig. 2. Emergy diagram for the CLT manufacturing phase. Flows from the ecosystem are represented in green together with human labor.

stories, and one of 6 stories) with stories 3.25 m high. The same building can be realized with traditional concrete-based materials or engineered timber. For the latter, the bearing structure is based on a post and beam system. The columns and the beams are made of glulam, while floors and roofs (both flat) are made of CLT panels, as well as the technician and staircase shafts (core) and stabilizing walls. Finally, the façades are built with an LVL skeleton. These are the elements replaced by engineered timber materials.

The façades consist of wood skeleton elements in Laminated Veneer Lumber (LVL) with 2 layers of 15 mm gypsum on the inside, 15 mm Oriented Strand Boards (OSB) in the middle, 300 mm of mineral wool insulation, 8 mm cement-based windbreaking boards on the outside, and a rain shield of tiles. Outdoor balconies are made of steel as bearing structure and fiber cement plates as the bottom of the balconies and as front plates.

The construction is modeled for the same year in which the CLT was assumed to be manufactured, i.e., 2021. As the focus is on the building materials for structural applications, the initial excavation phase, as well as the finishing elements (e.g., windows, electrical system, etc.), are excluded on a ceteris paribus basis. The same is assumed for the transport to the construction site of all materials, and the assembly and use phases (Fig. 3). In practical terms, transport and energy required for the building construction, transport of the materials, and energy required for the building use and maintenance, transport and processes for the end-of-life phase are excluded, as detailed in Fig. S2. These exclusions, justified by the primary focus on the building materials, make the location of the building irrelevant to the aim of the present study.

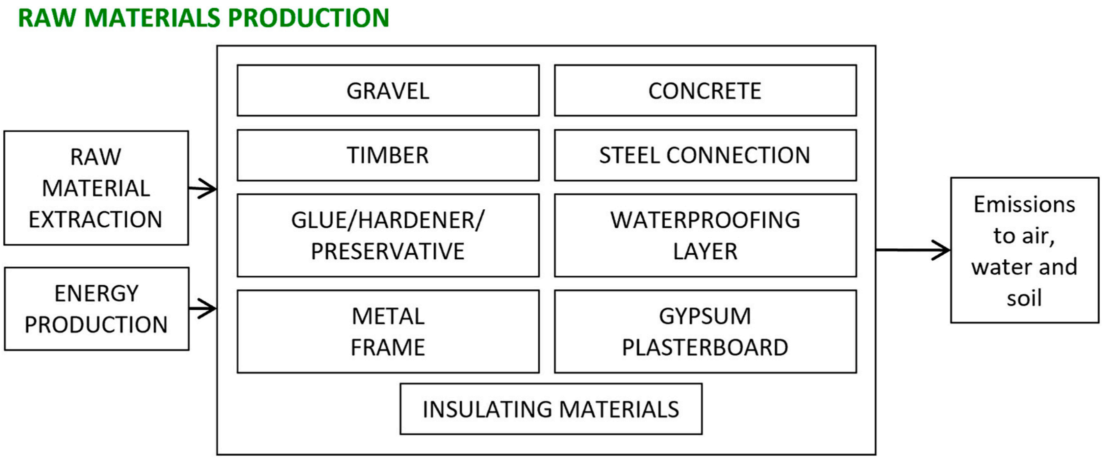

Fig. 3. Schematic representation of the materials and elements involved in the residential building application phase. Excluded materials and phases are shown for completeness. The detailed material inventory for this phase is provided in the supplementary material (Table S4).

3. Results and discussion

3.1. CLT manufacturing phase

EME reveals that for CLT manufacturing the major burden comes from the processes happening in the forest, with roundwood production accounting for about 60 % of the overall flow (Table 1).

In terms of emergy, the manufacture of 1 m^3 of CLT required, on average, $6.06•10^{14}$ sej. Of this, wood covered 45 %, human labor covered 26 % (20 % at the sawmill and 6 % in the forest), energy covered 19 % (almost totally at the sawmill) and other materials (e.g., chemicals) covered 10 % – 6 % in forest and 4 % at the sawmill (Table 1). Considering the two different technological processes (wood harvest in forest and wood processing at the sawmill), it is evident that wood growth remains the main contributor, followed by the sawmill process (43 %), while wood harvest covers a significantly lower share (12 %) (Table 1).

The renewability of CLT equals 47 % and is mostly due to the use of wood and marginally from the human work input. The flows that are considered to estimate the renewability include the natural flows allowing the forest growth, part of the electricity, and a marginal part of the human labor flow.

The inclusion of nature's effort in the environmental account ascertains that almost half of the emergy required to manufacture engineered timber materials derives from forest growth (Table 1). Being the primary component of such emergy flow, an environmental assessment of wood-based materials cannot prescind from the inclusion of forest growth in the system boundaries. Furthermore, by capturing the role played by people's interactions with the goods provided by the biosphere (materials and energy), we showed that human labor covers a fourth of the same overall emergy flow, being the second largest contributor (Table 1).

These two components are neglected by the most commonly used methodologies, such as LCA. LCA performed on the same inventory used for EME (Fig. 2, Table 1) and focusing on climate change indicates that the manufacturing process of 1 m^3 of CLT generated the emission of 149.6 kg CO_2eq. Contrarily to EME, LCA identifies energy use as the major contributor to the impact (46 % of which 45 % at the sawmill and 1 % in forest), followed by other materials (54 % of which 34 % at the sawmill and 20 % in forest), while wood growth is not represented (Fig. 4). It is worth highlighting that in LCA wood is considered as a resource basically freely available, and the only processes captured are the ones that shift (burden-free) wood resources from the ecosphere to the technosphere, i.e., the harvesting process. This approach results in a total disregard for the ecosystemic effort required to grow the trees and forest themselves. Accordingly, "wood" resource generation itself is not accounted for in LCA, causing around 40 % of the burden considered in EME to be overlooked in LCA (Fig. 4). By considering the exclusion of labor as well, the environmental burden neglected by LCA compared to EME reaches around 70 % (Fig. 4).

Since wood growth and labor account for most of the burden according to EME, we tested the sensitivity of the evaluation to the geographical scope of these two inputs. Negative linkage between forest growth emergy flow and latitude (north) and positive linkage between labor emergy flow with latitude (north) were found (Table S5). This results in a variability of the results of about ±10 % in terms of both sej per m^3 of CLT and % R (53 %–59 % for Italy, 43 %–48 % for Germany, and 36 %–40 % for Norway; see details in Table S5). The sensitivity to the geographic scope in terms of LCA is larger, reaching −24 % to +19 % with respect to the average value in terms of kg CO_2eq per m^3 of CLT, mainly due to the country-specific energy mix rather than to latitude (138–176 kg CO_2eq/m^3 of CLT for Italy, 141–179 kg CO_2eq/m^3 of CLT for Germany, 114–150 kg CO_2eq/m^3 of CLT for Norway, see details in Table S6).

Energy being the major source of GHG emission according to LCA (Fig. 4), we tested the sensitivity of both EME and LCA results to the national electricity mix composition for the sawmill activity. Accordingly, we modeled the same production system though with 35 % of the electricity sourced from hydroelectric, 35 % from photovoltaic, and 30 % from the national grid. The choice considers power sources that are available in all the countries considered. This scenario resulted in a 4 % reduction in terms of emergy required for the production of 1 m^3 of CLT (i.e., the average baseline of $6.06•10^{14}$ sej/m^3 of CLT to $5.82•10^{14}$ sej/m^3 of CLT as average for the three geographic scenarios, see details in Table S7). The renewability instead increased, though only marginally (+2.5 % from 46.4 % to 48.9 % on average, and from 53 %–59 % for Italy, 43 %–48 % for Germany, and 36 %–40 % for Norway to 56 %–62 % for Italy, 46 %–50 % for Germany, and 38 %–42 % for Norway, see details in Table S7). Conversely, LCA showed that this kind of improvement would result in a remarkable decrease of the GHG emission for CLT (−28 %, from 150 kg CO_2eq/m^3 of CLT to 107 kg CO_2eq/m^3 of CLT on average, and from 138 to 176, 141–179, and 114–150 kg CO_2eq/m^3 of CLT to 92–126, 94–128, and 85–118 kg CO_2eq/m^3 of CLT for Italy, Germany, and Norway, respectively, see details in Table S8). Since forests might be located far from the sawmills, we conducted a sensitivity analysis to assess the effect of the distance between the forest and the sawmill on the baseline results. Focusing on the CLT manufacturing phase, by halving the distance the emergy flow would be reduced by around 1 % (Table S9), while the GHG emission would be reduced by 7 % (Table S10). Instead, by doubling the distance the emergy flow would grow by 3 % (Table S9), and the GHG emission would grow by 17 % (Table S10).

We showed that LCA clearly neglects the role played by both ecosystems and human labor by imposing boundaries limited to the harvesting of wood, thus overlooking anything that happened beforehand (thanks to natural ecosystems) to allow the provision of what is being harvested, i.e., the forest growth that generates wood. It also fails to deliver on the role of human labor in the manufacturing process. By showing that this neglect equals around 70 % of the whole emergy flow (Fig. 4), we identify a critical gap in the information provided by LCA, which leads to an inevitable misinterpretation of the results with possibly negative consequences when designing policies involving the construction sector.

Furthermore, not only EME captures the critical relevance of the ecosystem for the provision of CLT, with wood growth alone accounting for more than 40 % (Table 1), but it also enables to point out that 47 % of CLT is obtained by using renewable emergy flows, thus providing much richer information about the sustainability level of the assessed material: it reflects the fact that while the timber house is used a forest regrows. On the other hand, concrete does not regenerate during house use: new quarries are necessary for digging the raw materials required for concrete production. LCA fails to provide any information in this sense. While emergy flows implied in the forest system (tree growth and harvest) account for the largest part of the overall burden, according to EME, LCA indicates that sawmill activities account for the largest part of the overall GHG emission. This corroborates the findings, showing critical flaws in the conclusions drawn by solely using LCA.

3.2. Building application phase

In terms of emergy, the materials required for the construction of the modeled residential building required $1.08•10^{19}$ sej when utilizing exclusively traditional materials, whilst they required $6.30•10^{18}$ sej when engineered timber is used to replace concrete and steel as much as possible (Table 2). This means that a reduction of around 42.5 % of the required emergy is achieved passing from concrete-based materials to wood-based ones.

The renewability of the whole building equals 5 % (%R), thanks to the use of CLT and other engineered timber-based materials. However, it is necessary to consider that the engineered timber replaced only partly the concrete-based materials, which have 0 % renewability. Specifically, in terms of volume, concrete passed from accounting for 43 % to 15 % of

Table 1

Emergy flow and UEV calculation of CLT production system. Figures are provided for both inventories and for both production sites – forest and sawmill. Country-specific data are provided as average among the three scenarios considered. All values are referred to 1 m^3 of CLT. Inventory 1 and inventory 2 are defined in section 2.3.*An accurate identification of the respective volumetric quantities was not possible due to lack of data. **corresponding to 1.9 m^3 scraps from the initial input of roundwood in the bark.

Phase	Country-specific	Flow type	Item	UEV, sej $unit^{-1}$	UEV unit	Quantity Inventory 1	Quantity Inventory 2	Quantity unit	Flow - Inventory 1	Flow - Inventory 2	Notes	Source
Forest	Yes	Input	Forest growth	9.84E+13	sej/m^3	0.63	2.90	m^3	6.23E+13	2.85E+14	100 % R	After (Neri et al., 2014)
	Yes	Input	Human work for wood harvest	1.23E+13	sej/m^3	0.63	2.90	m^3	7.79E+12	3.57E+13	≈1 % R	(NEAD, 2023) (Rüter and Diederichs, 2012)
	No	Input	Material and energy for wood harvest	1.39E+13	sej/m^3	0.63	2.90	m^3	8.78E+12	4.02E+13		(Manufacturing company) (Rüter and Diederichs, 2012)
	Yes	**Output**	**Roundwood in bark**	**1.25E+14**	**sej/m^3**	**0.63**	**2.90**	**m^3**	**7.88E+13**	**3.61E+14**		**Own calculation**
Sawmill	Yes	Input	Roundwood in bark	1.25E+14	sej/m^3	0.63	2.90	m^3	7.88E+13	3.61E+14		Own calculation
	No	Input	Transport of roundwood	6.97E+10	sej/t/km	149.27	193.28	tkm	1.04E+13	1.35E+13	188/250 km distance	(Pulselli et al., 2008a, 2008b)
	Yes	Input	Kiln-dried softwood lumber	3.35E+14	sej/m^3	0.96		m^3	3.20E+14	–	Produced inside the system	Own calculation
	No	Input	Polyethylene	6.70E+12	sej/kg	0.56		kg	3.77E+12	–		(Cabezas et al., 2010)
	No	Input	Plastics	7.47E+12	sej/kg		0.45	kg	–	3.36E+12		(Brown and Buranakarn, 2003)
	No	Input	Diesel fuel	3.71E+12	sej/kg	1.81	1.09	kg	6.70E+12	4.04E+12		(Bastianoni et al., 2009)
	No	Input	Lubes	3.46E+12	sej/kg	0.36	0.41	kg	1.24E+12	1.41E+12		(Bastianoni et al., 2009)
	No	Input	Metal products	5.21E+12	sej/kg	0.02		kg	8.86E+10	–		(Cabezas et al., 2010)
	No	Input	Industrial organic chemicals	7.70E+12	sej/kg	0.02		kg	1.23E+11	–		(Cabezas et al., 2010)
	No	Input	Tires, Rubber Products	5.47E+12	sej/kg	0.06		kg	3.34E+11	–		(Cabezas et al., 2010)
	No	Input	Water from aqueduct	2.39E+09	sej/kg	88.99	0.08	kg	2.13E+11	1.94E+08		(Pulselli et al., 2011)
	No	Input	Freshwater	2.62E+09	sej/kg	25.49		kg	6.67E+10	–		(Campbell et al., 2014a)
	No	Input	Glue	4.90E+11	sej/kg	7.37	4.70	kg	3.61E+12	2.30E+12		(Cabezas et al., 2010)
	No	Input	Chemical additives	4.84E+11	sej/kg	0.19	0.21	kg	9.14E+10	1.02E+11		(Cabezas et al., 2010)
	Yes	Input	Electricity from national grid	6.25E+11	sej/kWh	101.78	96.95	kWh	6.36E+13	6.06E+13		(AIB, 2022; Campbell et al., 2014b)
	No	Input	Wood products for packaging	2.23E+12	sej/kg		2.30	kg	–	5.13E+12		(Cabezas et al., 2010)
	No	Input	Cardboard for packaging	2.65E+12	sej/kg		0.10	kg	–	2.65E+11		(Tilley, 1999)
	No	Input	Biodiesel	1.01E+11	sej/MJ	1.17		MJ	1.18E+11	–		(Saladini et al., 2018)
	No	Input	Liquefied gases (LPG)	4.07E+12	sej/kg		0.004	kg	–	1.60E+10		(Bastianoni et al., 2009)
	No	Input	Self-produced heat from biomass	0	sej/MJ	811.32*	797.14**	MJ	0.00E+00	0.00E+00		Reused co-product
	No	Input	Self-produced heat from bark	0	sej/MJ	33.56*		MJ	0.00E+00	–		Reused co-product
	No	Input	Straw-based district heating	4.58E+11	sej/kWh		51.42	kWh	–	2.35E+13		(Zhang and Long, 2010)
	Yes	Input	Human work at the sawmill	1.24E+14	sej/h	1.00	1.00	h	1.24E+14	1.24E+14	≈1 % R	(NEAD, 2023) (year 2015)
	Yes	**Output**	**Cross laminated timber (CLT)**			**1.00**		**m^3**	**6.13E+14**	**5.99E+14**		**Main product**
	Yes	**Output**	**By-products (chips and shavings)**			**0.588**		**m^3**	**3.60E+14**	**3.52E+14**	**Fully self-consumed**	**Co-product**
			CLT - 6 cases average		**sej/m^3**				**6.06E+14**			

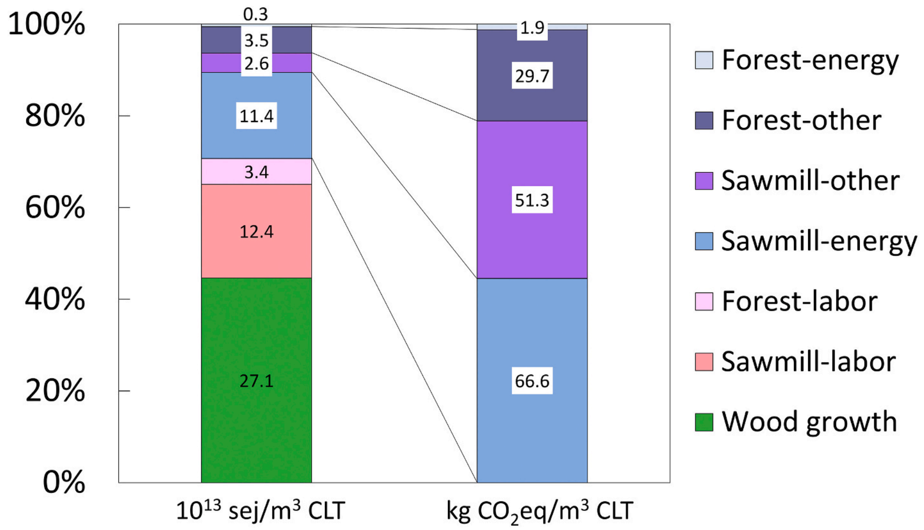

Fig. 4. Comparative breakdown of the results of the EME and LCA of a m^3 of CLT highlighting the contribution of each component. Solid black lines link the inputs that are common to the two methodologies. The related figures are shown on a white background.

Table 2
Emergy flow and UEV calculation of the building materials required for the construction of the modeled residential block. Figures are provided for both the concrete-based and the timber-based building. Engineered timber materials are reported in italics.

Element	Quantity		Unit	UEV	Unit	Flow (sej)		Reference
	Concrete building	Timber building				Concrete building	Timber building	
Chemical gypsum	–	73,913	kg	1.27E+09	sej/g	–	9.41E+16	(Pulselli et al., 2008a, 2008b)
Concrete	4,958,964	1,423,716	kg	1.43E+09	sej/g	7.10E+18	2.04E+18	(Hossaini and Hewage, 2011)
Fiberglass	197,250	97,125	kg	5.97E+09	sej/g	1.18E+18	5.80E+17	(Cabezas et al., 2010)
Gres	–	70,000	kg	3.64E+09	sej/g	–	2.55E+17	(Pulselli et al., 2007)
Miscellaneous	4050	4050	kg	3.40E+09	sej/g	1.38E+16	1.38E+16	(Bastianoni et al., 2009)
Plaster	115,560	183,060	kg	2.49E+09	sej/g	2.88E+17	4.57E+17	(Pulselli et al., 2007)
Plaster + paint	2500	2500	m^2	1.73E+13	sej/m^2	4.32E+16	4.32E+16	(Brown and Buranakarn, 2003; Meillaud et al., 2005; Pulselli et al., 2011)
Plastics	22,658	22,658	kg	7.47E+09	sej/g	1.69E+17	1.69E+17	(Brown and Buranakarn, 2003)
Sand and Gravel	621,000	621,000	kg	1.70E+09	sej/g	1.05E+18	1.05E+18	(Campbell et al., 2014b)
Steel	175,952	139,359	kg	5.28E+09	sej/g	9.30E+17	7.36E+17	(Pulselli et al., 2007)
Other Wood	6300	6300	kg	5.15E+08	sej/g	3.24E+15	3.24E+15	(Castellini et al., 2006)
Laminated Veneer Lumber (LVL)	–	74	m^3	1.94E+15	sej/m^3	–	1.43E+17	Own calculation based on (Rüter and Diederichs, 2012)
Glulam	–	268	m^3	8.93E+14	sej/m^3	–	2.40E+17	Own calculation based on (Rüter and Diederichs, 2012)
Oriented Strand Board (OSB)	–	38	m^3	6.06E+14	sej/m^3	–	2.27E+16	Assumed comparable to CLT
Cross Laminated Timber (CLT)	–	736	m^3	6.06E+14	sej/m^3	–	4.46E+17	Own calculation
Total building						1.08E+19	6.30E+18	

the whole volume of building materials required, while engineered timber materials covered 29 % (Table S11). It is even more remarkable in terms of mass since concrete passed from accounting for 81 % to 45 % of the total mass of materials required, while the engineered timber materials only covered 15 % (Table S12). These aspects are ultimately reflected in the breakdown of the result, which shows that concrete was linked to 32 % of the emergy required for the whole building, while the engineered timber materials were linked to only 12 % (Fig. 5).

LCA was conducted to investigate the transfer of the consequences deriving from neglecting ecosystemic efforts from the CLT environmental assessment to its application in a residential building. LCA results highlight that the materials required for the construction of the modeled blocks generated 1209.45 t CO$_2$eq when utilizing exclusively traditional building materials, whilst they caused the emission of 1173.23 t CO$_2$eq when engineered timber materials were used to replace concrete (Fig. 6). LCA results indicate that the advantage derived from the use of engineered timber materials is quite marginal, resulting in an emission reduction of about 3 %. In this case, concrete passes from covering 38 % to 12 % of the GHG emissions, whereas steel passes from 31 % to 34 %. Part of the GHG emissions is now covered by engineered timber (17 %), substituting part of the concrete-based materials. Remarkably, LCA indicates that by passing from concrete to wood, the impact of materials other than concrete and steel increases, while the opposite is shown by EME (Fig. 5). The marginal relevance of the environmental benefits indicated by LCA results is in remarkable contrast with EME results (Fig. 5), which clearly indicates concrete replacement as a valid opportunity.

By transferring the results of the energy improvement scenario (more renewable energy) from the CLT manufacturing phase to the whole building, as detailed above, EME reveals that the emergy flow would decrease only marginally (0.4 % from $6.30 \bullet 10^{18}$ sej to $6.27 \bullet 10^{18}$ sej on average, see details in Table S13), and the renewability would increase marginally as well (0.07 % from 5.18 % to 5.24 % on average, see details in Table S13). Instead, the sensitivity for LCA shows that the GHG

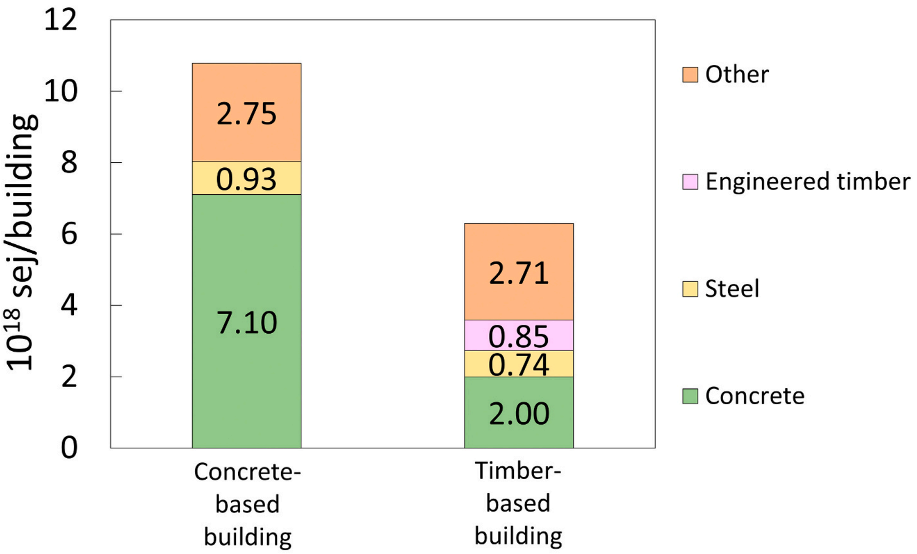

Fig. 5. Breakdown of the results of the EME of the modeled residential building block highlighting the contribution of each type of material. Engineered timber includes CLT, Glulam, LVL, and OSB. "Other" includes materials other than engineered timber, concrete, or steel.

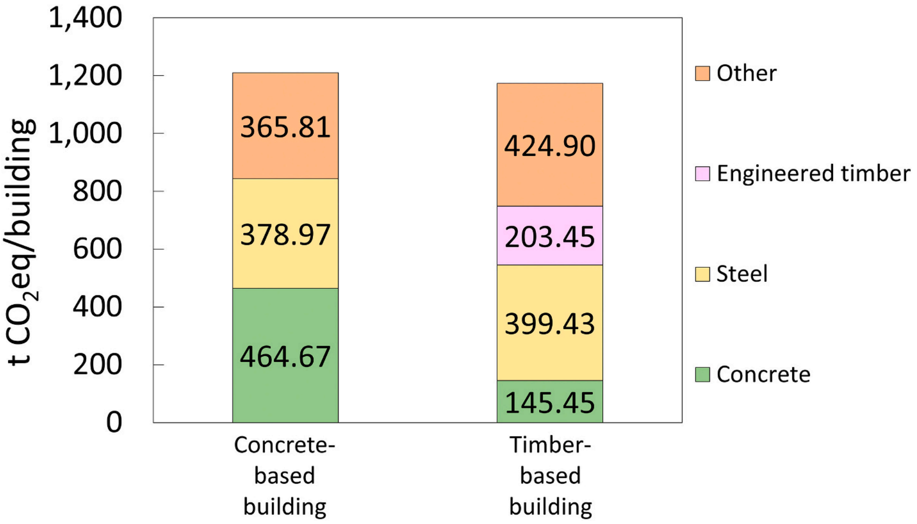

Fig. 6. Breakdown of the results of the LCA for the studied residential building block highlighting the contribution of each material to GHG emission. Engineered timber includes CLT, Glulam, LVL, and OSB.

emission would decrease for the modeled residential building block (by 2.7 % on average, and from 1165 to 1193, 1167-1195, and 1160–1187 t CO_2eq to 1173.23 to 1141.94 t CO_2eq on average, and from 1131 to 1156, 1133-1157, and 1126–1154 t CO_2eq for Italy, Germany, and Norway, respectively. See details in Table S14), indicating an overall marginal sensitivity of the results on the energy mix. The improvement would not affect the difference between the concrete-base building and the timber-based one in terms of EME (Table S13), while in terms of LCA, it would double such difference linking timber building with 6 % (1142 t CO_2eq for the timber building and 1209 t CO_2eq for the concrete one) less GHG emissions with respect to the concrete-based one (Table S13, S14). Conversely, the significance of the geographic variable for CLT production becomes irrelevant for both methodologies (Table S13, S14).

The effect of the distance from the forest to the sawmill on the results for the whole building would were tested too, based on the outcome obtained for CLT manufacturing. The sensitivity analysis showed that the effect would be marginal for both reduced (0.1 % and 0.7 % reduction in terms of emergy and GHG emission, respectively, Table S15, S16) and increased distance (0.2 % and 1.6 % increase in terms of emergy and GHG emission, respectively, Table S15, S16) as engineered timber is not the main material used for the modeled building block. Nor would renewability be significantly affected in terms of emergy (Table S15). This consideration leads to wondering if and how it would be possible to model buildings where wood-based materials can replace a larger part of the traditional ones.

Once again, these differences show the consequences of restricting the boundaries of the analyzed systems to human/technological intervention. In this case, a mitigation strategy based on LCA results seems to be highly effective, while only marginal effectiveness is detected when performing a comprehensive assessment via EME. Regardless, LCA maintains its capability to provide information about various and specific potential environmental impacts.

The difference between the results of the application of the two methodologies is exacerbated when comparing engineered timber materials and traditional ones in functional terms. While according to LCA, the advantages of partly replacing the concrete with engineered timber materials are marginal in terms of GHG emission (3 % reduction), EME reveals that the required natural effort would be almost halved (Fig. 5). Once again, this discrepancy is due to the different system boundaries and scope of the two methodologies. While EME captures and backtracks the past effort of nature to provide and regenerate materials and goods to support both human life and industrial activities (e.g., the biosphere and technosphere), LCA sets the boundaries to the technosphere; that is, it accounts for goods and services in terms of their industrial value. As such, in LCA, the wood contained in a living tree is provided as free of burden, while the only impactful elements are the processes within the technosphere required to extract and transform it, that is, the industrial processes. Conversely, EME captures nature's effort to provide the wood contained in a living tree (biosphere), on top of accounting for all the downstream processes exclusively related to the technosphere. The remarkable difference between wood-based materials and cement-based ones in terms of emergy is due to the mineral nature of the components of concrete: they are non-renewable, and they required a much larger (and/or longer) natural effort to be generated – and/or they would require a much larger/longer effort to be regenerated – compared to wood-based materials. This fundamental aspect is totally neglected by LCA, which would be misleading by suggesting that wood-based materials would only be marginally beneficial compared to traditional ones. The temporal aspect of this result assumes an even more remarkable significance from the functional perspective considered in this study. Indeed, if we consider 100 years lifespan for the modeled building it would be reasonable to consider the same time enough to regenerate the forest from which the wood was harvested. Conversely, at the same time, it would not be enough to regenerate the minerals required for cement production. This means that, at the end-of-life phase of the engineered timber-based building, new renewable material would be available for the construction of another building to replace the previous one – though still not for the cement-based materials.

It is important to note that a higher replacement rate of concrete and steel by engineered timber could be possible, with results that would highlight an even higher benefit in the environmental sense. The hypothesized building was modeled to match the strictest structural requirements (Danish standard - - Danish Ministry of Economic and Business Affairs and Danish Enterprise and Construction Authority, 2010), which forces the use of concrete to ensure the building's resistance to severe meteorological conditions such as strong wind gusts, fire, and noise. This was a highly conservative approach. Nevertheless, in many countries, construction regulations are much less strict, allowing a much larger replacement of concrete and steel with engineered timber.

While LCA remains a valid tool for an analytical approach on goods and services dominated by industrial processes, i.e., where the inputs from the technosphere cover most of the material flows, EME is a fundamental complement for analysis where inputs from the biosphere account for a large part of the good generated in the studied system, such as forestry and agriculture.

By focusing on building materials, our results clearly indicate that in a world transitioning from non-renewable resources to renewable ones (e.g., anything based on biomass), environmental sustainability assessments must go beyond the mere techno-centric evaluation, thus accounting for the role played by natural ecosystems, both in the present and past. In this sense, the joint application of EME and LCA will become fundamental. Furthermore, such consideration indicates that since natural ecosystems transcend political boundaries and reach planetary dimensions, a global effort is required to protect all global ecosystems and regenerate the degraded ones for both the current transition and future generations.

Our results indicate that the simultaneous application of LCA and EME is recommended to ensure a sustainable shift from fossil-based to bio-based solutions. The respective scope constraints are mutually compensated to obtain an environmental evaluation with a much more comprehensive scope than the one derived from the exclusive application of either methodology, i.e., either mostly focused on ecosystemic dynamics or mostly focused on technological processes. In this way both the environmental impacts (LCA) and the ecosystem efforts (EME) are captured to deploy information from both a user perspective (LCA) and a donor perspective (EME), and for both a short- and a long-term sustainability perspective. This is a key feature of the approach utilized in the present study as it ensures that conclusions are drawn not exclusively considering the environmental impact assessment from the technosphere or the ecosystemic effort but both, allowing the decision-makers to prioritize choices based on specific contexts. In particular, the renewability metric characterizing EME can instruct urban developers in the long-term planning of future sustainable cities. The expansion of the environmental assessment is quite immediate thanks to the possibility of (at least partly) basing EME on life cycle inventories characterizing LCA and the use selection and use of appropriate intensive emergy metrics such as transformities and UEVs that can be sourced from available databases (De Vilbiss et al., 2024; NEAD, 2023).

3.3. Comparison with previous studies

The results of LCA for the CLT manufacturing process in the present study are fully in line with the average (CO_2eq/m^3 CLT) found in the recent comprehensive literature review conducted by Younis and Dodoo (2022). Similarly, our results for both the concrete-based and timber-based buildings, expressed per unit of surface area (419.80 kg CO_2eq/m^2 and 407.23 kg CO_2eq/m^2, respectively) are in the range reported in Younis and Dodoo (2022) for various studies, ranging between 90 kg CO_2eq/m^2 and 800 kg CO_2eq/m^2. In terms of EME, the results for the traditional building expressed as sej per unit of volume ($9.64 \bullet 10^{14}$ sej/m^3) are comparable with the results that Pulselli et al. (2007) obtained for a traditional multistorey building ($8.11 \bullet 10^{14}$ sej/m^3). The results in terms of sej per unit of surface of the concrete building ($3.74 \bullet 10^{15}$ sej/m^2) are about 25 % higher than the results that Pulselli et al. (2007) obtained for a traditional multistorey building ($3.00 \bullet 10^{15}$ sej/m^2), while for the results from the present study for timber-based building ($2.19 \bullet 10^{15}$ sej/m^2) are about 25 % lower if compared with the concrete building studied in Pulselli et al. (2007). Chen et al. (2022) found a value $6.76 \bullet 10^{15}$ sej/m^2 considering the materials for a multistorey traditional building, about 80 % more than our result for the traditional building, due to intrinsic differences in the building design and linked inventory. Although their study adopted an LCA approach, it did not implement LCA; thus, no impact assessment result is presented, hampering the possibility of comparing with results of this evaluation. He et al. (2023) found $9.01 \bullet 10^{14}$ sej/m^2 as the aggregate average for the building sector in China, a non-specific value that is significantly lower than the present results for the traditional building. Finally, Reza et al. (2014) found $1.20 \bullet 10^{15}$ sej/m^2 considering a traditional multi-unit residential building in Canada, about 67 % lower than our results for the concrete-based building, possibly due to a different building design and assumptions. At present, the authors could not find any study comparing two functionally equivalent multistorey buildings with both LCA and EME, and none estimated the renewability of the building, identifying a knowledge gap.

The present work lays the foundation for filling such a gap and instructing future research to broaden the system scope and ensure the soundness of the results and their interpretation by performing a fair comparison between the engineered timber and traditional materials on a functionally equivalent basis. The application of EME together with LCA appears to be fundamental for bio-based solutions, i.e., to fathom the implications of the shift from a fossil-based to a bio-based economy, especially regarding ecological benefits. The joint application is facilitated by the common underlying matrix calculation framework. Future research should consider other impact categories to expand the scope beyond climate change. Another future research direction could imply an investigation of the whole building life cycle, i.e., including the use phase and the end-of-life (EoL), with various scenarios. In particular, it would be relevant to investigate how bio-based materials and traditional materials affect HVAC energy use from both LCA and EME viewpoints, i.e., one of the most impactful phases together with material production

(Röck et al., 2020). Even more relevant would be focusing on the EoL since timber-based materials lend themselves to more reuse (retaining the initial function), recycling (with the change of function due to the variation of the material properties), or disposal (with the loss of both energy and property) options, compared to traditional materials, especially concrete. Regarding modeling, future research could investigate the potential effects of extending the lifetime of the buildings, especially considering the effect of using timber-based materials versus traditional materials in terms of both EME and LCA.

4. Conclusions

Emergy evaluation captures the major relevance that ecosystems play in the provision of wood-based construction materials. The forest growth phase accounted for about half ($2.71 \bullet 10^{14}$ sej/m^3 of CLT) of the total emergy flow required for the production of CLT ($6.06 \bullet 10^{14}$ sej/m^3 of CLT), granting renewability of 47 %, which was quantified for the first time for a multistorey timber-based building. Moreover, LCA quantified the GWP of the production of CLT in 149.6 kg CO_2eq/m^3 of CLT. Concrete replacement with engineered timber as construction material for a functionally equivalent residential building block ensured a sharp decrease in terms of emergy flow demand, from $1.09 \bullet 10^{19}$ sej to $6.30 \bullet 10^{18}$ sej, while LCA showed a marginal change shifting from 1209.45 t CO_2eq for the traditional building, to 1173.23 t CO_2eq for the timber-based building. LCA results were more sensitive to the variables tested (forest location and distance and national electricity mix) due to the relevance of the impact of energy use according to the methodology's results for the LCA manufacturing process. The sensitivity to the same variables was marginal for both methodology for the building application.

This paper shows that shifting from traditional construction materials to engineered timber-based materials is highly beneficial in terms of emergy, since engineered timber is highly renewable, while steel and concrete are mostly obtained with non-renewable flows. This paper revealed the consequences of this peculiarity not being captured through the sole application of LCA, which would show just marginal improvements. We discussed how the inherent differences between the system boundaries and scope between EME and LCA affect the provision of significantly discrepant results, which can lead to ineffective or counterproductive actions.

Therefore, the joint application of LCA and EME is fundamental to properly assess the environmental sustainability level of renewable resources-based materials and products, such as timber-based buildings. The shift from a production system dominated by non-renewable resources to one where their use is limited in favor to renewable ones must be guided by a shift from an LCA-based sustainability assessment approach – a methodology particularly suitable for technology-dominated processes – to an integrated one based on the joint application of LCA and EME. In this way, the assessment can fully capture the role of both the biosphere and the technosphere that underpin the generation (and regeneration) of renewable resources.

The methodological approach applied in this study shows that the joint application of LCA and EME is feasible thanks to the similar underlying calculation framework and that such approach should be applied to fully capture the insights on the environmental sustainability of shifting from fossil-based to bio-based product systems, that is a fundamental point of the Sustainable Development Goals, and especially the backbone of the global climate agenda.

CRediT authorship contribution statement

Fabio Sporchia: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Morena Bruno:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Elena Neri:** Writing – review & editing, Validation, Supervision, Data curation. **Federico M. Pulselli:** Writing – review & editing, Validation, Supervision. **Nicoletta Patrizi:** Writing – review & editing, Validation, Supervision. **Simone Bastianoni:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179030.

Data availability

Data will be made available on request.

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