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A Lifecycle Assessment of a Low-Energy Mass-Timber Building and Mainstream Concrete Alternative in Central Chile

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Abstract: While high-rise mass-timber construction is booming worldwide as a more sustainable alternative to mainstream cement and steel, in South America, there are still many gaps to overcome regarding sourcing, design, and environmental performance. The aim of this study was to assess the carbon emission footprint of using mass-timber products to build a mid-rise low-energy residential building in central Chile (CCL). The design presented at a solar decathlon contest in Santiago was assessed through lifecycle analysis (LCA) and compared to an equivalent mainstream concrete building. Greenhouse gas emissions, expressed as global warming potential (GWP), from cradle-to-usage over a 50-year life span, were lower for the timber design, with 131 kg CO_2 eq/m^2 of floor area (compared to 353 kg CO_2 eq/m^2) and a biogenic carbon storage of 447 tons of CO_2 eq/m^2 based on sustainable forestry practices. From cradle-to-construction, the embodied emissions of the mass-timber building were 42% lower (101 kg CO_2 eq/m^2) than those of the equivalent concrete building (167 kg CO_2 eq/m^2). The embodied energy of the mass-timber building was 37% higher than that of its equivalent concrete building and its envelope design helped reduce space-conditioning emissions by as much as 83%, from 187 kg CO_2 eq/m^2 as estimated for the equivalent concrete building to 31 kg CO_2 eq/m^2 50-yr. Overall, provided that further efforts are made to address residual energy end-uses and end-of-life waste management options, the use of mass-timber products offers a promising potential in CCL for delivering zero carbon residential multistory buildings.

Keywords: LCA; LCIA; mid-rise timber buildings; carbon storage; passive zero carbon housing

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1. Introduction

The use of sustainably sourced mass-timber technologies to build multistory residential buildings (mainly cross-laminated timber (CLT) and glue-laminated timber (glulam)) has the potential to mitigate global climate change and benefit developing economies [1–3]. While it is well known that the building sector is responsible for about 40% of global carbon emissions [4], there is a large body of scientific research showing that, compared to reinforced concrete (RC), mass-timber (MT) buildings can store large amounts of biogenic carbon, reduce the embodied carbon of building materials, and avoid useful life emissions from auxiliary space-conditioning energy [5–8]. In recognizing these advantages, large forest product exporters, such as China (CN), Brazil (BZ), and Chile (CL), are currently seeking synergies with their timber sector to tackle large housing deficits and meet carbon emission targets by 2050 [9–11]. In Chile, since over 90% of new multistory constructions are RC apartment buildings [12], the surge of a high-rise MT industry could lead to a transition towards decarbonizing the national construction sector.

The rapid global expansion of the MT industry, which has quintupled over the last decade, reaching a production of over three million cubic meters by 2019 [13], has posed many research challenges to assess its long-term environmental impacts. Recent lifecycle assessments (LCA) comparing carbon emissions between MT and RC buildings in the US, Austria (AT), the UK, and CN have shown that through sustainable forestry practices, MT buildings could help offset most lifecycle emissions with per-square-meter carbon storage rates between 145 and 490 kg CO_2 eq [2,3,14,15], reduce emissions from cradle-to-construction by 35–47% [1–3], and avoid emissions from space-conditioning energy by 30–40% over useful life [5,6]. These ranges are due to differences in local manufacturing, building codes, and construction practices that are just being acknowledged and, if not well understood, may lead to unforeseen adverse effects on greenhouse gas (GHG) emissions and global fossil fuel depletion [1,2]. Mass-timber production in Chile is low scale, has incipient CLT production, and leaves several gaps yet to be addressed regarding sourcing, manufacturing, and environmental performance.

Over two-thirds of primary energy use, greenhouse gases, and solid waste generated by the building sector in Chile comes from housing [15,16]. This is partly because 75% of new constructions are residential buildings, 100 thousand units per year [12], and partly due to the thermal inefficiency of its existing housing stock leading to acute overconsumption of fuels for space heating, which accounts for over half of national residential energy use, an annual average of 4280 kWh per dwelling [17]. Although the country extends over a wide range of latitudes (17–56° S), more than 90% of its population is concentrated in the mild climatic region of its central valley (32–43° S) [18], where 98% of the country's sawn timber is produced—8 million cubic meters yearly [19]. Due to the mild climate and improved thermal performance of MT envelopes compared to mainstream cement and steel [7], there is great potential for MT buildings to cut most useful life emissions. To date, the major constraints for MT construction in CL are stringent seismic codes and the lack of tested MT products and design guidelines to meet local standards, namely, to fulfill current code requirements for fire safety, soundproofing, and thermal insulation.

This study aims to bridge the existing knowledge gap regarding the carbon and energy impacts of sourcing, manufacturing, and space-conditioning of mass-timber buildings in central Chile (CCL). The study is part of a larger research effort led by the Nature Conservancy (TNC), a nonprofit environmental organization, that seeks to assess the impact of increased MT construction on global forest and carbon stocks [20,21]. Six cities were selected by the TNC project—Atlanta (US), Boston (US), Seattle (US), Santiago (CL), Beijing (CN), and Vienna (AT) [21]. This paper reports the results of the first LCA performed on a mid-rise low-energy MT building in Santiago and compares it with an equivalent mainstream RC building, considering current national building codes [22]. The objectives of the study are:

- Perform a cradle-to-construction LCA of the low-energy mass-timber design;
- Perform a cradle-to-construction LCA of a building with similar functionalities but constructed with reinforced concrete;
- Assess the space conditioning performance of the buildings over useful life.

2. Case Study Building

The case study building selected for the LCA is a mid-rise social housing apartment block (Figure 1) classified as type B2 according to the Chilean Ministry of Housing [23]. The building is part of a large public multi-apartment development that would be built on an underused parking lot in downtown Santiago [24]. The development, which was designed for a solar decathlon contest held in 2019 in Santiago [25] by a Chilean architectural team of the TNC project, has six apartment blocks of 20 flats each, four large open courtyards, ground-floor facilities, and retail shops. Aiming to reduce lifecycle emissions, the design of the blocks was adapted to integrate locally sourced prefabricated CLT designs and passive envelope features [26]. As shown in Figure 1, to simplify the building modeling, material quantifications were performed on a base module of 10 flats separated from the rest of the block by a structural expansion joint. As is common for social housing in CL, the height of the blocks was set at five stories, the maximum allowed by code without incurring additional expenses for mandatory elevators [27].

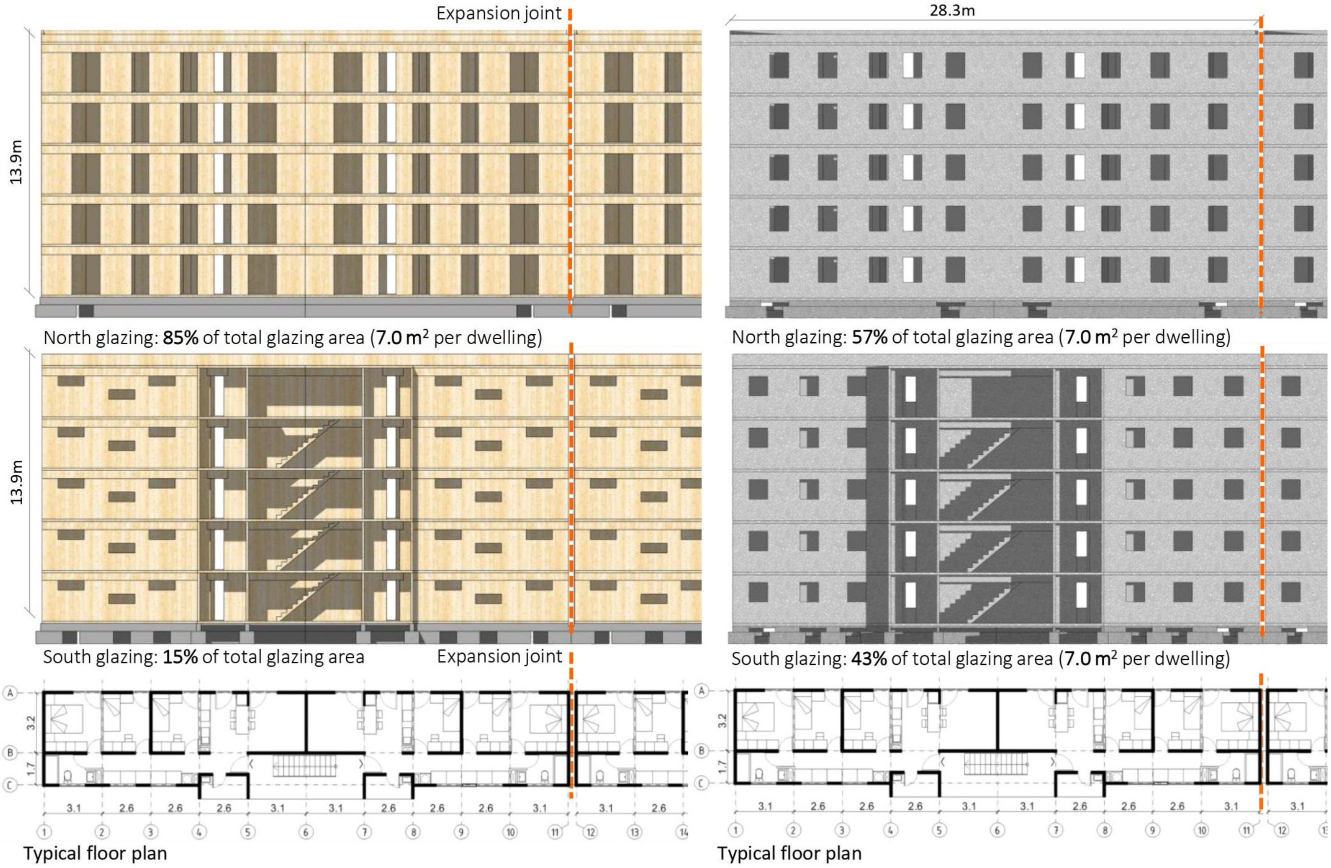


Figure 1. Case study buildings: (**left**) low-energy MT design; (**right**) mainstream RC alternative.

The MT and RC buildings were both modeled to conform to Chilean standards (NCh) and regulations set by the General Construction and Urbanism Ordinance (OGUC in Spa-nish) [27]. A functionally equivalent approach was adopted to quantify building materials by which components that were comparable between the two building types were not considered (e.g., windows, frames, railings, etc.). Non-structural elements, such as aesthetics and interior finishing, may differ between the two buildings. However, MT and RC elements requiring additional materials to meet minimum code standards, such as thermal insulation, acoustic barriers, and fire-retardants, were modeled. To account for emissions from space-conditioning energy over useful life, it was assumed that the MT apartment building would feature passive designs proposed for the solar decathlon contest, summarized in the axonometric shown in Figure 2, whereas the RC building would keep mainstream design features complying with minimum national OGUC regulations.

Although no particular site was considered for the LCA analysis, for structural design purposes, specific seismic demand and the static and dynamic soil-bearing capacities were assumed. Dynamic load characteristics were drawn from seismic hazard zone II, a region of intermediate seismicity according to Chilean standard NCh-433: Earthquake Resistant Design of Buildings [28]. Soil mechanical properties were classified as stiff, drawn from soil class C, Supreme Decree DS-61: Seismic Soil Categories [29]. Both design characteristics are representative of most built-up areas in the Santiago basin [30]. It should be noted that both zone II and soil class C have restrictive seismic design criteria comparable the most stringent site classes of US standards (classes D and F [30]). If, unlike the assumptions made here, a more restrictive hazard zone or soil class was the case, the size of structural members will increase more on the MT building than on the RC building requiring greater concrete foundations and lateral load reinforcement.

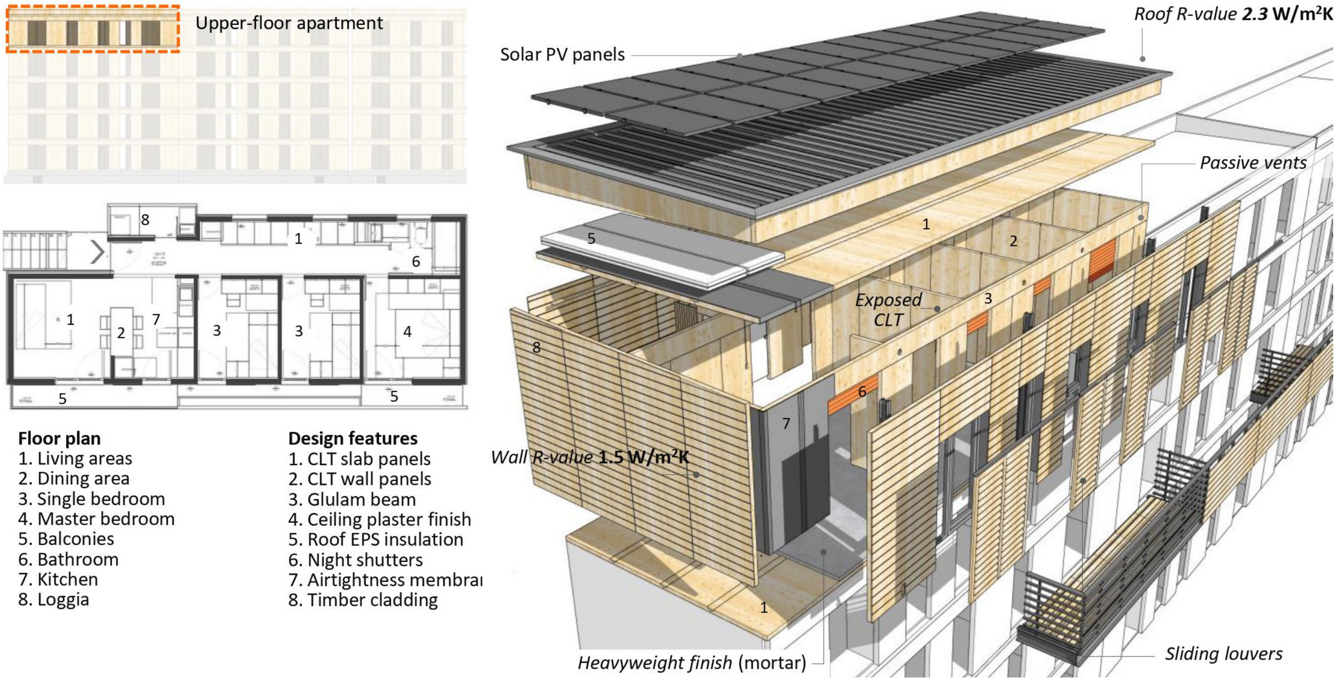


Figure 2. Exploded view and floor plan of the MT module built at the technological park [31].

To facilitate comparison, the MT and RC buildings were assumed to have the same overall dimensions, that is, structural grid and floor heights. As shown in Figure 1, the 20-unit apartment block modeled for the LCA analysis has a total habitable floor area of 1405 m^2, with a footprint of roughly 28 m × 5 m and 13.9 m overall height. The structural walls are spaced at around 3 m in each direction. The core is 2 m × 6 m. Floor-to-floor heights are limited to 3.2 m on the first floor and 2.66 m on the upper floors. All exterior circulation areas and distances between stairways and entries were designed as per OGUC code (Art. 4.2.1 General Safety Conditions [27]). The specifications and structural dimensions of MT members were informed by a pilot apartment module (Figure 2) built in 2021 as part of the framework of this project at the Technological Park of the University of Chile [31].

3. Materials and Methods

3.1. Lifecycle Assessment

Simplified bills for materials for the MT and RC designs were used for the LCA analysis (Tables A1 and A2, Appendix A). Primary data for tracing lifecycle processes were collected from mainstream local suppliers, manufacturers, and transport/equipment contractors. Secondary or reference data relevant to the CCL region were gathered from existing local literature and national databases (e.g., national average emissions for cement or electricity). When primary or secondary data could not be obtained, estimates were based on trusted databases (e.g., ECOBASE, CORRIM, Ecoinvent). Lifecycle inventory (LCI) data compiled for this study account for all relevant inputs of raw materials, energy, and GHG emissions from the whole lifecycle of the buildings, including upstream and relevant downstream processes, such as transport, product manufacturing, and operation. Carbon dioxide and equivalent GHG emissions, expressed as global warming potential

(GWP), were modeled using SimaPRO v. 8.0 environmental analysis software [32] under the lifecycle framework defined in ISO standards 14040/14044 [33,34].

The declared functional unit is 1 m^2 of total livable floor area. The system boundary includes lifecycle analysis from "cradle to construction," from the acquisition of raw materials until the installation of building products on site, and space-conditioning energy use over the entire useful lifespan of the buildings. "Product Stage" (A1–A3) and "Construction Stage" (A4–A5) were considered as per the buildings' product category rules (PCR) [35]. As illustrated in Figure 3, the product stage includes raw-material supply (module A1), transport to manufacturer (module A2), and manufacturing of building materials (module A3). The construction stage includes transport of building materials to the construction site (module A4) and construction-installation of the building (module A5). The use stage includes the space-conditioning energy use of the building (module B6) over a 50-year useful life span horizon as per local building category A2 [36]. Because of the lack of primary and reliable data at the time of the study with regard to the maintenance, use, and deconstruction of buildings in Chile, other use categories and end-of-life phases were not addressed in the analysis.

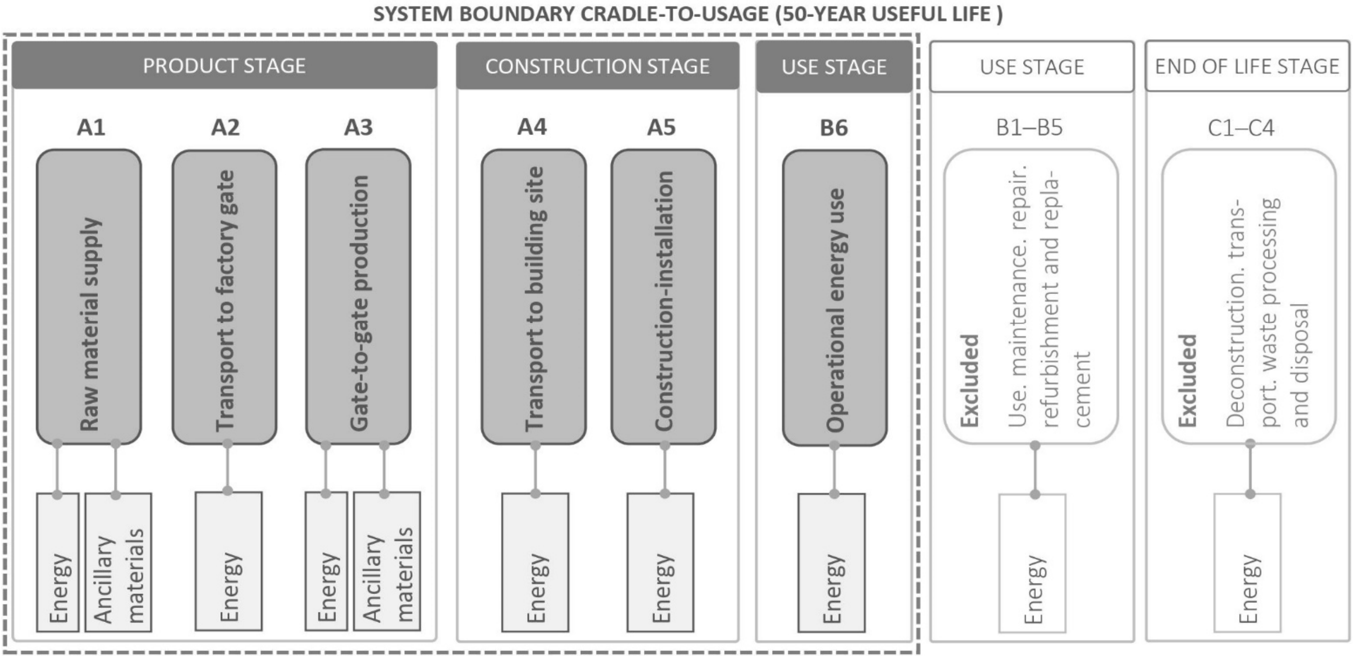


Figure 3. LCA system boundary used in this study.

3.2. Product Stage (A1–A3)

This stage includes all processes required to extract the raw materials from the environment and convert them into ready-to-use construction products. For the MT components, it was assumed that the source wood would be *Pinus radiata*, which is the single most used species in CL, accounting for over 96% of all national sawn timber production [19]. The wood would be supplied from a harvesting site located within the Bio-Bio region, where most of national pine plantations are found [19]. To keep the carbon biomass in the forest, further care should be taken to ensure responsible harvesting practices are employed. Since CLT panel framing is a relatively new construction method in CL, there are few manufacturing plants with the capacity to produce CLT, all based in the Bio-Bio region. It was assumed that CLT and glulam would be supplied from a plant located in the Bio-Bio region near Los Angeles (37.5° S, 72.5° W), 45 km from the sawmill and another 43 km from there to the plantation site. All MT components were modeled with the CORRIM database [37], modified using Chilean forestry operation and energy sources.

3.3. Construction Stage (A4–A5)

This stage includes the transport of building materials from the production gate to the construction site and their subsequent installation. Building components included in the analysis were the superstructure (walls, slabs, beams, etc.), exterior walls and roof, interior walls, and below-grade structure. It was assumed that the MT components would be shipped on a diesel truck from the manufacturing plant in Los Angeles to the construction site in Santiago, a total road distance of 487 km. All other materials were assumed to be produced and sold within the metropolitan region of Santiago (MRS), within a radius of 30 km from the assumed project site. The assumed road distances for each of the materials assessed in the study can be consulted in Table A3 in the Appendix A.

The installation phase includes the energy use of construction equipment to erect the MT and RC buildings. For the MT building, CLT panels and glulam beams were assumed to be lifted from the shipping truck at the construction site using a mobile tower crane (10-ton maximum load capacity). It should be noted that, as is the current practice in CL, MT structures are mainly composed of CLT wall and slab panels. As an indication, for the construction of the pilot apartment, which used a total of 27 m^3 of processed sawn timber (Figure 2), 47% was 5-ply CLT slabs, 36% was 3-ply CLT walls, and 6% was glulam beams. Thus, a multistory building in CL using the same construction system would require about 0.35–0.41 m^3 of processed mass-timber per square meter of floor area, a high usage rate compared to other studies in which usage rates are between 0.1–0.45 m^3 [3,38]. Other capital equipment and facilities, land use, maintenance, use, and final disposal were excluded from the system boundaries.

3.4. Operational Energy Use Stage (B6)

The use stage includes the energy consumed and GHG emissions over the entire useful life of the buildings. The focus was on the influence of building envelope assemblies on auxiliary energy demands for space-heating and cooling. TAS 9.2 [39] was used to estimate the energy performance of the case study buildings using TMY weather data for Santiago (WMO 855740) extracted from Meteonorm 7.0 [39]. TAS is a thermal analysis software that traces hourly energy demands by taking into account detailed weather data, building properties, and occupancy schedules [39]. Following the drawings shown in Figure 1, the entire 20-unit block of each building was modeled in TAS under multizone configuration. The material properties used in the simulations are given in Table A3 and the key input parameters are presented in Table A4. As an indication, for all of the apartments, occupancy was assumed to follow those of a reference household of four [40] using hourly heat gains of 5.0 W/m^2 per occupant, 5.0 W/m^2 for appliances on bedrooms, and 10 W/m^2 for appliances on the living area (see detailed schedules in Table A4).

As highlighted in Figure 2, based on passive design guidelines given for the climate of Santiago [26], the MT building has integrated design features that reduce demands for auxiliary space-conditioning energy. These are minor measures that have little impact on the overall resources involved in manufacturing and construction but may considerably reduce emissions throughout their useful life [26]. Compared to the RC building, as summarized in Table 1, these design features comprise higher envelope thermal resistances for less additional insulation (Appendix A); higher airtightness by adding a polypropylene membrane; larger room glazing-to-floor ratios for the same net glazing area (all windows being single glazing); a closer heat-storage capacity than mainstream timber frame given by the CLT structure, a 50-mm cement mortar flooring, and plaster finishes; and improved solar control through provision of operable shading blinds (Figure 2).

The results of simulations, given in kWh per square meter of floor area, were converted into GHG emissions using national emission factors [41]. Based on previous fieldwork performed for households in Santiago [26], daily and seasonal space-heating and cooling schedules were assumed for a 16-h day (7 a.m.–11 p.m.), with thermostats on the living area and bedrooms set at 17 °C from May to September (heating season) and 27 °C from December to February (cooling season). The major energy sources for space-conditioning in the MRS are liquified petroleum gas (54%), paraffin (32%), and electricity (12%) from coal, natural gas, or hydroelectricity [17]. Since electricity is projected to become the dominant source by 2050 [42], the carbon intensity factor of per-consumed kWh used in this study was 0.47 kg CO_2 based on CCL's electric power grid [41]. Due to the lack of reliable local data at the time of the study, building maintenance, repair, and refurbishment were excluded from the system boundaries.

Table 1. Passive design features applied to the low-energy MT building.

Design Parameter	Indicator	Low-Energy MT Building	Mainstream RC Building
Thermal resistance	Roof R-value (W/m^2K)	2.3	2.1
	Wall R-value (W/m^2K)	1.5	0.5
	Glazing R-value (W/m^2K)	0.18	0.18
Thermal capacity	Internal heat capacity (kJ/m^2K)	165	225
Building glazing area	Net glazing surface (m^2)	7.2	7.2
Glazing to floor ratio	GFR of habitable rooms (%)	20	10
Orientation of glazing	North glazing areas (%)	85	55
	South glazing areas (%)	15	45
Night insulation	Blinds U-value (W/m^2K)	0.9	-
Operable vents	Air exchange rate (ACH)	0.3	1.0
Operable shading	Exterior louvers (SF) [1]	0.4	-

[1] The shading factor (SF) is 1 in the absence of shading and 0 in the case of total shading.

4. Building Code Assumptions

The criterion for building materials' specification was to meet national codes with locally available mainstream products. To this end, detailed specifications were drawn from tested product assemblies provided by the Chilean Ministry of Housing and Urbanism (MINVU in Spanish), specifically for fire safety (E-12 [43]), soundproofing (E-14 [43]), and space conditioning (E-8 [43]). When no tested assemblies were available for MT construction, equivalent product specifications were taken from international guidelines and adapted accordingly. Material specifications and code-compliant standards are detailed in Figures 4 and 5.

Fire resistance: National fire safety standards for 5–6 story buildings (Type B under OGUC [43]) require minimum fire-resistive ratings of 1.0 h for roofs (b), 1.5 h for demising and load-bearing walls (c/f) and slabs (d), and 2 h for staircase walls (e). As per MINVU E-12 guidelines, no additional fire-retardant materials were required for the RC building. For the MT building (Figure 4), following specifications from northern Europe CLT pine [44], almost all assembly categories required additional fire protection, assuming gypsum wall boards (GWBs) and rock fiber as the requisite non-combustible materials.

Soundproofing: OGUC allows a maximum sound transmittance coefficient (STC) of 45 dB for demising walls and slabs (Figure 5c,d) and a minimum impact insulation coefficient (ICC) of 75 dB for demising slabs (Figure 5d). As per MINVU E-14, no additional soundproofing materials were required for the concrete building. Since no acoustic tests had been conducted for Chilean CLT products, reference assemblies were drawn from a recently published acoustical report by WoodWorks [45]. To comply with standards for demising CLT walls, a cavity space and two-layer GWBs were added on both ends (Figure 5c). For the CLT slabs, a cement mortar topping with a polyester sound-deadening mat underneath was used to meet the requisite soundproofing assembly (Figure 5d).

Thermal performance: Minimum admissible thermal resistances for Santiago (Zone D) are 0.5 m^2k/W for exterior walls and 2.1 m^2k/W for the roof [46]. For the RC building, a typical concrete wall assembly was used, including a 10 mm expanded polystyrene EPS board and gypsum plaster or stucco as exterior finish (Figure 4a). The same solution was used for the roof, which required a thicker EPS board of 80 mm (Figure 4b). For the MT building, no additional insulation was required for external walls and only 45-mm EPS was required for the roof (Figure 4a,b). The density and conductivity of MT elements, seen in Appendix A (Table A3), were drawn from results of laboratory tests undertaken as part of this study at the laboratory of mechanical engineering at the University of Santiago.

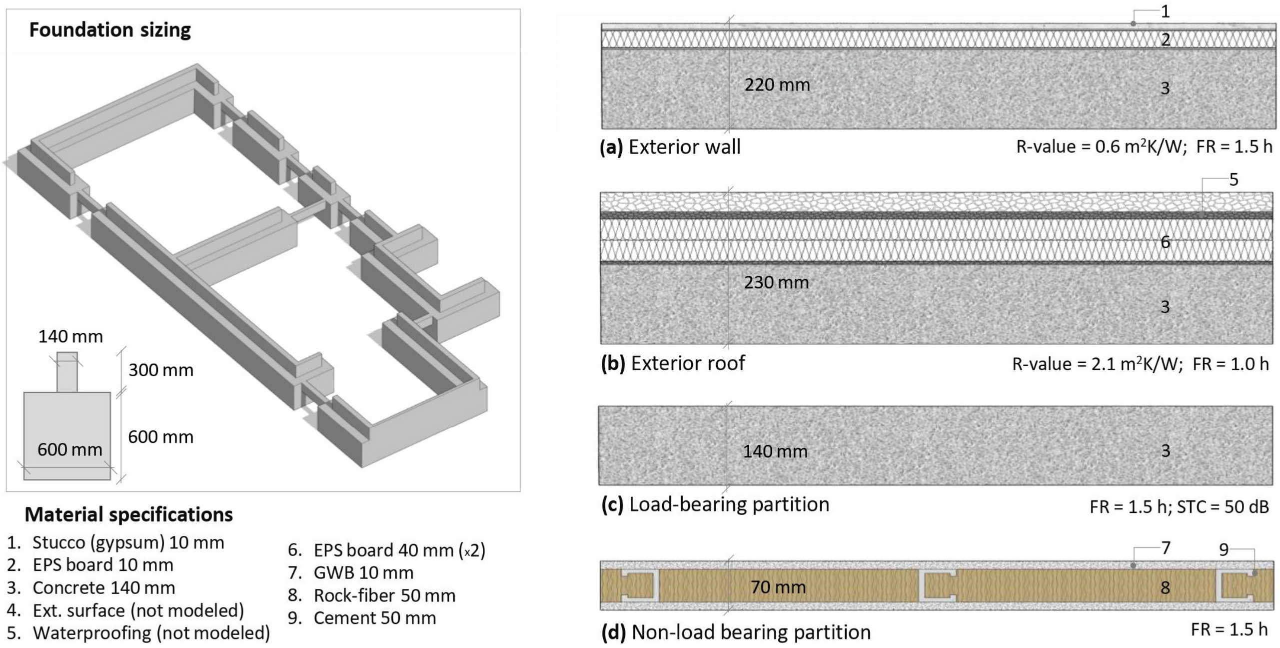


Figure 4. Illustrative construction assemblies for the mainstream RC building alternative. (**a**) exterior wall; (**b**) exterior roof; (**c**) load-bearing partition; (**d**) non-load bearing partition.

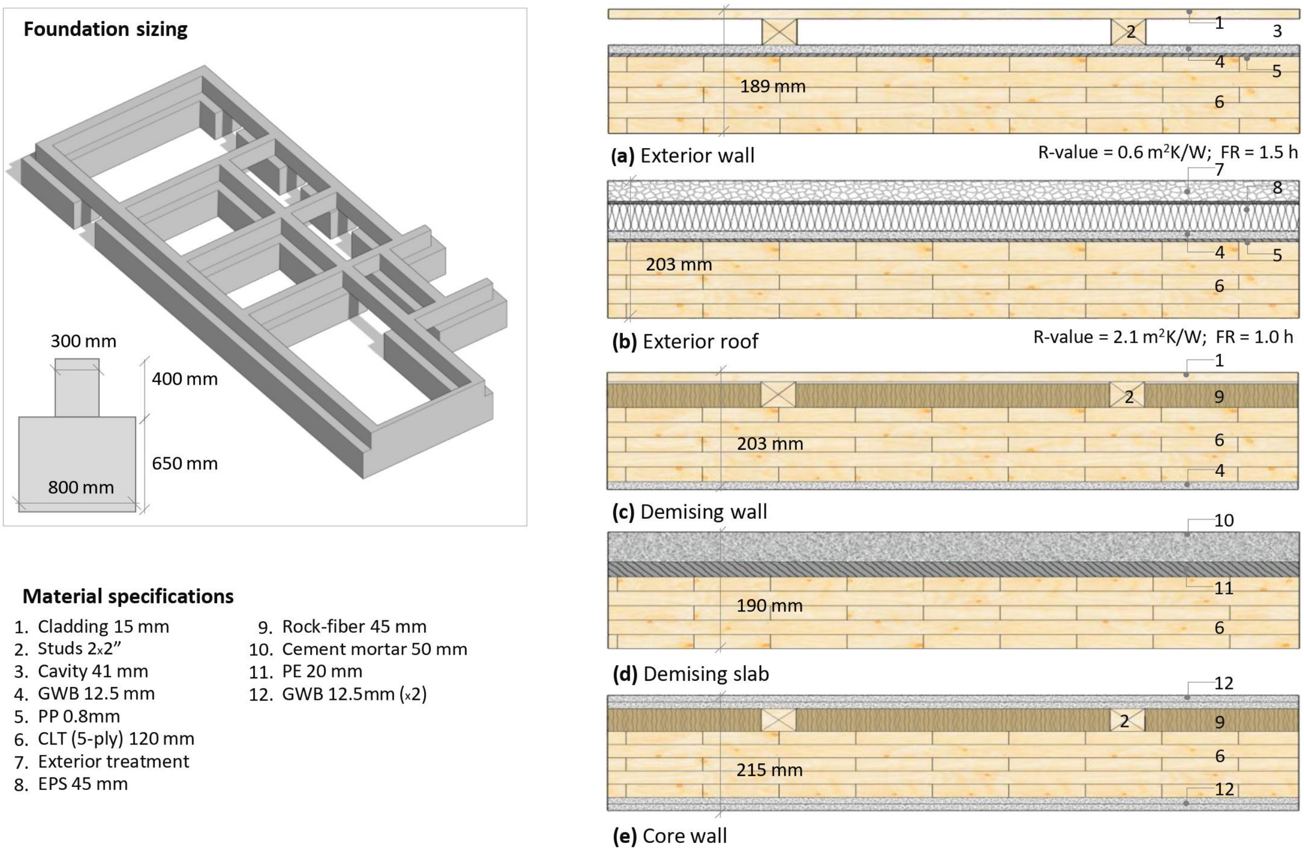


Figure 5. Illustrative construction assemblies for the low-energy MT building design. (**a**) exterior wall; (**b**) exterior roof; (**c**) demising wall; (**d**) demising slab; (**e**) core wall.

Structural design: Given that Chilean seismic codes are strict [30], additional consideration was given to meeting statutory resistance criteria by performing spectral modal analysis with ETABS v. 18 engineering software [43]. As a result of traditional construction practice and local code compliance, multistory buildings in CL generally have short floor spans and several load-bearing walls [30]. Unlike other countries with similar seismicity, such as the US or New Zealand (NZ), the design of high-rise buildings relies on redundant configurations and stiff framing to overcome the low drift limits imposed by standard NCh-433 (i.e., a maximum drift limit of 0.002 h_s, compared to 0.02 h_s (US) and 0.015 h_s (NZ) [47]). For this study, the seismic resistance of the MT building is provided by a dense grid of CLT walls confined with glulam beams and additional RC foundation reinforcement. Further shear resistance is provided by CLT steel connectors, such as typical hold-down angle brackets and bolts. No additional steel framing or buckling-restrained braces were specified as per structural design.

For dimensioning structural elements, uniform design criteria were applied to both buildings in compliance with national standards for seismic action, NCh-433 [28], soil classification, DS-61 [29], and permanent and live loads, NCh-1537 [43]. For the RC building, the assumed compressive strength of concrete was 25 MPa, and the ultimate and yield strength of reinforcing steel rebars 630 MPa and 420 MPa (grade A630-420H [43]). For the MT building, structural CLT and glulam components were assumed to be machine-strength graded *Pinus radiata* with a bending stress of 24 MPa, which is timber class C-24, according to Chilean standards [43]. Since CLT panel steel connectors were not modeled, they were assumed to equal 2% of all reinforcing steel rebars used for the foundations of the MT building. As per standard NCh1537 [43], additional dead loads of 150 kg/m^2 and live loads of 200 kg/m^2 were assumed in private areas, 300 kg/m^2 for common areas, and 100 kg/m^2 for the roof. The seismic mass of the buildings was calculated considering 100% of the dead loads and 25% of live loads. See Appendix A (Table A5) for detailed input parameters and the results of the spectral modal analysis.

5. Results

5.1. Material Quantities

The quantities of building materials required for the low-energy MT building and the mainstream RC building are displayed in Tables A1 and A2 (Appendix A). It should be remembered at this stage of the analysis that only different functionally equivalent materials were modeled, all identical design feature between the two buildings were excluded (e.g., windows, frames, railings, etc.). The MT building uses a total of 526 m^3 of sawn timber with 97% CLT and glulam. The mass timber usage rate is roughly 0.38 m^3 per m^2 of floor area. The exterior walls use 154 m^3 of 5-ply CLT (29%), interior walls use 97 m^3 of 3-ply CLT (18%), floor slabs 213 m^3 of 5-ply CLT (40%), and beams 45 m^3 of glulam (8.6%). To counteract the greater seismic tensile loading of CLT, the MT building uses 149 m^3 of concrete only for its foundations, almost double the amount of that of the RC building (89 m^3). The RC building uses 641 m^3 of concrete, 47% (302 m^3) for exterior walls, 39% (250 m^3) for the roof and floor slabs, and 14% for the foundations. In addition, by achieving better thermal insulation, the MT building uses only 16% of the total EPS required for the RC building to comply with OGUC regulations [43].

As seen in Figure 6, for both building designs, concrete accounts for the largest contribution by mass. For the RC building, concrete accounts for nearly 98% of the total building mass, followed by steel (reinforcing rebars) and the gypsum plaster used as exterior finish with low values around 1.5% and 0.3%, respectively. Mainly due to its additional seismic load reinforcement at foundations, concrete makes up nearly half (47.8%) the total mass of the MT building, followed by CLT and glulam (34%) and the cement mortar used as fire retardant and acoustic deadening of CLT slabs (16%). Besides these, all other supplementary materials used to comply with local codes were found to have negligible mass, representing only 1.2% and 0.94% of each total. These and other supplementary materials not included in this study (e.g., finishes, fixtures, or opening components) are typically found within the 0.5–2% margin of the total mass of multistory buildings [48,49].

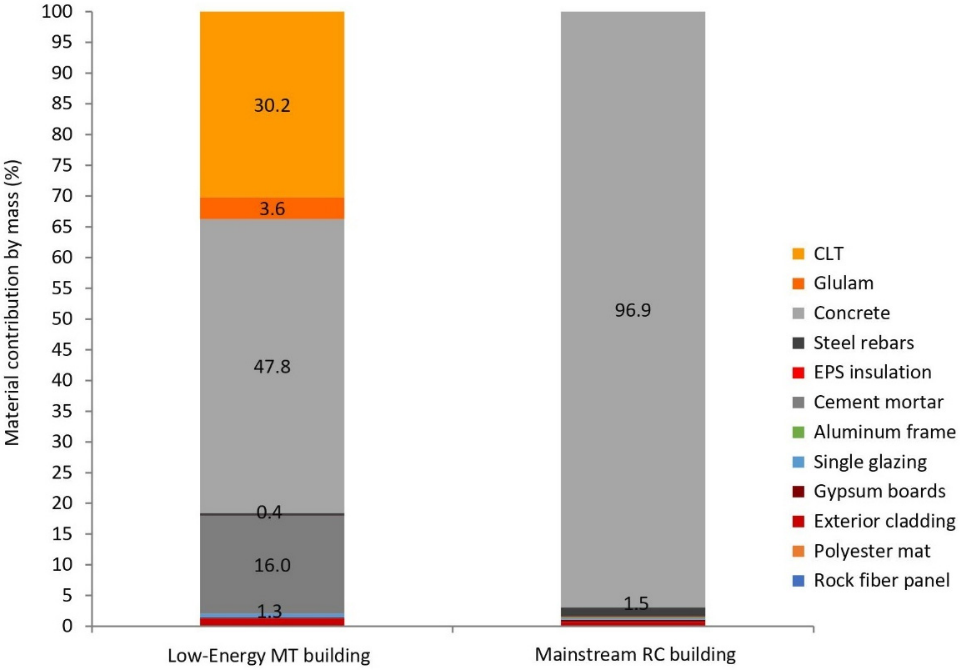


Figure 6. Material contribution by mass for the MT design and mainstream RC alternative.

5.2. Embodied Carbon

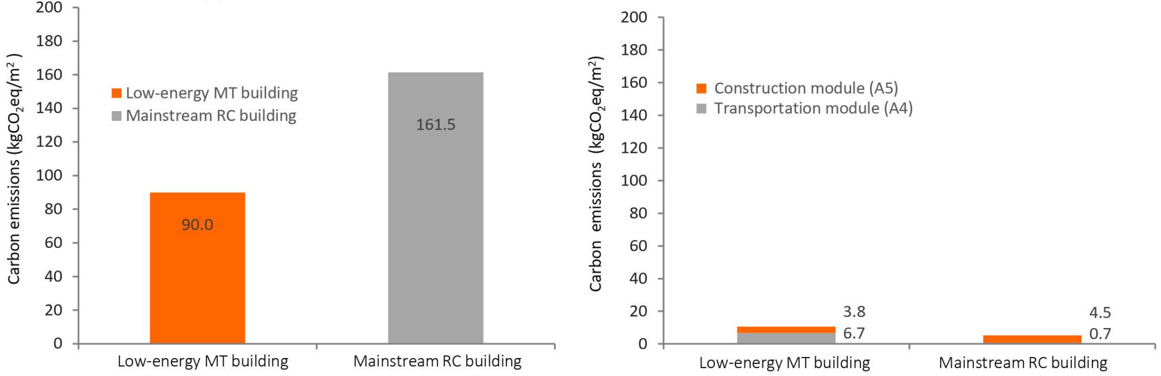
5.2.1. Product Stage (A1–A3)

The embodied carbon of materials for each building type, expressed here as GWP in kg CO_2 eq per square meter of floor area, are shown in Figure 7a,b. For both buildings, more than 96% of the total embodied carbon is generated during the product stage (A1–A3), which comprises the supply of raw materials, transport to factory, and gate-to-gate production. In this stage, the global warming contribution of the MT design was 44% lower (90 kg CO_2 eq/m^2) than that of the mainstream RC building (162 kg CO_2 eq/m^2), attributable to the relatively high usage of mass timber and differences in national energy source mixes. This is a considerable cut in emissions compared to other studies that found reductions from RC to MT buildings in the order of 18% and 28%, with the embodied carbon of MT buildings ranging from 190–240 kg CO_2 eq/m^2 [3,21].

5.2.2. Construction Stage (A4–A5)

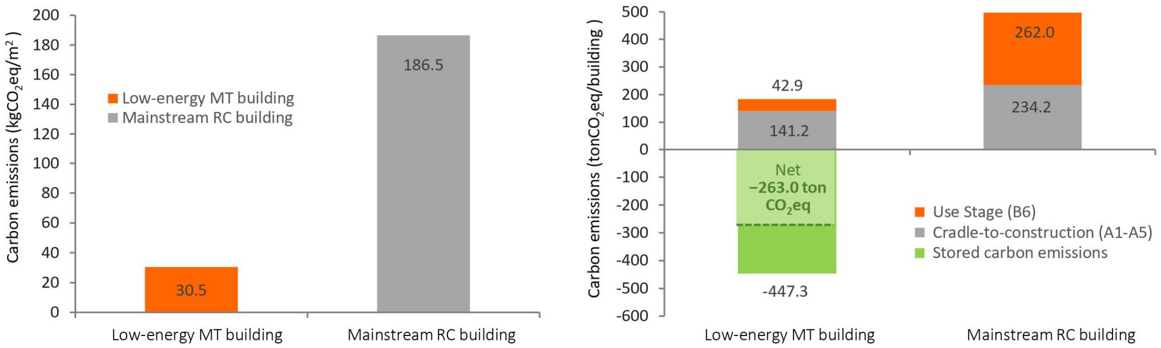
Transport (A4) account for 7% of the total embodied carbon of the MT building and only 0.4% of that of the RC building (Figure 7b). This is primarily due to differences in transport distances, as MT components are brought from the Bio-Bio region (487 km) and concrete from within the MRS region (30 km). If unlike this scenario, MT were to be sourced from an established manufacturer overseas, for instance from Austria (Biderholz Company [48]), an additional 18 kg of CO_2 eq/m^2 would be emitted, generating at least 10% more emissions than when MT is produced locally. As shown in Figure 7b, for the installation module (A5), consistent with the higher mass of concrete compared to *Pinus radiata* (radiata pine, Appendix A), the larger contributor to global warming was the mainstream RC building, which, compared to its mass timber equivalent, increased emissions by around 118%, from 3.8 to 4.5 kg CO_2 eq/m^2.

Compared to other LCA studies [14,50–52], the resultant emissions for both building types were found within the lower end of the spectrum. This can be seen in a recent publication by Puettmann et al. [51], which, as part of the same global TNC project [21], adopts a similar approach to this study by comparing the emissions of six equivalent MT and RC buildings across different regions of the US [52]. For the MT buildings of the study in the US, the emissions of modules A1–A5 were found within the 106–172 kg CO_2 eq/m^2 range whereas those for the RC buildings within 203–282 kg CO_2 eq/m^2 [52]. Besides other differences in bills of materials, material processing, and manufacturing discussed throughout this paper, the main reason of the lower emissions obtained for the RC building is shorter distances for supply of primary materials on module A4 which compared to the US study yielded differences in the order of 55 kg CO_2 eq/m^2 [52].



(a) Product Stage (A1–A3)

(b) Construction Stage (A4–A5)



(c) Use Stage (B6) *space-conditioning*

(d) Lifecyle Carbon Emissions (A1–A5/B6)

Figure 7. Summary of carbon emissions through all lifecycle stages considered in the analysis. (**a**) product stage; (**b**) construction stage; (**c**) use stage; (**d**) lifecycle carbon emissions.

5.2.3. Operational Energy Use Stage (B6)

Of all lifecycle stages, auxiliary space-conditioning energy accounts for 23% and 53% of emissions of the MT and RC buildings, respectively (Figure 7c). The annual emission rates expressed here in kg CO_2 eq/m^2 are the results of building thermal simulations performed in a 20-unit apartment block divided by the total conditioned area in square meters. For the mainstream RC building, the total annual emission rate for space-conditioning was 14.7 kg CO_2 eq/m^2, 12 kg CO_2 eq/m^2 for space-heating, and 2.7 kg CO_2 eq/m^2 for space-cooling. In turn, the passive envelope designs of the MT building help drop emis-sions to 2.4 kg CO_2 eq/m^2 per year with no need for mechanical cooling. Remarkably, as seen in Figure 7c, over the 50-year lifespan, the accumulated emissions for the MT building were as much as 83% lower (30.5 tons of CO_2 eq/m^2) than that of the equivalent RC building (186.5 tons of CO_2 eq/m^2).

5.3. Lifecyle Carbon Emissions

Considering that wood products are associated with carbon sink due to their photosynthetic nature and assuming that sustainable forestry practices allow to keep the carbon biomass in the forest, a net building carbon emission was also estimated. As both the MT and the RC buildings have a gross floor area of 1405 m^2, from cradle until end of use, the buildings will generate a total of 184,000 and 496,000 kg of fossil CO_2 eq, respectively (Figure 7d). On the other hand, from the standpoint of their value as carbon sink, the MT building stores 447,000 kg CO_2 eq in its timber structure, leaving a negative net of 306,000 kg CO_2 eq from cradle to construction and 263,000 kg CO_2 eq when including space-conditioning energy use. To retain the sequestered carbon through end-of-life, crucial decisions not discussed here should be evaluated [48,53]. As a result, until end-of-life, the use of sustainably sourced wood products helps reduce GHGs of an MT building by as much as 300% and 118% that of a functionally equivalent mainstream RC building.

5.4. Primary Energy Use

Both renewable (RPRE) and non-renewable primary energy (NRPRE) are used to create the inputs of the lifecycle process of the buildings. Embodied energy is the sum of the energy used from the extraction, transport, and manufacturing of materials. As shown in Figure 8, through all lifecycle stages (A1–A5/B6), the total share of non-renewable fossil energy is 55% for the MT and 72% for the RC building. From cradle-to-construction (A1–A5), the MT building uses 10% less fossil-based energy and 19 times more renewable energy per square meter. Renewable energy is used to produce lumber feedstock (A1–A3) as raw material to manufacture MT components. For CLT and glulam, most of the renewable energy is generated through combustion of biomass (sawdust, chips, and other waste from the milling process). The embodied energy of the MT design is 37% higher (2066 MJ/m^2) than that of its equivalent RC design (1308 MJ/m^2) with 93% and 95% generated in the product stage (A1–A3). For domestic space-conditioning, most electricity comes from non-renewables (66%), mainly coal and natural gas [41]. In all the lifecycle (Figure 8c), space-conditioning energy use represents 6% and 10% of the RPRE and NRPRE used by the MT building (432 MJ/m^2), and 42% and 63% of that of the RC building (2646 MJ/m^2).

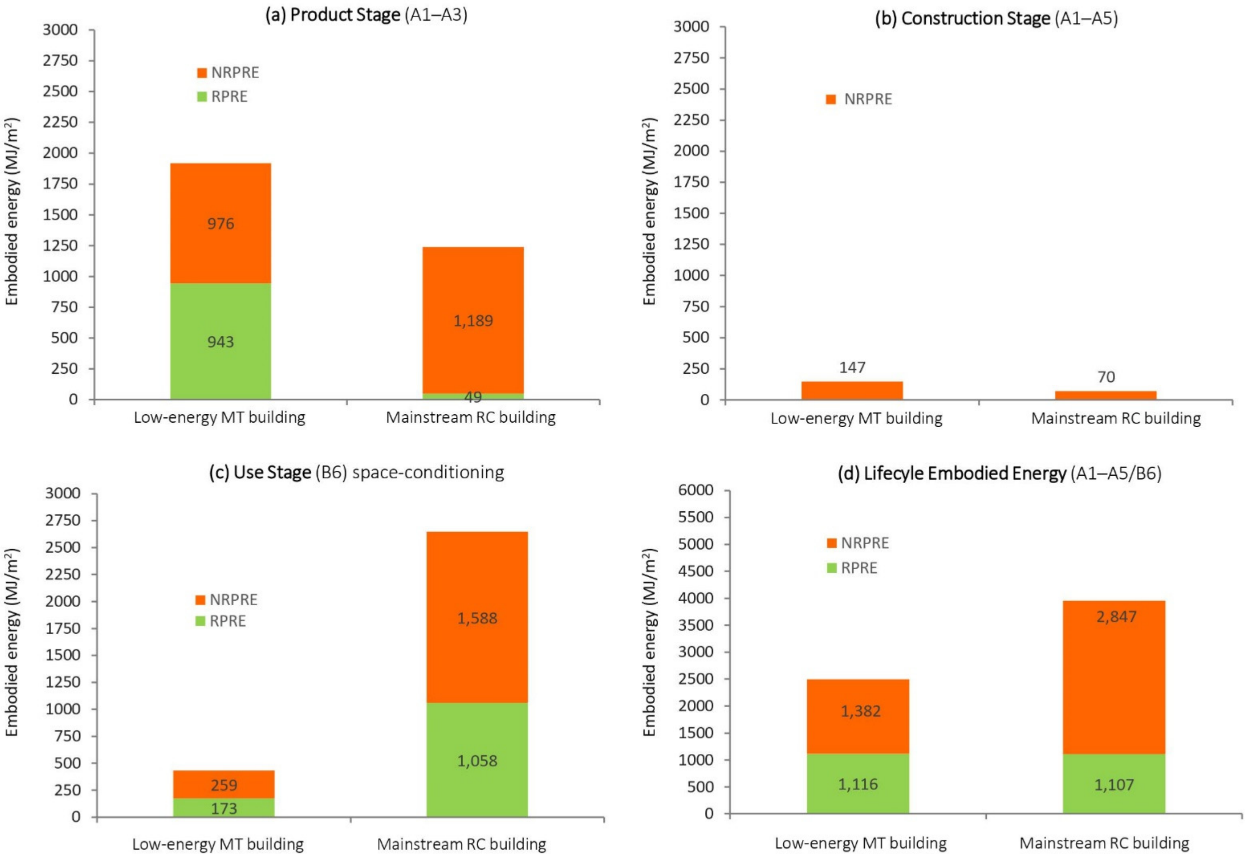


Figure 8. Summary of primary energy use through all of the lifecycle stages considered in the analysis. (**a**) product stage; (**b**) construction stage; (**c**) use stage; (**d**) lifecycle embodied energy.

6. Discussion

Based on LCA results which show that for a given location in Santiago (CCL), mass-timber has lower embodied emissions than mainstream concrete and steel, relevant design implications can be drawn on how to improve the carbon footprint of MT buildings. To examine these design issues, Figure 9 shows a GWP contribution analysis by material assembly. As can be seen for the MT design the large GWP share of the mass-timber structure (56%) could be reduced through carefully weighing losses in carbon storage capacity by substituting load-bearing CLT walls with glulam columns and beams [54]. Further savings can be made by reducing the GWP share of the concrete foundations (30%) distributing lateral loads on above-grade structures through either adding a concrete ground floor and concrete core walls [54] and/or hybrid steel-timber frames [55]. On sites with the same or more stringent seismic provisions than those assumed in this study which will yield larger emissions, an advisable choice to reduce seismic loads on the foundations would be to increase the compactness of the building shape.

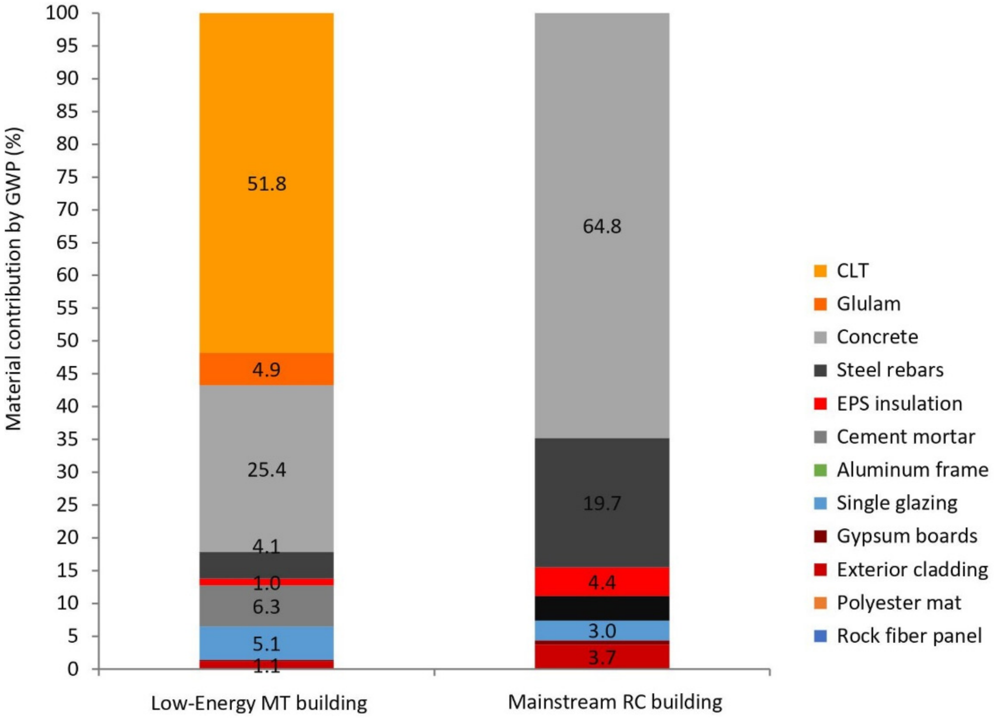


Figure 9. Materials' contributions to GWP.

Other design measures for reducing the embodied emissions of materials include exploring alternative assemblies to meet code compliance standards. As seen in Figure 9 after the concrete foundations, the largest GWP share for the MT design was the cement mortar topping (6.3%) used to meet the fire and acoustic ratings of CLT slabs which can be substituted using multiple layers of gypsum, wood fiber, and/or stone wool boards [56]. Although a more significant effect will be seen on buildings with 6 stories or more where national fire ratings are more stringent [26], the GWP share of non-combustible gypsum and rock-fiber (1.2%) could be lowered by adding a charring layer to CLT and glulam [57]. For non-load-bearing walls where minimum fire ratings are 0.25–0.5 h [26], an interesting alternative would be replacing aluminum frame with 60 mm thick CLT partitions. For any of the outlined choices, there should be careful consideration to weigh the embodied emissions of all substitute materials required to meet equivalent compliance.

With regard to space-conditioning, the LCA results also show that while the passive designs of the MT building increased its embodied emissions, their contribution to reduce useful life emissions were significantly much greater. In terms of additional materials, the embodied emissions of the improved design features applied to the MT building sum up 7.8 kg CO_2 eq/m^2 whereas over useful life, they help reducing by over 37 kg CO_2 eq/m^2 emissions from space-conditioning energy use. Since again the largest GWP is the cement mortar topping (5.6 kg CO_2 eq/m^2), further efforts should be placed in finding alternatives to increase the thermal capacity of mass-timber envelopes. Interestingly, compared to the concrete building, the most influential contributions in displacing auxiliary space-conditioning demands were the distribution of glazing areas (34%) and the inherent lower thermal transmittance of the mass-timber envelope (23%). Future work should be undertaken to provide a more comprehensive overview of the performance of MT buildings, including variations in indoor temperatures, occupant comfort, and household operation.

Overall, the results show that provided that further efforts are made to address end-of-life waste management options, the carbon stored in the MT building could help offset emissions of cradle-to-construction and space-conditioning energy use, leaving scope to address other domestic energy end-uses. As shown in Figure 7, until end-of-life, the MT building stores 318 kg CO_2 eq/m^2 which adding emissions from cradle-to-construction (101 kg CO_2 eq/m^2) and space-conditioning energy use (31 kg CO_2 eq/m^2) leaves a total negative net of 186 kg CO_2 eq/m^2 (A1–A5/B6). As an indication, the residual annual energy use of an average household in the MRS is roughly 4000 kWh (including LPG for water heating and cooking and electricity [17]) the equivalent of nearly 1000 kg CO_2 eq/m^2 (50-yr). As specified for the MT design (Figure 2), the installation of on-grid solar photovoltaics would help offset this total with four panels of 275 W per household a target that can be balanced through current subsidy schemes (MINEN [42]). On the other hand, to avoid releasing the stored carbon after end of life CLT and glulam components can be reused or combusted as a substitute of fossil fuel where previous studies have shown carbon retention rates of 85–90% [52,53]. To make definitive comparisons, future work should delve into evaluating other use modules and end-of-life scenarios.

7. Conclusions

A lifecycle analysis was performed to investigate the carbon and energy implications of manufacturing and using a low-energy mass-timber residential building and compare it against those of a mainstream concrete building in central Chile. The system boundary comprised sourcing and processing of radiata pine lumber, local manufacturing, and on-site installation of mass-timber products, transportation, and energy use for space-conditioning over useful life. For both buildings, reinforced concrete represented the largest contribution by mass. In the concrete design, reinforced concrete accounted for 97% of the total building mass. In the timber building, mass-timber materials such as CLT and glulam represented 30% and 4%, respectively. Global warming potentials for the mass-timber and concrete buildings were estimated at 101 and 167 kg of CO_2 eq/m^2, respectively. A 40% reduction in equivalent emissions was estimated when the reinforced concrete structure was replaced by CLT and glulam products.

By considering wood as carbon sink, until-of-life phases where significant emissions could be released due to waste disposal choices, the usage of mass-timber allows achieving a total negative net of 306 tons of CO_2 eq/building, decreasing emissions by 131% when compared to an equivalent concrete building. From cradle-to-usage, the embodied energy of the mass-timber building was 37% lower than that of the concrete building option, with a share of 45% and 27% in renewable energy, respectively. Furthermore, over the lifespans of the buildings, the accumulated emissions due to space-conditioning energy usage were as much as 83% lower for the mass-timber building design (30.5 tons CO_2 eq/m^2) than that of the mainstream concrete building (186.5 tons CO_2 eq/m^2). Finally, the use of mass-timber products such as CLT and glulam in a conventional five-story residential building located in Santiago, central Chile, generates potential benefits to the environment, decreasing the emissions of GWP when used to substitute concrete.

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Appendix A

Table A1. Material quantities for the low-energy MT design.

Component	Material	Unit	Quantity
Beams	Glulam	m^3	45.0
Exterior walls	CLT (5-ply)	m^3	153.9
Interior walls	CLT (3-ply)	m^3	97.0
Floor slabs	CLT (5-ply)	m^3	212.6
Topping slabs	Cement mortar	m^3	57.6
Slab-on-grade	Concrete (10 MPa)	m^3	24.6
Foundation walls	Concrete (25 MPa)	m^3	26.7
Spread footings	Concrete (25 MPa)	m^3	97.4
Foundations	Steel	m^3	0.4
Roof insulation	Expanded polystyrene	m^3	13.6
Interior finish	Gypsum boards	m^3	0.9
Cavity wall	Rock fiber	m^3	0.5
Acoustical mat	Polyester	m^3	23.0
Glazing	Clear glass	m^3	1.7
Vapor retarder	Polypropylene	m^3	0.6
Exterior cladding	Radiata pine	m^3	18.2

Table A2. Material quantities for the mainstream RC alternative.

Component	Material	Unit	Quantity
Exterior walls	Concrete	m^3	302.3
Interior finish	Gypsum	m^3	4.6
Cavity insulation	Rock fiber	m^3	15.4
Metal studs	Steel	m^3	0.4
Roof slab	Concrete (25 MPa)	m^3	26.8
Floor slabs	Concrete (25 MPa)	m^3	223.1
Slab-on-grade	Concrete (10 MPa)	m^3	28.3
Foundation walls	Concrete (25 MPa)	m^3	5.7
Foundation Beams	Concrete (25 MPa)	m^3	0.6
Spread footings	Concrete (25 MPa)	m^3	53.9
Rebar foundations	Steel	m^3	0.2
Rebar slabs	Steel	m^3	1.7
Rebar walls	Steel	m^3	1.1
Roof insulation	Expanded polystyrene	m^3	27.0
Wall insulation	Expanded polystyrene	m^3	60.0
Glazing	Clear glass	m^3	1.7
Exterior finish	Stucco	m^3	13.3

Table A3. Properties of building materials and assumed road distance from manufacturer to site.

Material	Density (kg/m^3)	Conductivity (W/mK)	Specific Heat (J/kgK)	Transport Distance (km)
CLT (*Pinus radiata*)	470 [1]	0.12 [1]	1880 [1]	487
Glulam (*Pinus radiata*)	470 [1]	0.12 [1]	1880 [1]	487
Cladding (*Pinus radiata*)	410	0.1	2850	487
Concrete	2200	1.63	920	16
Cement mortar	2000	1.40	920	12.3
Steel rebar	7850	-	-	18
Metal studs	7400	-	-	19
Gypsum board	1080	0.41	840	30
Polyester mat	7.5	0.06	1050	9
Glazing	2500	1.00	837	9
Stucco	800	0.35	837	30
EPS board	10	0.043	1200	7
Rock fiber	80	0.040	840	30

[1] Based on laboratory tests undertaken at the University of Santiago. The properties of materials are drawn from Chilean standard NCh 853 [58–60].

Table A4. Key parameters used in TAS modeling.

Parameter	Value	Comment	Reference
Floor area of an apartment	71.2 m^2		-
Number of apartments	20		-
Number of occupants per flat	4		-
External wall R-value	MT—1.5 W/m^2K RC—0.5 W/m^2K		[46]
Roof R-value	MT—2.3 W/m^2K RC—2.1 W/m^2K		
Glazing	0.18 W/m^2K		
Occupation main bedroom	10 p.m.–7 a.m.	2 occupants	[26]
Occupation bedrooms	10 p.m.–7 a.m.	1 occupant	
Occupation living area	8 a.m.–10 p.m.	1–4 occupants	
Internal heat gains	75 W per person		
Infiltration rate	MT—0.3 ACH RC—1.0 ACH	controllable vents	[59]
Ventilation	30 m^3/h per person	when occupied	
Thermostat set points	17 °C (heating) 27 °C (cooling)		[26]
Heating season (Santiago)	1st May–31 September	7 a.m.–11 p.m.	
Cooling season (Santiago)	1st December–31 March	7 a.m.–11 p.m.	

Table A5. Seismic design parameters and results of spectral modal analysis (/building).

Seismic Design Parameters (DS-61 [29]) [1]		**Spectral Modal Analysis**	
Max. effective ground acceleration	$A_o = 0.30$ g	Building fundamental period	1.55 s
T′	0.45 s	Modification factor	$R = 8.95$
n	1.40	Seismic weight (kN)	$P = 108.230$
S	1.05	Base shear ratio	$P/Q_o = 0.070$
T_0	0.40 s	Base shear (kN)	$Q_o = 7576$
p	1.6	Maximum drift	$\Delta_{xe} = 0.0014$

[1] Values according to site soil class C (DS-61 [29]) and seismic zone II (NCh-433 (NCh-433 [28]).

Table A6. Material, energy, fuel used, and data sources for mass timber and concrete buildings.

Material/Energy/Fuel	LCI Process	Database/Data Source
Acoustic panel	Gypsum plasterboard (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
Steel stud	Galvanized steel sheet, at plant NREL/RNA U	US-EI 2.2
Exterior finish—cladding	SAWN lumber, softwood, planed, kiln dried, packaged, at planer, m^3/Chile	Modified for Chilean energy wood density, and radiate pine forestry operations in Chile
Exterior finish—stucco	Thermal plaster, outdoor (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
CLT	CLT	(Chen et al., 2019 [60]; Huang et al., 2019 [61]); modified for Chilean energy, wood density, and radiate pine forestry operations in Chile
Concrete	Concrete, 25 MPa (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
Concrete	Concrete, 20 MPa (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
Construction energy	Diesel, combusted in industrial equipment NREL/US U	US-EI 2.2
Electricity	Chilean Grid, 2018	Vega-Coloma and Zaror, 2018 [41]
Glazing	Glazing, double (2-IV), $U < 1.1$ W/m^2K, at plant (20 kg/m^2)/US-US-EI U	EcoInvent 3.5
Glulam	Glulam	CORRIM and proxy processes; modified for Chilean energy wood density, and radiate pine forestry operations in Chile
Gypsum concrete	Proxy process	EcoInvent 3.5
Gypsum wallboard	Gypsum fiberboard (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
Insulation	Stone wool, packed (GLO) ∣ market for stone wool, packed ∣ Cut-off, U	EcoInvent 3.5
Insulation; polystyrene insulated sheathing	Polystyrene, extruded (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
Rebar	Reinforcing steel (GLO) ∣ market for ∣ Cut-off, U	EcoInvent 3.5
Road transport	Transport, freight, lorry >32 metric ton, euro3 (RoW) ∣ market for transport, freight, lorry >32 metric ton, EURO3 ∣ Cut-off, U	EcoInvent 3.5

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