PAPER #8.05

TIMBER BUILDINGS: A SUSTAINABLE CONSTRUCTION ALTERNATIVE

Jennifer Dayan Nuñez Avila[a] , Vicente Blanca-Giménez[a]
[a]Universitat Politècnica de València, Spain

How to cite
Nuñez Avila, Jennifer Dayan, and Vicente Blanca-Giménez. "Timber Buildings: A Sustainable Construction Alternative." In *Proceedings of 3rd Valencia International Biennial of Research in Architecture. Changing priorities.* Valencia. 2022. https://doi.org/10.4995/VIBRArch2022.2022.15307

ABSTRACT

The construction and building environment is one of the largest contributors to climate change, greenhouse gas emissions, depletion of natural resources and damage to ecological integrity. Therefore, the use of more sustainable materials in construction is currently of great interest. Structural wood is considered as a versatile renewable material, having an optimal strength-to-weight ratio, insulating properties, low carbon emissions in the operational life cycle and a great abundance in nature. Furthermore, unlike other materials, wood is the only one that stores carbon in its production. The purpose of this project is to evaluate, through the Life Cycle Analysis methodology, the environmental impact of the construction of buildings made of timber compared to reinforced concrete buildings, understanding the environmental benefits and disadvantages of each technology. The results obtained from the comparison of a timber building with its concrete counterpart confirm the feasible benefit of wood in the reduction of carbon emissions and non-renewable energy consumption, as well as other positive aspects such as the reduction of other emissions. By highlighting the benefits and opportunities of wood it is intended to promote the material in construction and the development of more efficient buildings.

KEYWORDS

Timber buildings; life cycle analysis; engineered wood products; environmental impact; sustainable construction.

1. INTRODUCTION

Due to rapid population growth, it is estimated that every year between 2019 and 2025, around two billion square meters of land will be needed for new construction, mainly housing (Arup 2019). Associated with this, in 2020, the construction sector accounted for 37% of carbon dioxide (CO2) emissions, with 10% caused by the manufacture of materials and products such as steel, concrete and glass (United Nations Environment Programme 2021). The report of the United Nations Department of Economic and Social Affairs (2021) states that, in order to meet the Sustainable Development Goals, a process of sustainable urbanization will be required to accommodate the increase in population.

"Sustainable construction" consists of the proper management, use and reuse of energy, natural resources and materials throughout the life cycle of a building. The "Committee on Climate Change" of the United Kingdom affirms that the implementation of wood in the construction of buildings is a sustainable response to reduce greenhouse gas emissions in relation to growing urban demand (Spear, et al. 2019). In this sense, the publication:

"Communication on opportunities for the efficient use of resources in the construction sector" (European Commission 2014) stated that in order to reduce the environmental impact, it is necessary to improve the design and planning of construction, taking into account its full life cycle, as well as a greater use of materials with potential for recycling or reuse.

Wood emerges in construction as a sustainable structural material due to it being a renewable, biodegradable, reusable, recyclable resource and carbon sink, in addition to reducing the total construction time. When performing a life cycle analysis (LCA) of building materials, wood generally has a lower environmental footprint and lower energy consumption in its extraction and manufacturing, compared to conventional materials (Sathre 2007) (Hill and Zimmer 2018) (van Wijnen 2020).

Wood is the only material that retains carbon in its generation of approximately 1 ton of CO_2 per cubic meter (Beyer, et al. 2011), offsetting the emissions generated during its processing. In addition, forest residues, obtained in processing, can be used as biomass for the factory's own power generation (van Wijnen 2020). Therefore, the production, construction and use of buildings with wood structures require less energy consumption and lower emission of pollutants than buildings with concrete or steel structures (Canadian Wood Council 2004).

To combat climate change, architectural projects are being developed using engineered wood products (EWP) as an alternative with less environmental impact compared to construction with other traditional materials. EWP have a lower global warming potential (GWP), at the product stage, compared to reinforced concrete, even when carbon sequestration from wood is excluded (van Wijnen 2020). If the carbon sink effect is included, wood stands out as a highly sustainable material both in production and throughout the material's life cycle. Consequently, the use of EWP as a construction material has been promoted due to its results and benefits discovered in sustainability evaluations, among which LCA stands out.

In this study, the environmental impacts of a mass timber building (MTB) are evaluated and compared using the LCA, with respect to a similar reinforced concrete building (RCB). The LCA constitutes an important tool and guide in the selection of construction materials and systems according to their specific environmental impacts throughout the life cycle of the building (from the extraction of materials to final disposal).The evaluation will make it possible to assess the environmental benefits of wood compared to other structural materials and its potential for sustainability in buildings.

2. MATERIALS AND METHODS

2.1. Buildings design

As a point of reference for the development of the LCA, we have selected the 12-story prototypes in the report "The Case for Tall Wood Buildings: Second Edition" (2018), designed by Michael Green Architecture and Equilibrium Consulting. The structural system of the RCB is a combination of a frame and a rigid reinforced concrete core. The proposed concrete building model is a concrete frame structure "The typical floor and roof structures are suspended slabs supported on concrete columns and beams" (Michael Green Architecture 2018, 189). The structure of the MTB is made up of cross-laminated timber (CLT) core walls, glued laminated timber columns and steel and glued laminated timber beams. Floor and roof structure is of CLT. Also, two layers of 5/8" Fire-Rated Type X Gypsum Board on the exposed surfaces of the EWP elements have been added as an important fire protection aspect of the system. Both buildings are supported by typical footing foundations with a concrete slab on grade.

2.2. Goal and scope

The objective of this study is to evaluate the environmental impact of a MTB in comparison with a counterpart RCB, determining which construction system provides an environmentally preferable structural option. Comparative analysis is performed using the fast-track LCA method which identifies differences as well as the relative contribution of structural assembly groups and building materials to the total environmental impact of each type of building.

For a fair comparison, both buildings were designed to be functional equivalents. Since the research focuses mainly on the comparison of the structural framework of buildings, the LCA includes the core, load-bearing walls, columns, beams, floors, fire protection and foundations. Partitions, envelope, installations, insulation, ceiling finishes and other construction elements not mentioned in the previous list are excluded. The functional unit is described as a residential building with 12 stories, located on a theoretical site in Vancouver. The reference study period is 60 years.

The analysis is performed "cradle-to-grave" according to the EN 15804 standard. This includes the product stage (A1–A3), the construction stage (A4–A5), and the end-of-life stage (C1–C4). The use stage (B) is excluded from the comparative LCA, due to the assumption that the structural system does not need any type of maintenance during the period of time considered. On the other hand, an expansion of the system is applied to take into account the permanent biogenic carbon sequestration of stage D, which considers the benefits and loads beyond the useful life of the building. Stage D data is reported separately due to the high degree of forecast uncertainty. Table 1 reflects the boundary of the analysis system with differentiation of the stages included and excluded.

2.3. Life cycle inventory and impacts

The inventory of each structural option is organized in three sections: (1) compilation of the general information (location of the building, type of building, area, height and useful life); (2) identification of the materials of the assembly groups; and (3) building model development.

SYSTEM BOUNDARY																EXPANSION
Product Stage (A1-A3)			Construction Stage (A4-A5)		Use Stage (B)							End-of-Life Stage (C)				Potential Benefits and Loads (D)
INCLUDED			INCLUDED		EXCLUDED							INCLUDED				INCLUDED
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Installed product in use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction Demolition	Transport	Waste Processing	Disposal	Recovery Reuse Recycling Potential

Table 1. Boundary of the evaluation system. Source: Authors based on EN15978

The amounts of steel and concrete required in the foundations are calculated directly by the Athena Impact Estimator for Building LCA tool by entering the dimensions of the elements. The construction quantities of the rest of the assembly groups of both buildings are calculated and assumed from the structural plans published in the report by Michael Green Architecture (2018). Numerical data handling and processing is done in Microsoft Excel®.

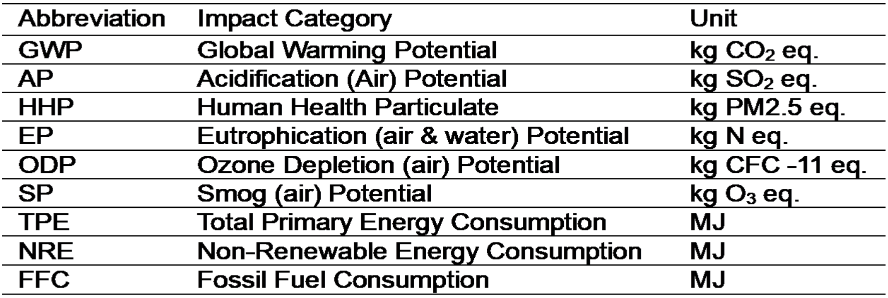
The Athena Impact Estimator for Building tool is free Canadian software that applies the "Tool for Reduction and Assessment of Chemical and Other Environmental Impacts" methodology to perform the life cycle impact assessment. The environmental impact for some stages, such as transportation and demolition, are automatically estimated by the software. The environmental data of construction materials and processes come from the Athena® life cycle inventory database, with regional sensitivity and with a data age of less than 10 years, generally complying with ISO 14040/44 standards (Athena Sustainable Materials Institute 2016). Once the quantities of construction materials have been entered, the data for the rest of the stages is calculated in the background by the software, in accordance with the EN 15804 standard. The midpoint life cycle impacts assessed by Athena Impact Estimator for Building, in accordance with ISO 21930/31, are indicated in table 2.

3. RESULTS AND DISCUSSION

3.1. Life-cycle assessment comparison for environmental impacts of the two buildings

As shown in figure 1, the life cycle impact assessment illustrates that the MTB, from cradle-to-grave, had a lower environmental impact than the RCB, in all nine environmental impact categories. Additionally, if stage D is added, it is estimated that the wooden structure reduces GWP by 125%. While in the rest of the categories, except for the ozone depletion potential, stage D increases the difference in the attenuation of the impacts, meaning a reduction of 91% in favour of the MTB.

At the cradle-to-grave boundary, the difference between both buildings is an emission reduction of 23%, 33%, 48%, 65% and 80% in categories of smog potential, acidification potential, eutrophication potential, human health particulate and ozone depletion potential, respectively, in favour of the timber building. Adding stage D means an increase of no more than 3% in the aforementioned differences. Regarding the GWP, in the cradle-to-grave boundary, the result for the MTB is 64% lower than the RCB. Also, if stage D is included, the wooden building has 126% lower greenhouse gas emissions. For total primary energy



Abbreviation	Impact Category	Unit
GWP	**Global Warming Potential**	**kg CO_2 eq.**
AP	**Acidification (Air) Potential**	**kg SO_2 eq.**
HHP	**Human Health Particulate**	**kg PM2.5 eq.**
EP	**Eutrophication (air & water) Potential**	**kg N eq.**
ODP	**Ozone Depletion (air) Potential**	**kg CFC -11 eq.**
SP	**Smog (air) Potential**	**kg O_3 eq.**
TPE	**Total Primary Energy Consumption**	**MJ**
NRE	**Non-Renewable Energy Consumption**	**MJ**
FFC	**Fossil Fuel Consumption**	**MJ**

Table 2. Impact categories studied. Source: Authors based on (Athena Sustainable Materials Institute 2016)

consumption (TPE), non-renewable energy consumption and fossil fuel consumption, the MTB has a lower impact than the conventional structure. In the TPE, the difference between both buildings is relatively smaller in both boundaries: 4% from stages A to C and 7% from stages A to D. While in the non-renewable energy consumption, the difference between both buildings is significantly higher at both boundaries: 40% (from stages A to C) and 42% (from stages A to D). Regarding the fossil fuel consumption, the difference is 38% (from stages A to C) and 44% (from stages A to D).

Figure 2 graphically shows the proportion of environmental impacts for the evaluated life cycle. It is observed that for both buildings the contribution of the product stage (especially extraction and manufacturing sub-stages) is dominant in all impact categories. For the RCB, end-of-life stage (especially of demolition [C1], waste processing [C3] and energy use of disposal equipment [C4] sub-stages) has the second largest impact in almost all categories, with the exception of human health particulate and ozone depletion potential, where second place is occupied by the stage construction stage (especially the construction and installation sub-stage). In the case of adding

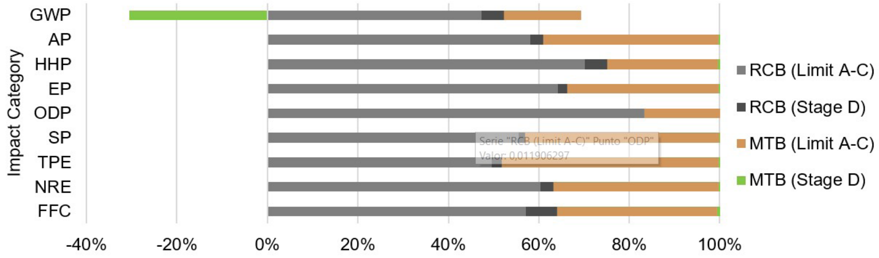


Figure 1. Comparison of the total impacts of the life cycle, excluding stage B, of the buildings evaluated

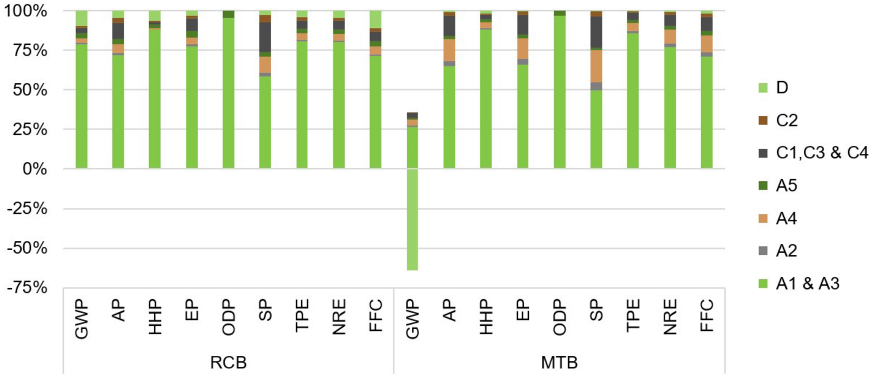


Figure 2. Environmental impacts, in percentage, of each stage of the life cycle for each building evaluated

stage D, the stage with the second largest impact in the GWP, human health particulate and fossil fuel consumption categories would be the added stage. Meanwhile, for the MTB, construction stage (especially the transport) has the second largest impact in all categories, with the exception of smog potential , where second place is occupied by end-of-life stage. In the ozone depletion potential, the second largest impact occurs in the construction and installation sub-stage. The extension of stage D assumes a significant reduction in GWP emissions. The importance of the impact of the rest of the categories is maintained.

In the extraction and manufacturing sub-stages within the system boundary, the MTB reduces emissions by 36%, 42%, 57%, 67%, 69% and 80% for smog potential, acidification potential, eutrophication potential, human health particulate, GWP and ozone depletion potential, compared to the RCB. In the TPE, the MTB only reduces 2% of emissions; however, the non-renewable energy consumption and fossil fuel consumption is 1.8 times higher for the RCB. The impacts generated by the transportation in either the product or the construction stage are greater for the MTB; however, the difference is not substantial enough to have an effect in favour of the RCB in the total impact. On the contrary, in the transport of the end-of-life stage, the MTB offers a reduction of 46% compared to its counterpart, in all impacts. In the construction and installation sub-stage, the reduction that the MTB represents over the RCB is between 43 and 88%. While for the total of C1, C3 and C4 sub-stages, the reduction is between 20% and 46%. In the case of stage D, the MTB has a 91% lower impact than the RCB in seven of the nine categories. In relation to the GWP, the MTB has a 712% reduction in greenhouse gas emissions in the stage D. For its part, the ozone depletion potential does not account for impacts.

3.2. Comparison of global warming impacts and total primary energy consumption by building assembly groups

Figure 3 shows the GWP and TPE of the building assembly groups. For the RCB, greenhouse gas emissions came mainly from floors and walls, representing, from cradle-to-grave, 42% (629,103 kg CO2 eq.) and 23% (341,242 kg CO2 eq.) of its total emissions, respectively. The addition of D to the analysis does not result in a big change to the overall results. For the MTB, floors accounted for 42% (232,629 kg CO2 eq.) and walls 9% (50,182 kg CO2 eq.) of its total cradle-to-grave carbon emissions. By adding stage D, the elements represented a reduction in total carbon emissions of 110% (-472,032 kg CO2 eq.) and 20% (-83,925 kg CO2 eq.), respectively.

From cradle-to-grave, compared to the RCB, the MTB assembly groups significantly reduced greenhouse gas emissions by

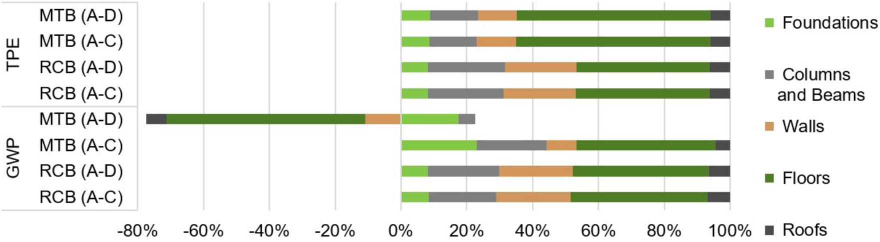


Figure 3. Comparison of the impact of global warming potential and total primary energy consumption by assembly groups of each building

85% (walls), 63% (floors and "columns and beams") and 77% (roofs). With the expansion of the boundary, the MTB assembly groups compared to the RCB, drastically reduced greenhouse gas emissions by 168% (floors), 144% (roofs), 123% (walls) and 89% (columns and beams).

Regarding the TPE category, for the RCB the consumption comes mainly from the floors and the columns and beams, representing, from the cradle to the grave, 41% (6,578,822 MJ) and 23% (3,700,147 MJ) of the total use, respectively. For the MTB, floors accounted for 59% (9,185,033 MJ) and columns and beams 15% (2,259,189 MJ) of the total cradle-to-grave consumption. The addition of stage D does not cause a change in the results for both buildings for these assembly groups. From cradle-to-grave, compared to the RCB the assembly groups of the MTB, with the exception of the floors, have a lower consumption of 48% (walls), 39% (columns and beams) and 5% (roof); the floors have a consumption greater than 40%. From stages A to D, the high consumption of the MTB floors drops to 34% with respect to the RCB, while the comparative consumption of the other assembly groups also changes to 50% (walls), 42% (columns and beams) and 8% (roofs).

3.3. Building material comparison

Figure 4 shows the total mass of each assembly group with respect to the materials used. Floors made up the largest share (by mass) of materials among all assembly groups, followed by walls. The total mass of the materials for the MTB was 2,357 tonnes, while the RCB was 7,378 tonnes, that is, about 3 times heavier. For the RCB, more than 95% of the material mass is concrete, followed by steel. Meanwhile, for the MTB, the most used material by mass was wood, followed by concrete (foundation) and gypsum board. It should be noted that the RCB uses 8.8 more concrete than the MTB.

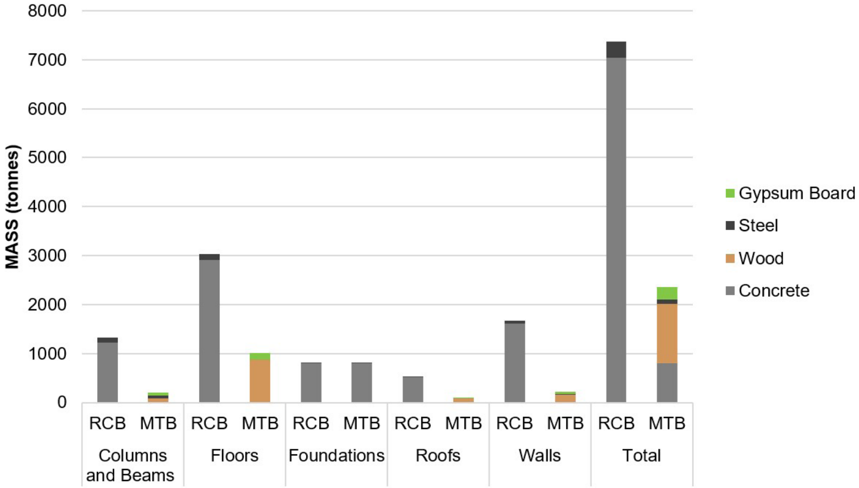


Figure 4. Mass comparison of materials used in mass timber buildings (MTB) and reinforced concrete buildings (RCB)

3.4. Discussion

3.4.1. Environmental impacts

The results reveal that the RCB, compared to the MTB, produces a greater negative impact in all the categories considered, with the product stage being the one with the highest emission and consumption. It follows that these facts are associated with the material used, demonstrating the benefits of wood compared to concrete, such as, for example, the reduction of liquid waste in bodies of water, which harms aquatic biodiversity. The increased toxicity associated with the RCB may also be associated with the high release of various contaminants in cement kilns (Soberón 2017).

For both buildings the GWP category shows a large impact in terms of CO2 release. The structural wood for the MTB potentially reduces its carbon footprint. The greenhouse gas emissions from the transport of the construction stage are higher for the MTB due to the greater distance between the CLT manufacturer and the construction site. The CO2 sequestration of the EWP, in stage D, decreases the GWP emitted for the MTB by a factor of almost two.

The results of the TPE should be analysed from a different perspective. Although the difference in consumption between the RCB and the MTB is marginal, the real difference lies in the type of energy consumed. It is observed that 95% of the energy consumed for the RCB is non-renewable, while for the MTB it is only 60%. Wood offers the possibility of using the residues of its extraction and processing as biomass, counteracting the effects of energy consumption. In contrast, the higher consumption in either the product or the construction stage may be linked to the greater distance travelled to supply the material and the final product, so that the transport trucks consume more fossil fuels in the product stage. On the contrary, in the construction and installation sub-stage, the 43% reduction for the MTB emissions with respect to the RCB is consistent with the greater total mass of the materials for the RCB (specifically, more than three times that of the MTB materials), so more heavy machinery is required.

3.4.2. Life-cycle stage analysis

All the indicators have shown the largest impacts during the product stage, specifically in extraction and manufacturing sub-stages. From stages A to C, the aforementioned sub-stages had an impact in the categories between 60%-95% for the RCB and between 50%-97% for the MTB. The difference in sub-stage impacts between structures is due to embodied emissions from the construction material used, indicating that structural wood products, and thus the MTB, embody less impact than concrete.

On the contrary, the transport of product stage and the transport of end-of-life stage, as well as the construction-installation sub-stage, have shown the least contribution to the environmental impact of the evaluated structures, with a maximum total of 5% for the buildings. In the construction and installation sub-stage, the RCB has a greater negative impact in all categories than the EWP counterpart because the former naturally has a higher total material weight and consequently requires more energy for construction and installation activities.

After the product sub-stages, the next most impactful sub-stages for the MTB are: firstly, the transport of the construction stage and secondly, the total of C1, C3 and C4. As regards the RCB, following the product sub-stage, the total of C1, C3 and C4 is the most significant.

In comparison, the greater relevance of the transport of the construction stage for the MTB, compared to the RCB, is due to the greater distance between the structural wood factories and the construction site. As far as concrete is concerned, being a common structural material, suppliers are usually within 50 km of the construction site. In North

America, construction with CLT is not yet a common practice (Pei, et al. 2016) so its commercial production in Canada is relatively recent (Karacabeyli 2010). This implies a limited CLT industry in the area and, therefore, longer transportation distances, which generates greater impacts in the transport of the construction stage for the MTB, such as the greater consumption of fossil fuel. The increase in structural wood factories would reduce these transportation distances, resulting in a lower impact for the MTB.

The relevance of the end-of-life and D stages for the RCB is due to the problems linked to construction and demolition waste management operations, which include the difficulty in the separation and recycling of the components since the concrete waste is voluminous, difficult to compact and takes up considerable space (Badraddin, et al. 2021). In contrast, the wooden elements offer the possibility of dry construction, which facilitates the disassembly, classification and storage of the construction elements. This reduces the amount of waste and allows recyclable or reusable materials to be reinserted into the production cycle, favouring the circular economy. Additionally, the carbon sequestration by the EWP used in the MTB offsets the GWP generated during the other stages and results in a drastic reduction compared to the RCB.

3.4.3. Building assembly groups

The results indicate that the floors represent the highest percentage of greenhouse gas emissions and TPE consumption in both buildings. In the GWP category, the assembly group with the second largest impact for the RCB is walls (23%), while in the case of the MTB this assembly group only represents 9%. The impact of the RCB walls is 6.8 times higher than the MTB walls. According to the results, the reduction in greenhouse gas emissions from the floors and walls of the MTB, compared to the RCB, is due to the large amount of CLT that replaces the concrete and steel of the assembly groups.

The benefit of wood in floors and walls becomes evident by adding stage D to the GWP category. Carbon sequestration in both assembly groups counteracts the damaging effects of the structure throughout the building's life cycle. Therefore, in the construction of buildings, the substitution of concrete and steel for structural wood results in environmental benefits.

Regarding the TPE of the MTB, the high consumption of both the floors and walls, as well as the columns and beams, is related to the use of the EWP, which requires a greater amount of energy in its production than concrete. However, the distinction must be made that almost half of this comes from bioenergy used in the sawmill processes.

Given that floors and walls make up the majority of the total building mass, and as more levels increase the total mass of assembly groups, designers should consider selecting materials that have less environmental impact , while also meeting the structural requirements.

3.4.4. Building material

Firstly, it is shown that cast-in-place concrete, compared to other products, is the material that produces the most damaging environmental impact in eight of the nine categories. In the TPE category, larger impacts are due to the use of EWP; however, as indicated in section 3.4.1, a large part of this consumption comes from renewable sources. On the other hand, the carbon footprint of concrete is highly significant compared to EWP, which is demonstrated by the higher greenhouse gas emissions for the RCB, compared to the MTB. Additionally, construction with EWP results in carbon being stored throughout the life of the product. This means that choosing a structural material with low emissions, such as CLT or glued laminated timber, substantially reduces the environmental impact of buildings.

Secondly, it is shown that both floors and walls make up a substantial part of the environmental impacts studied. Both assembly groups are mainly composed of concrete and CLT in the RCB and the MTB, respectively. Subsequently, the environmental impact of the assembly groups is directly linked to these materials.

In essence, building with wood consumes approximately one third the amount of fossil fuel compared to building with reinforced concrete. Likewise, wood offers a substantial greenhouse gas emissions reduction benefit even when CO2 storage is not considered. Additionally, the lighter weight of CLT, while offering essentially the same structural strength, leads to lower greenhouse gas emissions during the MTB frame construction compared to the RCB.

4. CONCLUSIONS

This study conducted a comparative LCA of two functionally equivalent buildings in Vancouver, Canada, using the Athena Impact Estimator for Building. The results illustrate that using wood instead of reinforced concrete in the structural framework produces notable reductions in almost all the environmental impacts of a 12-story building. In the TPE category, the difference between the MTB and the RCB is minimal; however, this impact does not take into account how much energy comes from renewable sources. If the energy obtained from wood residues as biomass is taken into account, the impact of the MTB is substantially lower compared to the RCB.

Regarding the stages of the life cycle, the results show that for the two materials, the larger contamination is generated in extraction and manufacturing sub-stages, which is significantly greater for reinforced concrete structures. The sub-stage with the second largest impact on the MTB is the transport of the construction stage due to the lower commercial production of wood as a structural element. The impact of transportation distances can be reduced if structural wood trade and industries increase. In the case of the RCB, the sub-stage with the second largest impact is the construction and installation sub-stage, while for the MTB its impact is relatively minor, which is be related to the lightness and ease of handling of the EWP that allow reducing the amount of heavy machinery required, the associated emissions and the times and costs of the construction stage.

Regarding the efficiency of material resources, the RCB uses three times more mass than the MTB. Additionally, it is shown that the use of CLT in the assembly groups is a significantly more sustainable option than concrete. Its use in the walls and floors would imply a great reduction in the total impact of the structure.

From this quantitative research, it is shown that the construction of the MTB is a more environmentally friendly selection (as long as the wood comes from sustainable forests) than the RCB and, in addition, reduces the carbon footprint of the buildings considerably. However, the large-scale potential is limited by its management and commercial production.

Overall, the study reinforces the growing global recognition of the need for a comprehensive LCA to understand the various environmental impacts of different building designs. Based on environmental performance, as well as structural advantages (strength, ductility, and durability), hybrid wood structures may lead to increased use of wood in building construction, fostering the development of more sustainable and efficient buildings. The results obtained herein clearly demonstrate significant environmental benefits in the selection of EWP for the construction of buildings.

REFERENCES

Arup. *Rethinking Timber Buildings. Seven perspectives on the use of timber in building*. London, 2019. https://www.arup.com/-/media/arup/files/publications/r/rethinkingtimberbuildings.pdf

Athena Sustainable Materials Institute. "User Manual and Transparency Document. Impact Estimator for Buildings v.5." *Athena Institute*. December 2016. https://calculatelca.com/wp-content/uploads/2017/02/IE4B_v5.2_User_Guide_December_2016.pdf.

Badraddin, Abdulmalek K.,, Rahimi A. Rahman, Saud Almutairi, and Muneera Esa. "Main Challenges to Concrete Recycling in Practice." *Sustainability* 13, no. 19 (October 2021). https://doi.org/10.3390/su131911077

Beyer, Gunilla, et al. *Tackle Climate Change: Use Wood*. European Confederation of Woodworking Industries (CEI-Bois), 2011. https://europanels.org/wp-content/uploads/2018/09/Tackle-Climat-Change-EN.pdf

Canadian Wood Council. "Sustainability and Life Cycle Analysis for Residential Buildings." *Canadian Wood Council*. 2004. https://cwc.ca/wp-content/uploads/publications-IBS4_Sustainability_SMC_v2.pdf.

European Commission. "Resource efficiency opportunities in the building sector." 01 July 2014. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52014DC0445.

Hill, Callum, and Katrin Zimmer. *The environmental impacts of wood compared to other building materials*. Division of Forest and Forest Resources, Ås: Norwegian Institute of Bioeconomy Research, 2018. https://core.ac.uk/download/pdf/285993494.pdf

Karacabeyli, Erol. "CLT: Implementation in Canada – Status report." *Internationales Holzbau-Forum* 10. Vancouver: Holzbau-Forum, 2010.

Michael Green Architecture. "The Case for Tall Wood Buildings: Second Edition." Vancouver, 2018, 272.

Pei, Shiling, Douglas Rammer, Marjan Popovski, Tom Williamson, Philip Line, and John W. van de Lindt. "An Overview of CLT Research and Implementation in North America." *World Conference on Timer Engineering, WCTE 2016*. Vienna, 2016.

Sathre, Roger. "Life-Cycle Energy and Carbon Implications of Wood-Based Products and Construction." PhD Thesis, Mid Sweden University, 2007.

Soberón, Francisco Sánchez. "Assessment of the human health risks and toxicity associated to particles (PM10, PM2.5 and PM1), organic pollutants and metals around cement plants." PhD Thesis, Rovira i Virgili University, 2017.

Spear, Morwenna, Callum Hill, Andrew Norton, and Colin Price. "Wood in Construction in the UK: An Analysis of Carbon Abatement Potential." Bangor University, Gwynedd, 2019.

United Nations Department of Economic and Social Affairs. "World Social Report 2021. Reconsidering Rural development." 2021.

United Nations Environment Programme. "2021 Global Status Report for Buildings and Construction: Towards a Zero emission, Efficient and Resilient Buildings and Construction Sector." Nairobi, 2021.

van Wijnen, Wouter. "Sustainable timber structures: Quantitative research evaluating the potential effects of carbon sequestration and cascading strategies in the Netherlands based on a comparison of the Dutch and European life cycle assessment methodologies." Master Thesis, Delft University of Technology, 2020.