Sustainable Analysis of Building Materials for Social Housing: A Comparative Study of Embodied Energy of Concrete and Glued-Laminated Timber (GLT) Structures

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Abstract. This study aims to conduct a sustainable comparative analysis of embodied energy between different materials to produce social buildings in Brazil. The study compares structures and enclosure made of glued laminated timber (GLT) and reinforced concrete with enclosure made of ceramic block masonry to produce the same 48m² single-family housing unit following the COHAB MG standard. The accounting of materials used for building production was made through a BIM platform, and subsequently, total embodied energy was calculated, weighted according to the amount of each material used. Results indicates that buildings constructed with GLT in Brazil can achieve up to a 40% reduction in total embodied energy when compared to the traditional construction model of reinforced concrete and red clay blocks.

1 Introduction

To prevent the escalation of climate change, it is essential to reduce energy consumption across all sectors. The energy consumption of the construction industry has a significant impact and can account for up to 34% of global energy demand. [1].

Although the country has its energy sources considered clean and renewable, is important to consider the impact of implementing new plants to meet national demand. Climate change also affects the country's rainfall patterns, causing unpredictability in the energy production of hydroelectric plants. Additionally, a portion of the generated energy comes from fossil fuels, especially during periods of drought. Therefore, it is necessary to seek alternative materials with lower energy consumption to construct new buildings. [1-3]

Brazil faces a severe housing shortage of 6,2 million homes. [4] Producing affordable, energy-efficient housing with low-emission materials is crucial, but challenging, especially for emerging economies.

Timber construction, as Glued Laminated Timber (GLT), is a promising alternative when compared to traditional construction systems due to several characteristics: the material's negative carbon emissions, significantly lower energy consumption in its processing and

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manufacturing compared to materials like concrete and steel, superior thermal performance due to its insulating properties which result in greater energy efficiency and better thermal comfort for buildings. Additionally, timber construction, given the prefabrication of components and the material's reduced weight, facilitates and accelerates assembly processes, reducing the total construction time. [5,6]

However, GLT faces some challenges as a construction system in Brazil. The high production cost, due to the need for advanced technology and skilled labour, makes it less financially competitive compared to conventional materials, especially on a small scale. Additionally, there is low tradition by the national industry in using the material. Wood faces cultural restrictions, as it is not commonly used as the predominant construction system in the country. [7,8]

Currently, in Brazil, there are no public policies or specific legislation aimed at encouraging the use of natural, renewable, and low-carbon emission products such as GLT (Glulam). The first step would be to implement tax exemptions to stimulate the national industry and make the production of these materials more competitive compared to imported ones. [8]

2 Material and Methods

2.1 Evaluation Criteria

This study aims to conduct a comparative assessment of concrete and timber structures using Embodied Energy as its main methodology. Embodied Energy is a concept that still lacks a fully defined consensus in the academic field due to various factors that may or may not be considered. It represents the initial stages of a Life Cycle Energy Assessment (LCEA), which is a variation of a Life Cycle Analysis (LCA) with a focus on energy consumption at different stages of the cycle. This approach allows for a detailed insight into what different materials and construction techniques contribute to a building's energy consumption.

2.2 Object of Study

The type of building analysed— referred to in this study as a Housing Unit (HU) — is a 44,78 m² social housing unit with an estimated lifespan of 50 years. The house comprises five rooms: a living room, two bedrooms, a kitchen, and a bathroom (see fig. 2 and 3). It replicates the construction standard of the Minas Gerais State Housing Company (COHAB – MG) [10] and aligns with the pre-established characteristics of the social housing program "Minha Casa, Minha Vida." [11]

Fig. 1. BIM Model of UH, MG-91-I-2-45 Standard from COHAB Minas [author]

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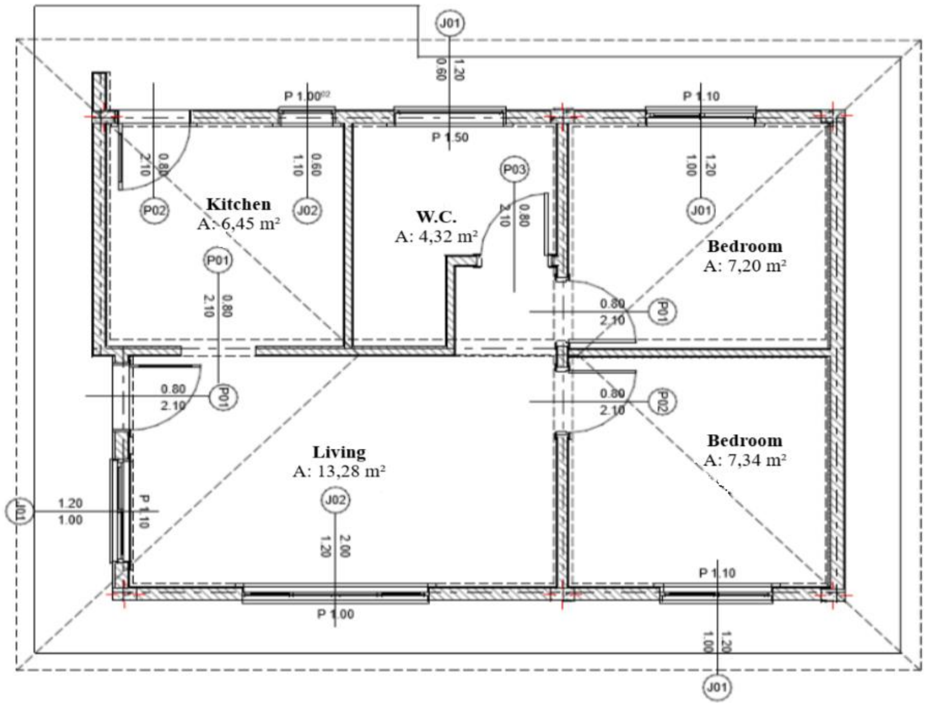

Fig. 2. Floor plan of HU, MG-91-I-2-45 Standard from COHAB Minas [10, adapted]

From this standard model, we sought to produce the same architectural project, but varying the construction system. The first one is a building designed with reinforced concrete beams and columns and red ceramic block (UH1 – RC/RCC) and the comparative one glued laminated timber (UH2 – GLT).

Other materials (OM), common to both buildings mentioned, such as the windows, internal wooden doors and external area doors will be used, made of aluminium louvers. The foundations, regardless of the model adopted, depend on the type of soil at the installation site and do not fall within the scope of this work.

The structures were designed according to the pre-dimensioning provided in the ABNT NBR 6118 (UH1 – RC/RCC) [12] and ABNT NBR 7190 (UH2 – GLT) [13] standards, and the quantities of each of the materials were calculated using ArchiCAD, a Building Information Modelling platform.

2.3 Analytical Formulas and Equations

Life Cycle Energy Assessment (LCEA) is a methodology used to evaluate the total energy consumption of a building throughout its entire life cycle.

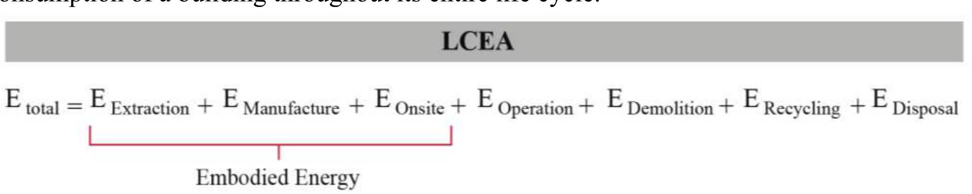

Fig. 3. Diagram Representing the Equation for LCEA and the Embodied Energy Stage [23, adapted]

The first three items indicated in the diagram represented above (Fig. 1) are the main elements that comprise the calculation of Embodied Energy. However, according to [23], it is necessary to consider other factors for energy calculation. For this, they are separated as shown in Eq. (1).

$$E_{embodied} = E_{initial} + E_{recurring} \quad (1)$$

$E_{initial}$ on Eq.(2) and (3) refers to the energy required to construct the building, considering the extraction, manufacturing, and on-site energy presented earlier. α_i represents the embodied energy intensity factor for the type of building material (measured in MJ/kg) and m_i denotes the total mass of the building material (measured in kg). The value of m_i in this stage should account not only for the quantities of building material used in the final construction but also for any wastage that occurs during the construction process, we will call this amount *Spillage*.

$$E_{inital,\,i} = E_{extraction,\,i} + E_{manufacture,\,i} + E_{on\,site,\,i} \quad (2)$$

$$E_{inital} = \sum_1^i \alpha_i\, m_i \quad (3)$$

$E_{recrruing}$ on Eq. (4) refers to the recurring embodied energy in buildings, which represents the total sum of the embodied energy used in the material due to maintenance, repair, restoration, refurbishment, or replacement during the building's lifespan. Lb is the service lifespan of the building, and Li is the lifespan of the building material. In Table 1, 2 and 3, $\frac{Lb}{Li} - 1$ will be referred to as the replacement factor, denoted by the abbreviation R.

$$E_{recrruing,i} = \left[\frac{Lb}{Li} - 1\right] m_i\alpha_i \quad (4)$$

The relationship between building design, energy use, and greenhouse gas emissions varies according to the region's climate and sociodemographic characteristics, as well as energy matrices. Therefore, a regional comparative analysis is relevant. [9] The literature demonstrates few studies on Embodied Energy in Brazilian contexts.

Table 1. Embodied Energy ($E_{embodied}$) for HU1 – CO/RCB

Material	α_i (MJ/kg)	Weight (kg)	Spillage (%)	m_i initial (kg)	E initial (MJ)	R	m_i recurring (kg)	E recurring (MJ)	E embodied (MJ)
Concrete	1.6 [21]	8858	2.0% [14]	9035	14456	0 [16]	0	0	14456
Steel Reinforcement	78.8 [20]	151	5.0% [14]	159	12531	0 [16]	0	0	12531
Red-Clay Bricks	3.9 [19]	15406	12.0% [14]	17255	67293	0 [16]	0	0	67293
Mortar	2 [21]	2407	6.0% [14]	2552	5104	0 [16]	0	0	5104
Total									99383

Table 2. Embodied Energy ($E_{embodied}$) for HU2 – GLT

Material	α_i (MJ/kg)	Weight (kg)	Spillage (%)	m_i Initial (kg)	E Initial (MJ)	R	m_i recurring (kg)	E recurring (MJ)	E embodied (MJ)

GLT Beam	4.46 [22]	1200	1.5% [15]	1218	5435	0 [17]	0	0	5435
GLT Post	4.46 [22]	408	1.7% [15]	415	1852	0 [17]	0	0	1852
GLT Triple Layer Wall	10.96 [22]	3515	5.0% [15]	3691	40446	0.14 [17]	517	5662	46108
Total									53395

Table 3. Embodied Energy ($E_{embodied}$) for Other Materials – OM

Material	α_i (MJ/kg)	Weight (kg)	Spillage (%)	m_i Initial (kg)	E Initial (MJ)	R	m_i recurring (kg)	E recurring (MJ)	E embodied (MJ)
Concrete Slab	1.6 [21]	31736	2.0% [14]	32371	51794	0 [16]	0	0	51794
Glass	23.7 [20]	127	16.0% [14]	147	3491	-	-	-	3491
Aluminum Windows Frame and Doors	84.1 [18]	655	0.0% [14]	655	55086	4 [16]	2620	220342	14456
Wooden Door	9.2 [18]	390	0.0% [14]	390	3588	-	-	-	3588
Red-Clay Roofing	3.6 [20]	9571	8.0% [14]	10336	37210	1 [16]	10336	37210	74421
Tiles	5.1 [20]	150	3.0% [14]	155	788	4 [16]	618	3151.8	3940
Paint	65 [18]	20	-	20	1287	9 [16]	178	11583	12870
Total									164560

3 Results and Discussion

The proportion of each material has a significant impact on the final analysis. In the HU1 model, a significant amount of red clay bricks is used, which, despite having low embodied energy (EE), represent the element with the greatest impact when considering the total embodied energy. Similarly, for the HU2 model, the enclosure with CLT panels is the largest contributor due to the volume of this material used.

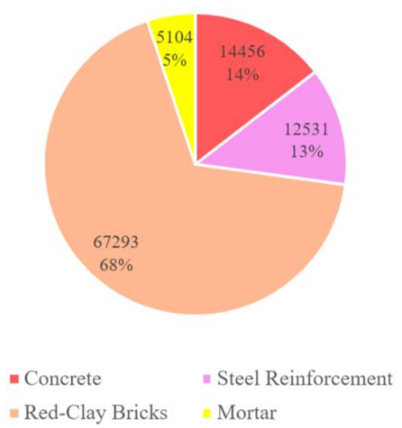

Fig. 4. HU1 – CO/RCB
Final Embodied Energy (MJ) [author]

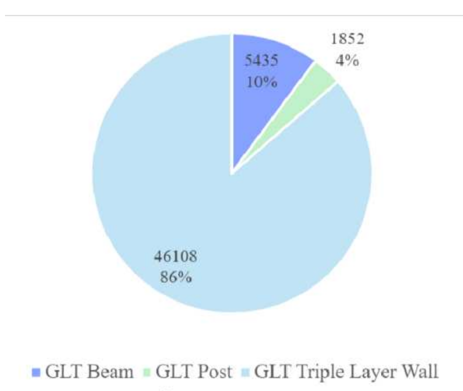

Fig. 5. – GLT
Final Embodied Energy (MJ) [author]

Although a smaller quantity of material is used in the HU2 model compared to HU1, the data shows that the total weight of the materials in the HU2 model is 4x lower. Lighter structures with simpler processing, such as those made of GLT, consequently present lower total EE.

Both models have waste percentages, but it is notable that the HU1 model generally has a higher waste rate compared to the HU2 model. This can be attributed to the characteristics of the materials used in each model and the associated construction processes, and consequently to the greater use of material and higher EE. Common materials to both models, such as ceramic roofing, floor slab, window frames, and ceramic coatings, represent more than 62.3% and 75.5% of the EE for the HU1 and HU2 models, respectively. Again, this is related to the weight and volume of these materials relative to the total building.

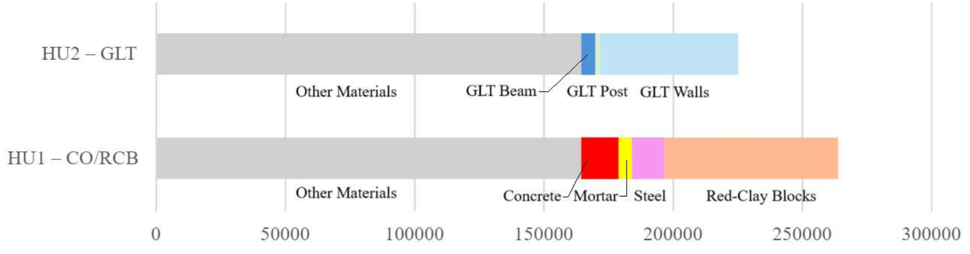

Fig. 6. CO/RCB x GLT Final Embodied Energy (MJ) [author]

4 Conclusions

- The analysis of different structural systems demonstrates that glued laminated timber (GLT) consumes up to 40% less embodied energy compared to reinforced concrete and red ceramic structures, making it an interesting alternative from an energy efficiency perspective.
- Red ceramic, despite having low embodied energy per unit, shows the highest total consumption due to the large amount used in building construction. Steel, on the other hand, although it has embodied energy, does not significantly impact the system due to the small quantities used.
- The roofing presents high energy consumption, resulting from the large amount of material and the need for replacement over a 50-year life cycle.

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