Life cycle analysis of timber roof structures

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Abstract. Construction industry is rapidly prospering. With numbers as high as they are in the construction industry, it is imperative to find alternative building materials and reduce waste. Proper combination and selection of materials helps to reduce the environmental burden on the surroundings. It is therefore appropriate to use local, natural, renewable, recyclable and low-emission materials in their production, which also helps to promote biodiversity and to restore and replace green spaces. In the fight against climate change, the construction industry is trying to reduce the emissions of buildings by means of life cycle assessment. The study assessed the life cycle of 55 wooden timber roofs in terms of their environmental impact. Based on the assessment of the timber roof compositions, it can be concluded that the best rating was achieved by the composition with structural construction timber, cellulose insulation, vented gap and aggregate backfill. When using wood fibre and cellulose insulation, a 65% reduction in global warming emissions is achieved.

1 Introduction

The construction industry and its impact on the environment is an under-discussed topic. Although the socio-economic development of the construction industry is important, its environmental impacts are significant [1]. The extraction of materials, production, transportation, construction, operation and storage of materials consume large amounts of energy, which leads to negative environmental impact and the production of greenhouse gas emissions, global warming, acidification and eutrophication [2]. More recently, several quantitative sustainability methods and tools have been developed which include life cycle assessment (LCA). LCA is an assessment method that calculates the environmental impact of product or service projects over their life cycle [ISO 14044] [3]. The LCA method is one of the tools that can assess environmental impacts at different system boundaries from cradle to gate, cradle to grave or cradle to cradle. It is also defined as a systematic analysis to measure industrial processes and products by examining the flow of energy and material consumption, waste generation and pollution that is released into the environment [4]. With

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the implementation of this method, planners, engineers, designers and stakeholders can contribute to the reduction of climate change and unknown environmental impacts. Therefore, it is essential to study and implement the results of LCA during architectural design, following construction, operation and also during demolition of the building [5]. The results of several LCA studies show that the energy consumption phase has the greatest negative impact. Therefore, efforts are made to reduce the operational energy consumption, which is often realized by increasing the insulation material. Between the two, an optimal solution should be found to reduce the depletion of natural resources and the overall environmental impact of the building. Efficient use of materials remains an important issue as well as adequate consideration of a wide range of impact categories. Recently, more and more studies have addressed these issues and highlighted their importance [6]. In addition, wood products used in buildings are increasingly being analysed to reduce greenhouse gas emissions. In their study, authors Hafner and Schäfer evaluated life cycle GHG emissions in residential buildings in the product and end-of-life (EoL) phases and reported reductions of 35% to 56% in wood buildings compared to mineral buildings. Therefore, the implementation of wood structures in buildings is also of great importance from an environmental point of view [7]. Ximenes and Grant compared the design of a baseline house with that of an optimized wood volume and also reported significant savings in greenhouse gas emissions. The roof structure, as one of the main parts of the building, significantly affects the emissions of the whole building. Moreover, as it is the horizontal impermeable area of the building envelope, the roof is also a very important element in terms of the material resources required for its implementation [8, 9]. The study evaluated the life cycle of 55 timber roofs in terms of their environmental impact. The life cycle was assessed using the LCA method.

2 Material and methods

Life Cycle Analysis (LCA) helps to analyse, evaluate, and interpret impacts. The LCA method is a systematic set of procedures for compiling and examining the input and output material and energy flows of the system under study and the environmental impacts directly related to the operation of the product or service system during the life cycle under study. Life cycle assessment according to ISO 14040 [10]. includes four steps: Defining the purpose and scope of the application, inventory analysis (LCI) and environmental impact assessment (LCIA), and interpretation.

2.1 Goal and scope

The aim of this research was to evaluate and analyse 55 roof design options in order to find the most environmentally advantageous one. The roof structure was converted to $1m^2$ to facilitate comparison. The estimated service life was set at 50 years and the system boundary set at "Cradle to Cradle". The life cycle phases that were evaluated are shown in Figure 1. The evaluation of the roof structures was carried out using OneClick LCA software and in accordance with the international standards EN 15804, EN 15978, ISO EN 14040 and EN 14044 [11, 12, 10, 3].

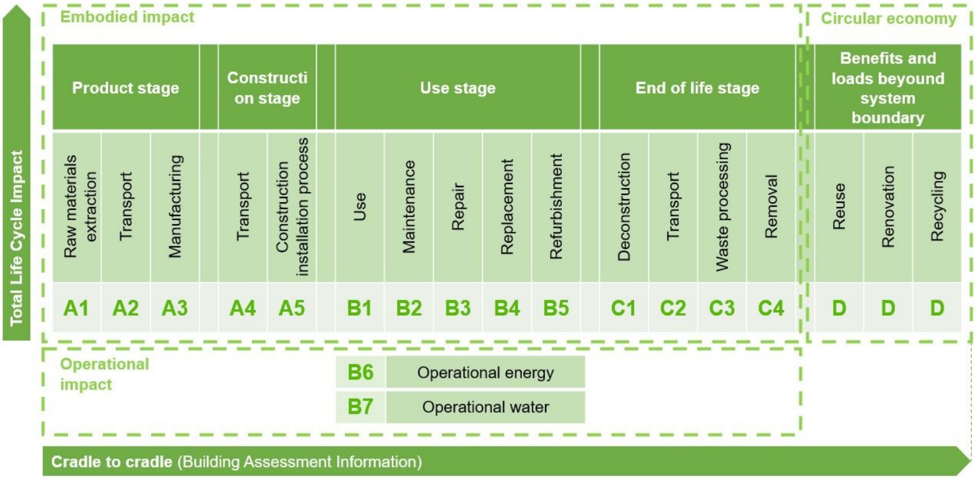

Fig. 1. System boundaries in LCA.

2.2 Life cycle inventory analysis

In the Life Cycle Inventory Analysis (LCI) section, the required data collection was obtained, based on information from the database available in the OneClick LCA software. For the study, 55 timber roofs were selected. Roof structures were marked with the acronym R for roof and the related number in sequence as 1. For example, the marking R1 (roof first in sequence). The load-bearing part of the roofs consisted of timber trusses, the other layers consisted of lathing, vapour barrier, thermal insulation, laths and roofing. Different thermal insulation and thicknesses were chosen in the roof variants. Figure 2 shows examples of roof structure compositions. The roof structures were designed in accordance with the national standard STN 730540-2+Z1+Z2 [13]. to meet the thermal technical requirements. The roofing materials used were baked clay tiles, galvanised sheet metal, gravel, wooden shingles or substrate. The roofs were designed to span 1 m^2 for easier comparison.

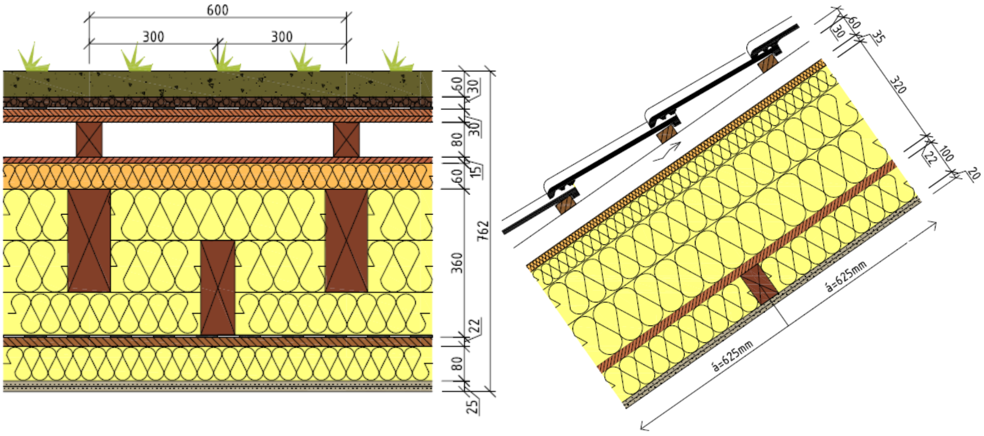

Fig. 2. Examples of timber roof structure variants.

Table 1 lists the materials that were used in the roof compositions. In all constructions, timber framing, a ceiling, lathing, a membrane, an air gap, various thermal insulation and a surface layer were used.

Table 1. List of materials applied.

Load-bearing structure	KVH, BSH, I profile, CLT panel, wooden beams
Ceiling	fibreboard, gypsum fibreboard, plasterboard, wooden ceiling
Lathing	wooden lath, MDF board, OSB board, DHF board
Membrane	vapour barrier PE, geotextile, waterproof membrane
Thermal insulation	**Roof composition**
Wood-fibre insulation	R1, R2, R3, R5, R7, R8, R9, R12, R13, R14, R19, R22, R23, R26, R28, R29, R34, R36, R37, R38, R41, R43, R44, R48, R51, R53, R54, R55
Hemp insulation	R2, R6, R10, R15, R18, R22, R26, R39, R41, R43, R50
Linen insulation	R3, R11, R13, R16, R19, R24, R34, R45, R54
Sheep wool insulation	R4, R6, R7, R11, R21, R25, R29, R30, R32, R35, R38, R53
Cellulose insulation	R4, R6, R7, R11, R21, R25, R29, R30, R32, R35, R53, R42, R47, R48, R52, R55
Mineral wool	R5, R23
Straw insulation	R8, R19, R28, R32, R39, R49
Cork insulation	R17, R27, R33, R40, R46
Roof cover	**Roof composition**
Gravel	R5, R7, R12, R24, R27, R33, R37, R41, R44, R46, R55
Titanium Zinc Sheet	R4, R14, R18, R23, R35, R52
Substrate	R2, R6, R9, R10, R11, R26, R28, R31, R32, R39, R40, R45, R49, R50
Burnt roof tile	R1, R3, R13, R17, R20, R22, R34, R38, R42, R47, R48, R54
Concrete tile	R15, R25, R30, R36, R42, R51
Wooden shingles	R8, R16, R19, R21, R29, R53

2.3 Life cycle impact analysis

According to ISO 14040, life cycle impact analysis (LCIA) is the third of the four main stages of LCA. The purpose of this step is to interpret the flows of the initial life cycle inventory in their potential contributions to the environmental impacts considered in the LCA. The study evaluated impact categories quantifying global warming, GWP total global warming potential, which included GWP fossil, GWP bio, and GWP LULUC. The impact categories are presented in Table 2.

Table 2. List of impact categories.

Global Warming Potential, total	Global Warming Potential, fossil	Global Warming Potential, biogenic	Global Warming Potential, LULUC
GWP total	GWP fossil	GWP bio	GWP LULUC
kg CO_{2e}	kg CO_{2e}	kg $CO_{2e\ bio}$	kg CO_{2e}

3 Results and discussion

The results for GWP total are shown in Figure 3. The results show that the R17 roof structure achieves the worst CO_{2e} emissions (107.96 kg CO_{2e}). This was followed by the R35 and R33 composition with values of 105.268 and 104.21 kg CO_{2e}, respectively. Among the materials in roof composition R17, cork insulation (54.66 kg CO_{2e}) and wood flooring (13.82 kg CO_{2e}) emitted the most. The best values were achieved by the timber elements, structural timber KVH (0.53 kg CO_{2e}), which also had a positive impact in terms of GWP bio (-13.62 kg $CO_{2e\ bio}$). The GWP bio results are presented in Figure 4. Of the phases that contributed the most to the negative environmental impact, phase A1-A3 (79.3%) came out the worst. In composition R35 and R33, the zinc-titanium alloy sheets (58.24 kg CO_{2e}) and cork insulation (55.9 kg CO_{2e}) were the most CO_{2e} emitting phases. The best CO_{2e} emission values were achieved by compositions R52, R45 and R7. Cellulose and linen insulation were used in the compositions. The most contributing materials included the load-bearing timber structure of the roof (CLT panels, KVH, structural timber) however their positive impact in terms of GWP bio values went to negative and thus the carbon emissions in phases A1-A3 were reduced (-131.15 kg CO_{2e}; -42.39 kg CO_{2e}; -64.45 kg CO_{2e}, respectively).

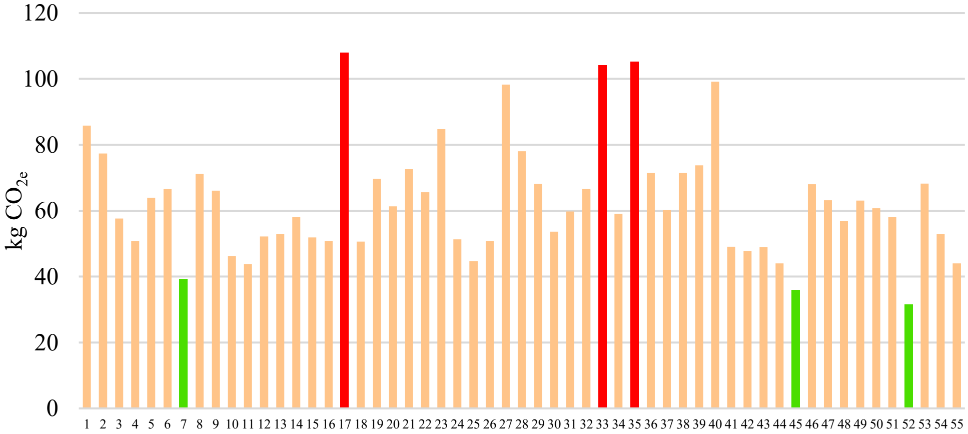

Fig. 3. GWP total results.

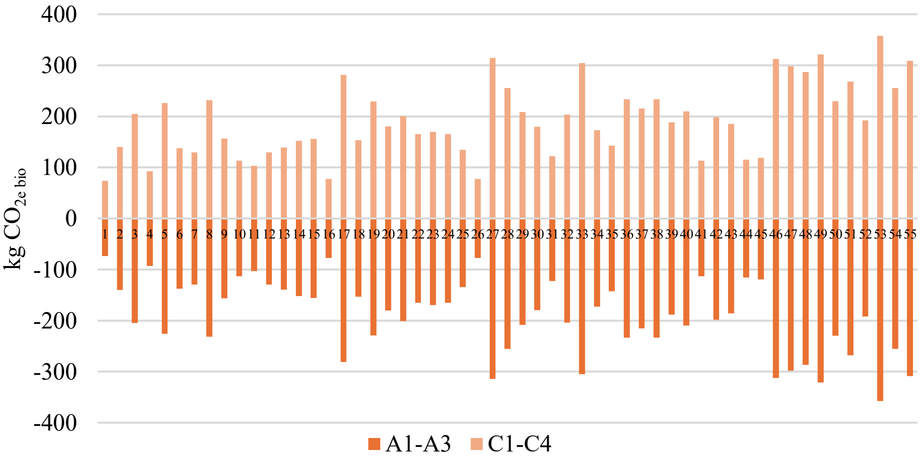

Fig. 4. GWP bio results.

Partially from the GWP total for the fossil GWP indicator (Figure 5.), composition R17 came out worst, followed by compositions R35 and R33 (107.94 kg CO_{2e}; 105.12 kg CO_{2e} and 104.16 kg CO_{2e}, respectively). The lowest emitting compositions were (31.36 kg CO_{2e}; 35.8 kg CO_{2e} and 39.16 kg CO_{2e}, respectively). For the LULUC GWP indicator (Figure 6.), roof composition R55 came out the worst, followed by R50 and R49 (0.28 kg CO_{2e}; 0.274 kg CO_{2e} and 0.278 kg CO_{2e}, respectively). Roof compositions R21, R17 and R13 (0.02 kg CO_{2e}; 0.021 kg CO_{2e} and 0.03 kg CO_{2e}, respectively) achieved the lowest emission values. There were four alternatives for the EoL phase: landfilling, recycling, incineration, and reuse. The results showed that a large proportion of the waste was reused, which contributes to waste reduction.

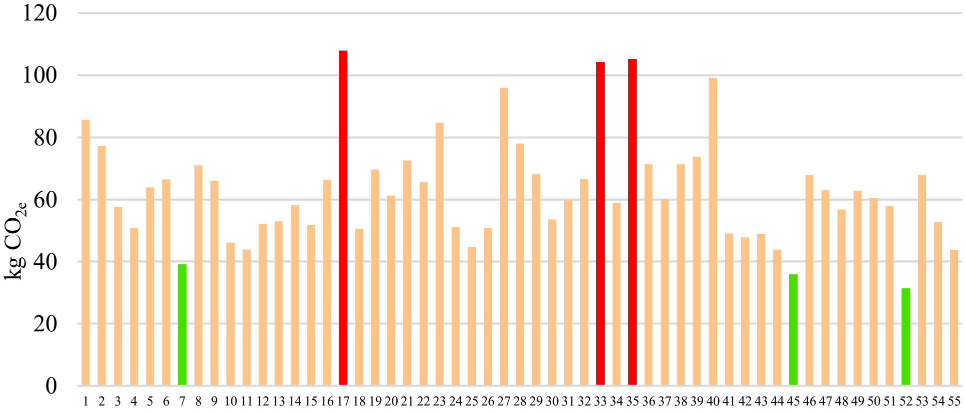

Fig. 6. GWP fossil results.

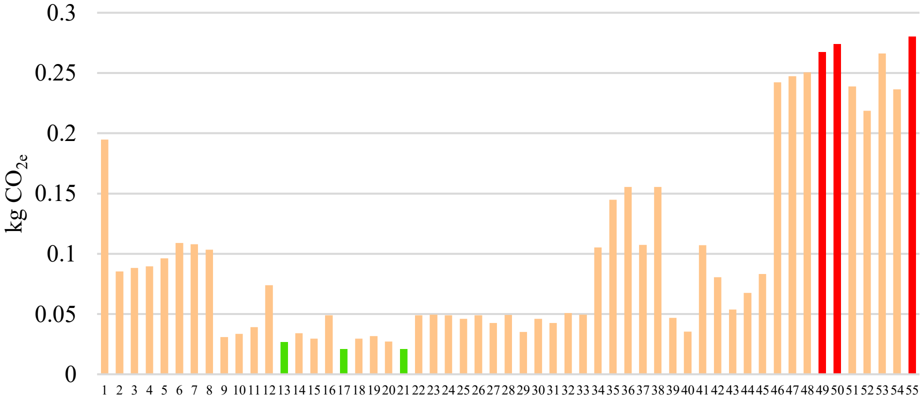

Fig. 7. GWP LULUC results.

In the study by Wijnants et al. the authors examined a timber wall and roof that were evaluated over a lifetime of 60 years with respect to material use and energy. Four different insulation scenarios for a roof composed of I-beams were analysed. In these roof compositions, an overall life cycle reduction of 14% was achievable, with a further 35% reduction in biogenic carbon taken into account [14]. Hafner and Schäfer analysed the GHG emissions from small residential buildings during the product and end-of-life (EOL) phase and reported potential reductions of 35%-56% in timber houses compared to mineral buildings [7]. In a study from New Zealand, the authors investigated the impacts of steel roofs and in particular metal roofing. The study found that the total impacts of steel roofs, including ancillary elements, were 12 kg CO_{2e}/m^2 [15]. However, thermal insulation was not used in the roof structures as in our study. Results from the thermal insulation study suggest that renewable materials tend to have a lower environmental impact but are not necessarily better. In the case of renewable sources, the main cause of negative environmental impacts are binders and additives [16]. In the case of cellulose, the authors Dickson et al. show that the raw material is positive because cellulose insulation is usually made from recycled paper. Cork-based insulation, according to the authors Sierra-Pérez et al. shows major impacts during the manufacturing process. Demertzi et al. supported this and pointed out its high emission values for GWP [17, 18].

4 Conclusion

Roof structures play an important role in the efficient use of energy in buildings. It is crucial to choose the right roofing material and construction to reduce the need for maintenance and extend the life of the entire structure. It is important to realise that every step towards better energy management and conservation contributes to our overall quality of life. The right choice of materials and design of roof structures can make a significant difference to the efficiency and quality of a building. Based on the assessment of the timber roof compositions, it can be concluded that the best rating was achieved by the R52 composition with KVH timbers, cellulose insulation, vented gap and aggregate backfill. When using wood fibre and cellulose insulation, a 65% reduction in global warming emissions is achieved. The next research work will aim at a detailed analysis and comparison of roofs in terms of life cycle costs and circular economy.

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