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ECOLOGICAL PERFORMANCE AND RECYCLABILITY OF TIMBER-BASED CONSTRUCTIONS

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ABSTRACT: The growing importance of large-volume timber construction in European metropolitan areas leads to the investigation of a possible optimization potential in the use of timber in combination with other materials. This results in further investigations to gain synergies from a combination of the individual composite systems. For this reason, different types of combined timber composite constructions are developed and evaluated with regard to structural implementation and environmental optimization. Through a suitable combination, a construction-optimized design with increased resource efficiency can be achieved both at the component level and at the level of the overall structure.

For a holistic ecological assessment of building structures, the whole life cycle of the construction system needs to be investigated. Sustainable recycling means employing the materials used for the construction and operation of a building after the initial use for a new purpose. In a progressive design process, recyclability of the materials has to be considered in the planning stage of construction projects. If possible, recyclable components or already recycled components should be used. The factors separability and absence homogeneity are particularly decisive for the assessment of the possible recyclability of materials. For this reason, various life cycle phases and exploitation scenarios beyond the production phase of the building materials ("from cradle to gate") are evaluated. Especially the timber-wood lightweight concrete-glass-façade, developed and further investigated at the research department "Structural Design and Timber Construction" at the Vienna University of Technology, is set in context to standardized exterior façades to demonstrate a sensible design process regarding recyclability, resource efficiency and ecological advantages.

In addition, the thermal behavior is assessed in multiple studies. In the process, different construction methods, including timber, reinforced concrete and brick construction, are investigated and impact factors such as the orientation and size of the windows, the total solar energy transmittance of the glazing and solar shading devices are evaluated.

KEYWORDS: Wood-based construction, Sustainable building, Environmental impacts, Recyclability, Energy efficiency

1 INTRODUCTION

The growing importance of large-volume timber construction in European metropolitan areas leads to the investigation of a possible optimization potential in the use of timber in combination with other building materials. This results in further investigations to gain synergies from a combination of the individual composite systems.

For this reason, different types of combined timber composite constructions are developed and evaluated with regard to structural implementation and environmental optimization. Through a suitable combination, a construction-optimized design with increased resource efficiency can be achieved both at the component level and at the level of the overall structure.

Within the scope of subprojects, material-specific potentials could be identified for the respective materials used, which combine timber in the form of integrated timber ribbed panels (HCLTP elements [1]), wood lightweight concrete (WLC) and glass to increase the overall resource efficiency. This construction is in the focus of the current research project (cf. Figure 1 and [2, 3]).

When timber-WLC-glass-façades are used, the combined panel and ribbed component geometry offers an ideal basis for the execution of a multi-layer polyvalent composite construction.

The ribbed structure makes it possible to mount stiffening glass elements on the outside of the ribs and to create a buffer plane in the space between the ribs. By using an additional adaptive planking made of WLC, this gap can contribute to the structural optimization of the supporting structure [4].

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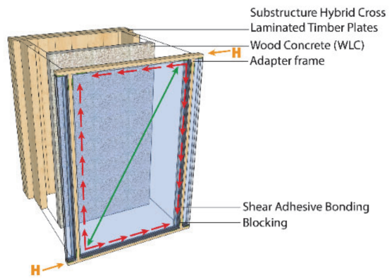

Figure 1: *Timber-wood lightweight concrete-glass façade*

The amount of glass used in this façade not only increases the resource efficiency of the construction, it also gives the opportunity to design optimal ratios of opaque and transparent elements. Nowadays the people feel the consequences of climate change very clearly. Especially in dense city areas the importance of climate resistant planning is invaluable. One of the key elements of climate resilient planning is designing glass façades to increase solar gains in the winter to reduce the heating demand but to look out for overheating in the summer.
To figure out clear factors for the design process, various simulations of different construction methods are carried out and put in context to the timber-WLC-glass-façade design decision. In the process, impact factors like orientation, window size, total solar energy transmittance (g-value) and solar shading devices are valuated.

2 LIFE CYCLE ASSESSMENT

Sustainable recycling means employing the materials used for the construction and operation of a building after the initial use for a new purpose. Waste products turn into secondary raw material. Easier dismantlability of an object into its components means that this object shows a better deconstruction. [5].
In a progressive design process, recyclability of the materials has to be considered in the planning stage of construction projects. If possible, recyclable components or already recycled components should be used. The factors separability and absence homogeneity are particularly decisive for the assessment of the possible recyclability of materials.
In consideration of their recyclability the lifecycle of different construction alternatives with a focus on timber and glass as building material is being analyzed and evaluated. For a holistic ecological assessment of building structures, the whole life cycle of the construction system needs to be investigated. For this reason, various life cycle stages and exploitation scenarios beyond the production phase of the building materials ("from cradle to gate") are evaluated according to the European standards EN 15804 [6] and EN 15978 [7], including the use and end of life cycle stages, such as energy consumption, maintenance and repair, respectively deconstruction, disposal and recycling ("from cradle to grave").

Thereby considered assessment criteria are the renewable **P**rimary **E**nery **I**nput (PEI_e), the non-renewable **P**rimary **E**nergy **I**nput (PEI_{ne}) and the **G**lobal **W**arming **P**otential over 100-year time horizon (GWP_{100}).
With these environmental computations, the ecological properties and impacts of wood-based construction systems can be shown. Furthermore, decisively design criteria for sustainable structural systems can be derived thereof [8].
The ecological assessments are calculated with integration of the databases "IBU-EPD" [9] and "ÖKOBAUDAT" [10], both managed by the German Federal Ministry of Housing, Urban Development and Building (BMWSB). In the last years the database updated from EN 15804 (now called EN 15804 + A1) [6] to the new system EN 15804 + A2 [11] because the new standard DIN EN 15804 + A2 [11] is introduced. With this change the ecological parameters differ a lot from the old ones and must not be mixed in the calculation process. The new system will be the basis of future calculations, especially within the Assessment System for Sustainable Building (BNB) [12]. The ecological assessment in this paper focuses in the comparison of different materials and the timber-WLC-glass-façade from before the change, so the used data is based on the system according to EN 15804 + A1 [6].
To put the decision to use wood- and glass-based materials as primary investigation in the timber-WLC-glass-façades in a clear context, different building materials and components are compared [13].

Figure 2 compares the primary energy demand, categorized in renewable and non-renewable (grey energy), of different building materials per m³ for the life cycle stages A-D (production, construction process, use and end of life stage as well as supplementary beyond the building life cycle).

The comparison of the materials concrete (different compressive strength classes), brick (insulating and non-insulating), timber (coated, structural and medium density fiberboard) and glass panels shows that timber and glass have high primary energy values. Nevertheless, most of the primary energy of timber is the renewable part (mostly solar power in the production phase) and glass is calculated as 1 x 1 x 1m block (of glass) to ensure comparability. Concrete with low compressive strength (C25/30) has lower primary energy demand than concrete with higher compressive strength (C50/60). Bricks without insulation and lower density of 740kg/m³ lead to lower environmental impact than its perlite filled version with 800kg/m³. In need of insulation material later on in most cases, the low-density version is more likely to be used within a solid brick construction.

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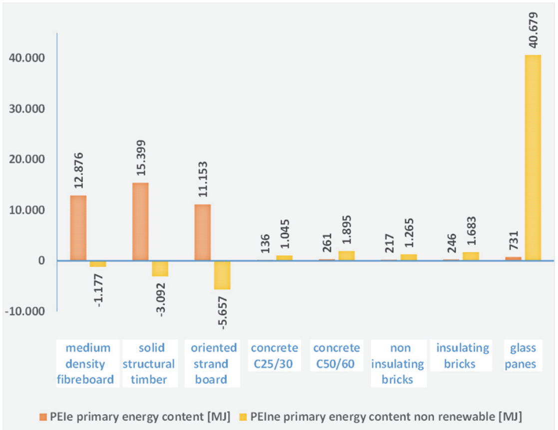

Figure 2: *Primary energy demand of building materials per m³ for the life cycle phases A-D*

Figure 3 illustrates one of the great advantages of timber-based materials. With a negative input for the global warming potential, wood has a considerable environmental balance. In contrast, concrete and brick materials cause more environmental impacts depending on density and compressive strength, similar to the calculations of the primary energy demand. Glass materials again cause the most GWP value due to the framework conditions, but have a high potential when used as individual panes.

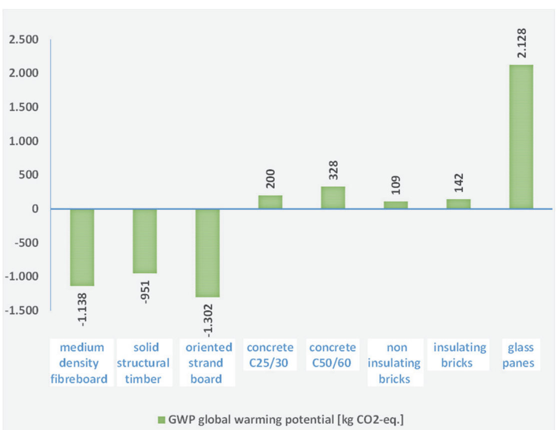

Figure 3: *Global warming potential of building materials per m³ for the life cycle phases A-D*

In a comparison of different exterior walls with concrete and brick materials (cf. Figure 4), vertically perforated brick and monolithic concrete require the most primary energy. Monolithic brick, perlite-filled brick and concrete with **e**xternal **t**hermal **i**nsulation **c**omposite **s**ystem (ETICS) roughly tie here.

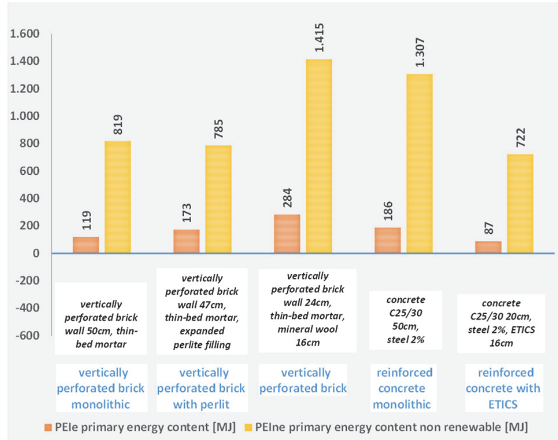

Figure 4: *Primary energy demand of brick and concrete exterior walls per m² for the life cycle phases A-D*

As can be seen in Figure 5, the perlite-filled brick in particular stands out in comparison, because of its high GWP value due to its filling. The GWP data of the other exterior walls are similar, with the ETICS concrete and the monolithic brick having the lowest GWP values.

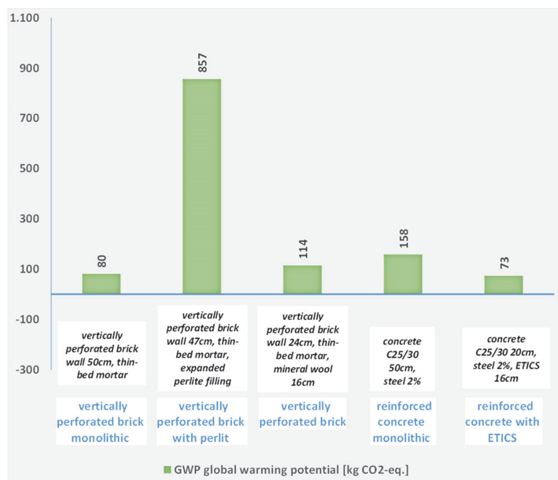

Figure 5: *Global warming potential of brick and concrete walls per m² for the life cycle phases A-D*

The analyzed timber exterior walls perform significantly better in terms of primary energy demand, especially the non-renewable part (cf. Figure 6).

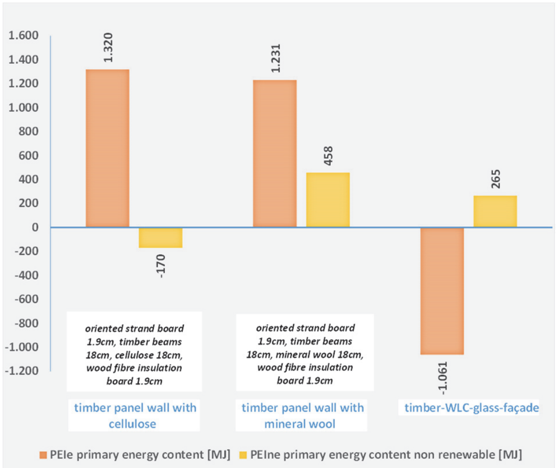

Figure 6: *Primary energy demand of timber exterior walls per m² for the life cycle phases A-D*

The results of the timber-WLC-glass-façade are particularly interesting and noteworthy. In the calculations per m² of façade, the strength of a mixed construction method from an ecological point of view is clearly shown by the very low primary energy values.

The same tendency is just as evident when considering the global warming potential. The timber exterior walls have a lower GWP value than the concrete or brick walls, especially the timber panel with cellulose and the timber-WLC-glass-façade (cf. Figure 7).

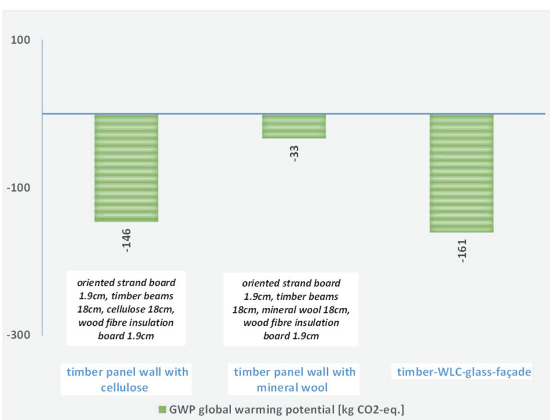

Figure 7: *Global warming potential of timber exterior walls per m² for the life cycle phases A-D*

A sensitive mixture of building materials (including glass) in a façade can therefore lead to ecological advantages if connected correctly. These studies show the potential of hybrid timber façades especially in case of the overall resource efficiency and recyclability potential.

3 ENERGY EFFICIENCY

At the present time, the required energy standard of buildings according to building regulation is at the level of a low-energy house. By introducing the "Energy Performance of Buildings Directive", the European council established the basis for uniform valuation. These guidelines indicate that a building has to be sustainable, the used construction materials and components have to be recyclable and the use of environmentally friendly resources and secondary materials is welcome [14].
Coherences of sustainability and energy efficiency on component and on overall system level can most suitable be shown by the assessment of a building model with a maximum geometrical simplicity. Consequently, a quadratic one-storied simulation model in different variations (wood-based and conventional building structures) is defined (cf. Figure 8) and subsequently investigated and compared with regard to its thermal behavior (heating energy demand and operative room temperature).

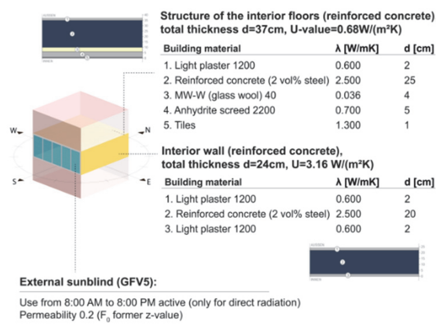

Figure 8: *Isometric view of the simulation model*

The simulations are carried out with the 3D online tool Thesim 3D [15]. Thesim 3D simulates the thermal behavior of a room in a steady-state, periodic condition (period length: 1 day). It is therefore particularly suitable for standardized summer overheating tests according to EN ISO 13791 [16] or ÖNORM B 8110-3 [17].
To evaluate these assessments, different types of conventional constructions are compared with the timber-WLC-glass-façade. The comparison is made with respect to materialization at the component level as well as at the overall structure level, which allows a scale-independent evaluation of the investigated types of construction to be achieved. This evaluation is made possible by a broad spectrum of calculations, ranging from static and dynamic thermal simulations for annual heating-up and overheating periods to the resulting various ecological impact calculations.

As a starting point for the simulations, a critical room with the dimensions 4 x 4 x 6m is defined (cf. Figure 9), which is initially calculated with the timber-WLC-façade in Vienna, Austria (average temperature is 24.9°C ± 7K). In the first calculation neither shading nor night ventilation is applied, the windows are triple glazing (U-value = 0,5; g-value = 0,48).

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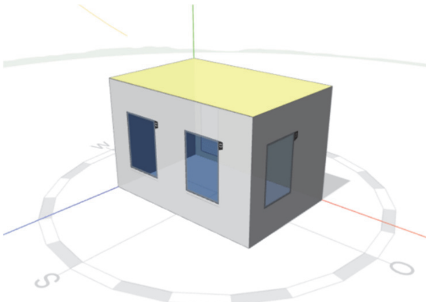

Figure 9: Isometric view of the critical room model

As shown clearly in Figure 10, the operative room temperature far exceeds the 27°C limit according to ÖNORM B 8110-3 [17]. Due to the closed windows facing south and lack of ventilation, the heat in the critical visibly accumulates and cannot escape.

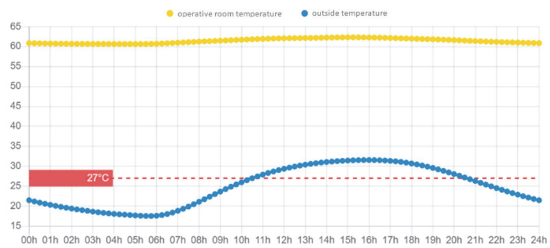

***Figure 10:** Thermal simulation of the critical room*

Therefore, some optimization measures has to be taken (cf. Figure 11). This time shading (F_c = 0.2) in direct sunlight and night ventilation from 08:00 PM to 08:00 AM (tilted window) is applied.

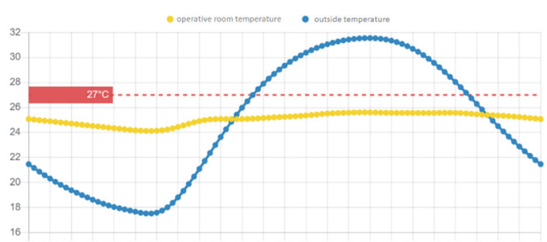

***Figure 11:** Thermal simulation of the critical room with optimization measures*

As a result, the critical room does not exceed an operative room temperature of 25.8°C even during the hottest summer days.

Furthermore, to evaluate other influencing factors several thermal simulations of existing buildings in the cities Vienna and Wels (Austria), Bochum (Germany) as well as London (England) are carried out. The critical room dimensions are congruent, but other framework conditions are unquestionably different in these European cities. The wide range of climatic conditions and various construction made out of timber, reinforced concrete and brick should lead to nuanced solutions. To save energy on the one hand and to avoid summer overheating on the other hand the factors "orientation and size of windows", "g-values of window panes" and "awnings" are identified.

As the studies show, the building design contributes significantly to the desired indoor climate in summer. Independent of the location the highest solar radiation occurred in the south and west zones of the buildings and has no shading available. Consequently, the placement and size of windows as well as the use of balconies and shading devices are crucial for the overheating aspect.

In terms of g-value of window panes the case study in London with a solid wood building (daily average exterior temperature: 16.3°C) shows that a lot of emphasis must be placed on orientation and the g-value during the planning phase.

Especially in this context, the question between double and triple glazing arises. In winter, triple glazing (U-value = 0.7; g-value = 0.48) is more advantageous than double glazing (U-value = 1.4; g-value = 0.27) because of its low U-value. In summer, however, low U-values and higher g-values are counterproductive, as less heat is lost through the windows and overheating occurs (cf. Figure 12).

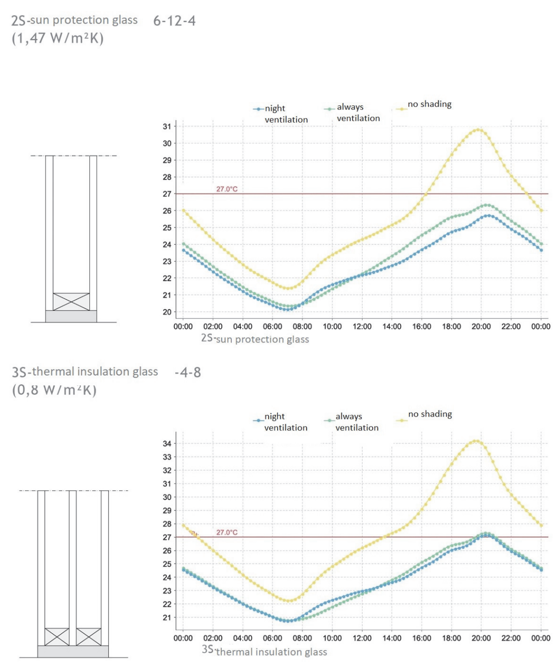

***Figure 12:** Thermal dynamic building simulations with double and triple glazing, building in London (© ITI/TU Wien)*

4 CONCLUSIONS

This paper illustrates how timber-based structures can be used both optimally and sustainably in terms of their ecological value, recyclability and energy efficiency. On the basis of these investigations, the competitiveness of timber construction compared to conventional construction methods is demonstrated. Especially the timber-WLC-glass-façade, developed and further investigated at the research department "Structural Design and Timber Construction" at the TU Wien is set in context to standardized exterior façades to demonstrate a sensible design process regarding recyclability, resource efficiency and ecological advantages.

When looking at the ecological values of individual building materials, it is apparent that in terms of non-renewable primary energy input (primary energy necessary to construct a building; so-called "*grey energy*") and global warming potential, timber-based materials have a good environmental balance. Nevertheless, building materials such as concrete or even glass can also offer an ecological advantage in certain building components. The timber-WLC-glass-façade is an example of the environmental benefits that mixed construction can have, as long as it meets the structural requirements.

Furthermore, multiple studies are carried out to assess the thermal behavior of the timber-WLC-glass-façade and other materials. In the process, different construction methods, including timber, reinforced concrete and brick construction, are investigated and impact factors such as the orientation and size of the windows, the g-value of the glazing and solar shading devices are evaluated. In conclusion a thermal sensitive design should always consider structural sun protection, the situational number of glass layers in windows, appropriate ventilation behavior and orientation of the most critical room in the given location.

Ultimately, a well-thought-out planning process requires many factors. In order to move towards a sustainable circular economy, the issues of environmental sustainability, recyclability and resource efficiency must be considered in particular.

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