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Conceptual Design of Timber-Wood Concrete-Glass façades | A holistic approach

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Within several research projects and with the aim to optimize structural performance, energy efficiency and ecological characteristics of structural building components the Department of Structural Design and Timber Engineering (ITI) at the Vienna University of Technology (TU Wien) developed several wood-based composite systems combining timber and wood concrete as well as structural glass components. Certain advantages in the application of these individual composite systems could be shown within the described former research activities. Due to a suitable combination of the named materials, a structural optimized construction with increased resource efficiency on component level as well as on the overall construction level can be achieved. For the assessment of this opportunity, different types of timber-wood concrete-glass façades with a special focus on varying glass components are developed and compared to conventional wall structures. The comparison is carried out regarding to the materialization on component level, as well as to the overall construction level, whereby a scale-independent assessment of the examined constructions types can be reached. This assessment shall be enabled by a broad spectrum of computations ranging from static and dynamic thermal simulations for annual heating and overheating periods up to various thereof resulting ecological impact calculations.

Keywords: Resource-efficient planning, Timber-glass façades, Thermal simulation, Ecological evaluation

1. Introduction

One of the main challenges of the 21st century is to minimize anthropogenic climate change and the associated consumption of energy and resources. The construction sector is responsible for around 30% of global CO_2 emissions, 30-40% of energy consumption and 40-50% of raw material consumption (Bauer et al. 2013). Vigorous efforts to improve resource efficiency in this sector are essential. Therefore, in the sense of a holistic approach and with regard to all life cycle phases, care must be taken to ensure responsible use of the materials as early as the design phase in order to enable a resource-saving construction phase, an energy-efficient use phase, as well as material separability and recycling in the deconstruction phase, and to guarantee adequate disposal of non-recyclable materials.

Material components play an important role in the energy discourse of the construction sector. The energy flows considered over the entire life cycle of the materials and components used, as well as their environmental impact, set new standards for the evaluation of sustainability. The goal of reducing CO_2 emissions and greenhouse gases means that buildings must not only use renewable resources, but also ecological materials. An important component is the building envelope. From a structural point of view, translucent components, especially glass and its substructures play an important role. The design of the façade has a considerable influence on the energy consumption of a building for cooling, heating and lighting. Solar energy can be generated via the façade and at best architectural qualities - strongly determined by the façade design - can be controlled. In order to achieve the required reduction in resource consumption, the weak points of conventional construction methods must be questioned and examined for alternatives and optimization possibilities.

Several previous research projects (Fadai and Winter 2014; Fadai et al. 2017) at the Department of Structural Design and Timber Engineering (ITI) of the Vienna University of Technology (TU Wien) focused on the research topics "Composite structures with wood-concrete (WLC)" and "Composite structures with glass as a load-bearing element" in detail as well as the possible applications and potentials were pointed out. In addition, in the course of the inter-university research project "Hybrid cross-laminated timber plates (HCLTP)" (Sustersic et al. 2016) the development and evaluation of hybrid load-bearing structures of combined timber panel and timber rib elements for vertical and horizontal load-bearing application was performed. Within these subprojects, material-specific potentials could be identified for the respective materials used, which is why a combination of the materials wood (in the form of HCLTP elements), wood concrete and glass to increase the overall resource efficiency of structural solutions is moving into the focus of the current research project (Fig. 1).

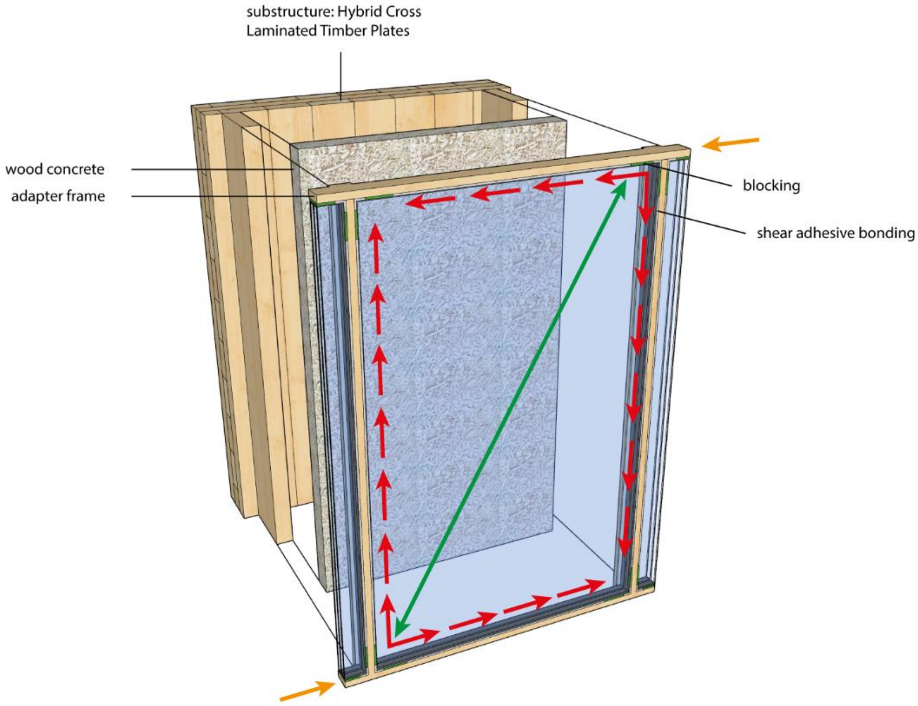


Fig. 1 Basic idea of the combination of timber-wood concrete-glass facades.

The combined panel- and rib-shaped component geometry of the load-bearing material timber in the form of HCLTP elements provides an ideal basis for the execution of a multi-layer polyvalent composite construction. As shown in Fig. 1, the ribbed structure allows the installation of stiffening glass elements on the outside of the ribs as well as a further buffer space in the gap between the ribs. This space between the ribs should contribute to the optimization of the structural physics of the load-bearing structure by the use of an additional adaptive planking of wood concrete (WLC).

If the above-mentioned materials are arranged accordingly at component level, there is the possibility of increasing the overall resource efficiency at building level, which is why this article pays special attention to the overall energy efficiency and the resulting ecological effects in the use of timber-wood concrete-glass facades.

For this purpose, the structural physical properties of wood-based composite wall elements are assessed. In a first step, measurements of the thermal properties with respect to thermal-insulating properties and thermal storage capacity are carried out. Furthermore, different variants of load-bearing structures are analyzed in terms of their thermal building behavior (heating demand or operative room temperature in the case of summer overheating) and further ecologically evaluated on the basis of these characteristics. Thus, on the one hand conclusions can be drawn about the general building physical applicability of the construction variants, and on the other hand recommendations can be given about the ecologically adequate use of wood-concrete-glass façades.

2. Development of timber-wood concrete-glass façades

Timber as a renewable raw material meets the high static requirements of façade construction. The softer wood-profiles (compared to the metal profiles) can serve as reinforcement and edge protection for the brittle building material glass and together with an appropriate bonding, transfer forces into and out of the glass, and thus involve glass components into load-bearing tasks. It is well known, that glass can absorb large compressive forces, if the forces are applied uniformly (without stress peaks). This potential of glass can be used by a circumferential elastic bonding and blockage in the corner areas. This allows the glass to transfer the forces into the substructure and transfer them into the foundation.

2.1. Combination potential of timber and glass

The objective of various research projects of the ITI at the TU Wien was to use glass in structural timber constructions as an equal partner – as a load-bearing and stiffening element (Hochhauser 2011; Fadai et al. 2015; Fadai et al. 2016). So far, two different timber-glass-composites (TGC)-systems were established which follow the same main principles. Both systems are based on a timber post and beam system for the vertical load transfer. The glass pane, that can be made of float-, heat strengthened or laminated glass, is itself glued to an adapter frame made of birch plywood, which is screwed to the post and beam substructure. In (Edl and Schober 2005) a system with a toothed adapter frame was published by Austrian Forest Products Research Society (Holzforschung Austria; HFA) to guarantee a narrow visible width of the post and beam substructure (patent no. 502 470 (Austria Patent 2005)).

The second system, developed by ITI/TU Wien (Hochhauser et al. 2011) uses an L-shaped adapter frame and additional to the silicone bond line, blockings in the corners of the glass pane to transfer compression forces in glass. So, this system avails the shear area as well as a compression diagonal to transmit higher forces and to provide higher stiffness (patent no. 511373 (Vienna Patent 2013)). Fig. 1 shows a schematic display of the system.

Further research (Fadai et al. 2018) deals with the TGC-construction built as an L-shaped adapter frame (Rinnhofer 2017) in terms of its stiffening potential as a shear wall for multi-story frame buildings. Based on the standard system, 2.10 m wide and 2.80 m high TGC-construction (Fadai et al. 2016), some variants were investigated, which differ mainly by the used adhesives and the glass thickness. As shear bonding, the silicone adhesive OTTOCOLL® S660 (OTTO Chemie 2013) and the silane-terminated two-component epoxy nolax C44.8508 (Nolax 2012), are used. As blocking material, HILTI HIT-RE 500 (Hilti AG 2014) is used for all variants. Semi-rigid adhesives such as (Nolax 2012) in pure shear bonding also have an effect as a blocking material. In addition, an important focus was to clarify the influence of coupling (single element, group or façade) on the increase in efficiency of TGC elements.

Furthermore, the resulting loads and deformations (Fadai et al. 2018) were calculated using a structural analysis software and generated for different building geometries (floor plans with an aspect ratio of 1:1, 1:1.5 and 1:2). In reality, these horizontal loads occur as wind or earthquake on the TGC-elements. The spring model (Hochhauser et al. 2011) was used to determine the wall stiffness at short-term stress for all construction and coupling variants. Based on this, on the one hand their limit load capacity and on the other hand, the percentage of utilization was investigated. It was investigated that the reduction of the glass thickness has not almost any effect on the wall stiffness. Because the glass thickness is very small compared to the element dimensions, the flexibility of the affected springs varies scarcely.

Consequently, coupling of TGC-elements and the use of the semi-rigid adhesive as (Nolax 2012) resulted in an enormous increase of wall stiffness for the building bracing, in addition to a reduction of deformations.

2.2. Wood Concrete

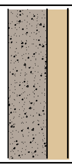
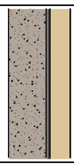
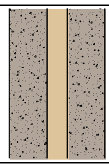
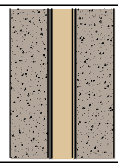
Wood concrete is a mixture of cement, wood chips or saw dust, which can be applied for building interior and outer construction. Wood-particles, as they are used in wood concrete, are a by-product of the timber production. The primary advantage of waste wood aggregate (around 90% of the volume content) is the low weight and high thermal insulation value. Wood concrete is a well-established building material for use in non-structural components. Many products are on the market e.g. cement-bonded wood, wood wool or wood-fiber boards, typically used for insulation and surface finishing.

In the ongoing research projects of the ITI/TU Wien, industrially produced wood concrete products, in which organic aggregates are used in conjunction with inorganic binders, various additives and water, are used. Through the combination of different material parts, a new castable, self-compacting building material could be researched, which combines positive physical and ecological criteria (Fadai et al. 2014). The focus in the development of the material composite is, on the one hand, the optimization of the material properties of the building material, such as the strength properties, the weight, the thermal or noise insulation or the fire protection properties, and on the other hand the resulting environmental impacts. Wood concrete also provides an ecological added value at the end of its life cycle. After its use it can be recycled easily in the form of combustion in spite of good fire protection properties. This is made possible by the increased calorific value of the panes. Since the surcharge consists of residual and waste materials, the production of statically effective constructions is possible with low energy consumption or low CO_2 emissions.

2.2.1. Thermal insulation properties

The thermal insulation properties were tested on a prefabricated WLC element (noise insulation chipboard WSD 50, Type A in Table 1) and four different composite constructions consisting of timber and glued prefabricated WLC elements (noise insulation chipboard WSD 50, types B2 and C2 in Table 1), as well as on loose WLC elements without additional composite materials (types B1 and C1 in Table 1). The tested WLC element is a mineralized noise protection chipboard with increased gross density and high dynamic stiffness according to the Austrian standard OENorm B 6022 (OENORM B 6022 2009) used for interior or exterior walls and residential partition walls, where a high level of noise protection is required.

Table 1: Overview of specimen.

Type	A	B1	B2	C1	C2
Sketch					
Composite	WLC 50mm	WLC 50mm Timber 27mm	WLC 50mm Adhesive 5mm Timber 27mm	WLC 50mm Timber 27mm WLC 50mm	WLC 50mm Adhesive 5mm Timber 27mm Adhesive 5mm WLC 50mm
Thickness t	50mm	77mm	82mm	127mm	137mm

The tests were performed according to OENorm EN ISO 8990 (OENORM EN ISO 8990 1996). It is apparent from the results in Table 2 that the thermal insulation properties of the tested prefabricated WLC material is between the properties of conventional thermal insulation and timber (e.g. $\lambda \approx 0.44$ [$Wm^{-1}K^{-1}$] for mineral wool and $\lambda \approx 0.11$-0.13 [$Wm^{-1}K^{-1}$] for spruce). The calculations show that the manufacturer's data correspond to the measured values except for small deviations of 2-5%. This result represents a satisfactory range, taking account of arithmetic errors and statistical distribution. In addition, the results in Table 2 show that the experimentally determined thermal insulation properties of pure WLC (Type A) are significantly better than the manufacturer's data ($\lambda = 0.125$ [$Wm^{-1}K^{-1}$]). The results of the experimental investigations show a significant contribution of WLC to the thermal insulation of buildings, as well as a potential for use in thermally activated floor elements. Comparable results are derived for castable WLC for wall elements.

Table 2: Thermal insulation properties of wall elements made of timber and WLC.

Type	Thickness t [m]	$R_{T,Test}$ [m^2KW^{-1}]	U_{Test} [$Wm^{-2}K^{-1}$]	λ_{Test} [$Wm^{-1}K^{-1}$]	$R_{T,Calc}$* [m^2KW^{-1}]	U_{Calc}* [$Wm^{-2}K^{-1}$]
A	0.050	0.421	2.375	0.119	0.400	2.500
B1	0.077	0.643	1.555	0.120	0.656	1.524
B2	0.082	0.616	1.623	0.133	0.660	1.516
C1	0.127	0.973	1.028	0.107	0.990	1.011
C2	0.137	0.929	1.076	0.147	0.997	1.003

* calculated using the manufacturer's data (VELOX Werk GesmbH, 2015)

2.2.2. Thermal storage capacity

In addition to the investigations of the thermal insulation properties, further tests were carried out to determine the thermal storage capacity of prefabricated WLC. Experimental investigations were carried out on two test specimens. The results of the thermal storage capacity measurements are represented in Table 3.

Table 3: Thermal storage capacity properties of prefabricated WLCs.

	Density ρ [kgm^{-3}]	Thermal conductivity λ [$Wm^{-1}K^{-1}$]	Specific heat capacity c_p [$kJkg^{-1}K^{-1}$]
WLC Insulation chipboard WS 50	560*	0.1*	1.74
WLC Noise protection chipboard WSD 35	750*	0.125*	1.64

* Manufacturer's data (VELOX Werk GesmbH, 2015)

The results in Table 3 show that the specific heat capacity of WLC chipboards is significantly higher than the capacity of reinforced concrete and mineral rock wool ($c_p = 1.08$ [kJkg-1K-1] resp. $c_p = 1.03$ [kJkg-1K-1]). It lies approximately in the range of spruce timber but with a higher density.

3. Thermal simulation

To ensure an environmentally and resource friendly use phase, it is important to plan the operative room temperature in the design phase in such a way, that for example in the summer months there is no additional need for cooling and thus energy is saved.

Different types of simulation and calculation methods are required to analyze the thermal behavior of buildings. In order to enable an assessment of the overall energy efficiency in the use of wood-glass façades, a building structure of simple geometry is defined at the beginning, on the basis of which the thermal properties of different construction variants in the form of the operative room temperature can be simulated during summer overheating. On the basis of these characteristics, an ecological evaluation of the components will be possible. The study examines the manufacture of construction variants at component level, as well as ecological effects that can be derives from the thermal properties of the use phase of the building structure.

The calculation concepts of the thermal simulations are based on a static monthly balance procedure (according to OENorm B 8110-6 (OENORM B 8110-6-1 2019)) for the determination of the annual heating demand, as well as on a thermally dynamic calculation procedure of the operative room temperature in case of summer overheating. The ecological simulation and balancing based on these calculations is derived from the environmental product declaration for building products according to OENorm EN 15804 (OENORM EN 15804 2020). The life cycle phase "production" (A1 to A3), as well as the ecological effects resulting from the thermal use (observation period 50 years) are considered. All ecological parameters used for this simulation are based on the standardized database for ecological evaluations of buildings by the Federal Ministry of the Interior, Building and Community OEKOBAUDAT. The technical implementation of the simulations is carried out with the help of specifically created design routines (MS Excel) and the web-based software Thesim3D (Nackler 2018).

3.1. Boundary conditions of the simulation model

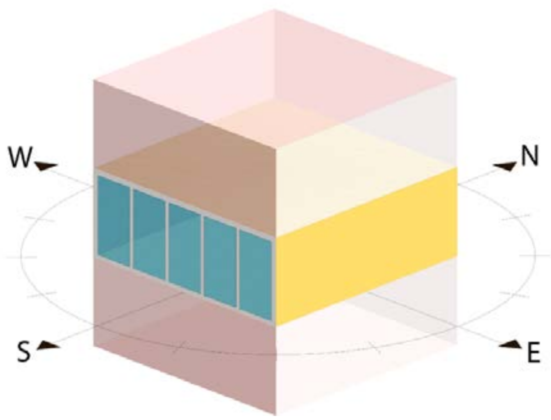


Fig. 2 Geometry of the thermal and ecological simulation model.

With the results, obtained from the thermal storage capacity measurements of prefabricated WLCs, a thermal building simulation is carried out, in which a building structure of simple geometry consisting of different research-related constructions (HCLTP/WLC/, HCLTP/WLC/glass) is compared to conventional building constructions (massive and lightweight structures) with regard to the operative room temperature, as well as the annual heating energy demand.

The simulation model has external dimensions of 8.00 x 8.00m at a height of 3.00m. The selected room size results from the maximum span of the HCLTP/WLC composite elements, which is 8.00m. All four walls adjoin the exterior space, floor and roof are adiabatic, which means that adjoining rooms above and below have the same thermal conditions as the room itself.

To ensure a certain level of spatial comfort, a required light entry area ≥ 12% of the floor area for common rooms must be ensured in accordance to OIB Guideline 3 (Austrian Institute of building technology 2018). As shown in Fig. 2, this requirement is met by the use of two window elements per vertical boundary surface. These are timber frame windows with double insulation glass (WSG 4/12/4) and intermediate krypton filling (U_g = 1.10 W/m²K, g = 0.62).

For improved comparability, all described window constructions are executed without additional sun protection and an exposure opening of 58.5 x 165cm, which is adapted to the axial grid of the examined HCLTP elements. In summer, a natural night ventilation is simulated through open windows to reduce the maximum indoor temperature.

In addition to spatial comfort, a certain thermal comfort of the users must also be ensured in form of minimum and maximum operative room temperatures according to OENorm B 8110-3 (OENORM B 8110-3 2020) and OENorm B 8110-6 (OENORM B 8110-6-1 2019) during heating and overheating periods. Therefore, the simulation model is based not only on the site-specific outdoor climate (the 1st municipal District of Vienna Vienna) but also on use-related minimum and maximum room temperatures of 20°C and 27°C respectively. In order to guarantee simulation results that are as close to reality as possible, the building structure is also provided with internal loads of a permanent resident (90W) as well as a heat output by devices (2W/m²).

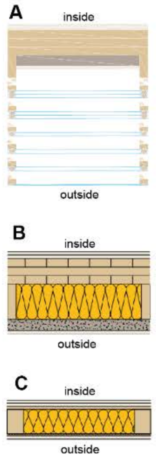
3.2. Component structures of the simulation model

As already mentioned in the introduction, the simulation model will be used to identify possible potentials of timber-wood concrete-glass façades and to make recommendations for an ecologically adequate use of these supporting structures. For this purpose, five different modifications of timber-wood concrete-glass façades are developed and compared to other lightweight and solid structures. The investigated variants of timber-wood concrete-glass façades are basically identical in their structural design, they only differ in the design of the respective glass structure. In order to enable the evaluation of the widest possible range of glass structures, single-layer safety glass (ESG) and two- to three-layer thermal insulation glass (WSG) with different types of air or gas fillings are taken into account in the simulation. An exact description or representation of these structures, as well as of the comparative superstructures, can be taken from Fig. 3.

A: HCLTP-CLT-glass facade (U=0.287 - 0.462 W7m²K)

building component layer	λ [W/mK]	d [cm]
gypsum plaster board 2 layers	0.250	3.0
cross laminated timber (CLT) 3 layers	0.120	12.0
rib constructioin		∑ 16.5
(axial dimension 62.5 cm, width 4.0 cm)		
intermediary materials:		
- wood-lightweight concrete (WLC)	0.104	5.0
- standard plaster	0.780	1.5
- air gap	0.556	10.0
glass panels		∑
(axial dimension 62.5 cm)		0.6-3.2
variants:		
A1 HRG** 4/12/4/12/4 krypton, g=0.47	0.024*	3.6
A2 HRG** 4/12/4/12/4 argon, g=0.47	0.031*	3.6
A3 HRG** 4/12/4 krypton, g=0.62	0.025*	2.0
A4 HRG** 4/16/4 argon, g=0.60	0.030*	2.4
A5 HRG** 4/16/4 air, g=0.61	0.039*	2.4
A6 single pane safety glas 6, g=0.83	0.035	0.6

*equivalent thermal conductivity $\lambda_{equ.}$ ** Heat Reflecting Glass



B: HCLTP wall (U=0.178 W/m²K)

building component layer	λ [W/mK]	d [cm]
gypsum plaster board 2 layers	0.250	3.0
cross laminated timber (CLT) 3 layers	0.120	12.0
rib construction		∑ 16.5
(axial dimension 62.5 cm, width 4.0 cm)		
intermediary materials		
mineral wool	0.039	16.5
wood lightweight concrete (WLC)	0.104	5.0
standard plaster	0.780	1.5

C: Timber-lightweight wall (U=0.332 W/m²K)

building component layer	λ [W/mK]	d [cm]
gypsum plaster board 2 layers	0.250	3.0
gypsum plaster board 1 layer	0.130	1.5
rib construction		∑12.0
intermediary materials		
mineral wool	0.039	12.0
MDF board 1 layer	0.100	1.0
standard plaster	0.780	1.5

Fig. 3 Structure of the simulation model.

3.3. Results of the thermal simulation

The decisive results of the thermal simulation regarding the annual heating demand, as well as the operative room temperature in case of summer overheating are shown in Fig. 4 and Fig. 5.

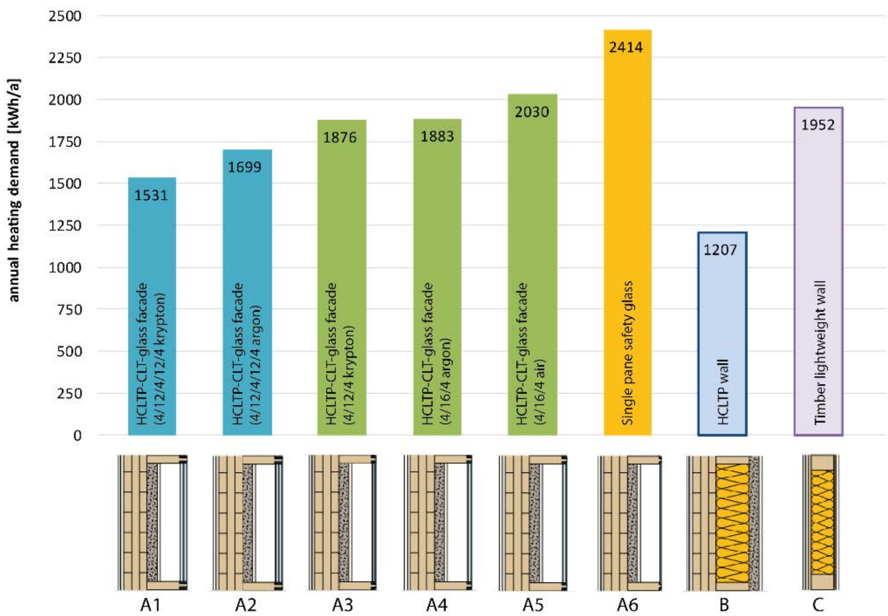


Fig. 4 Annual heating demand of the different components.

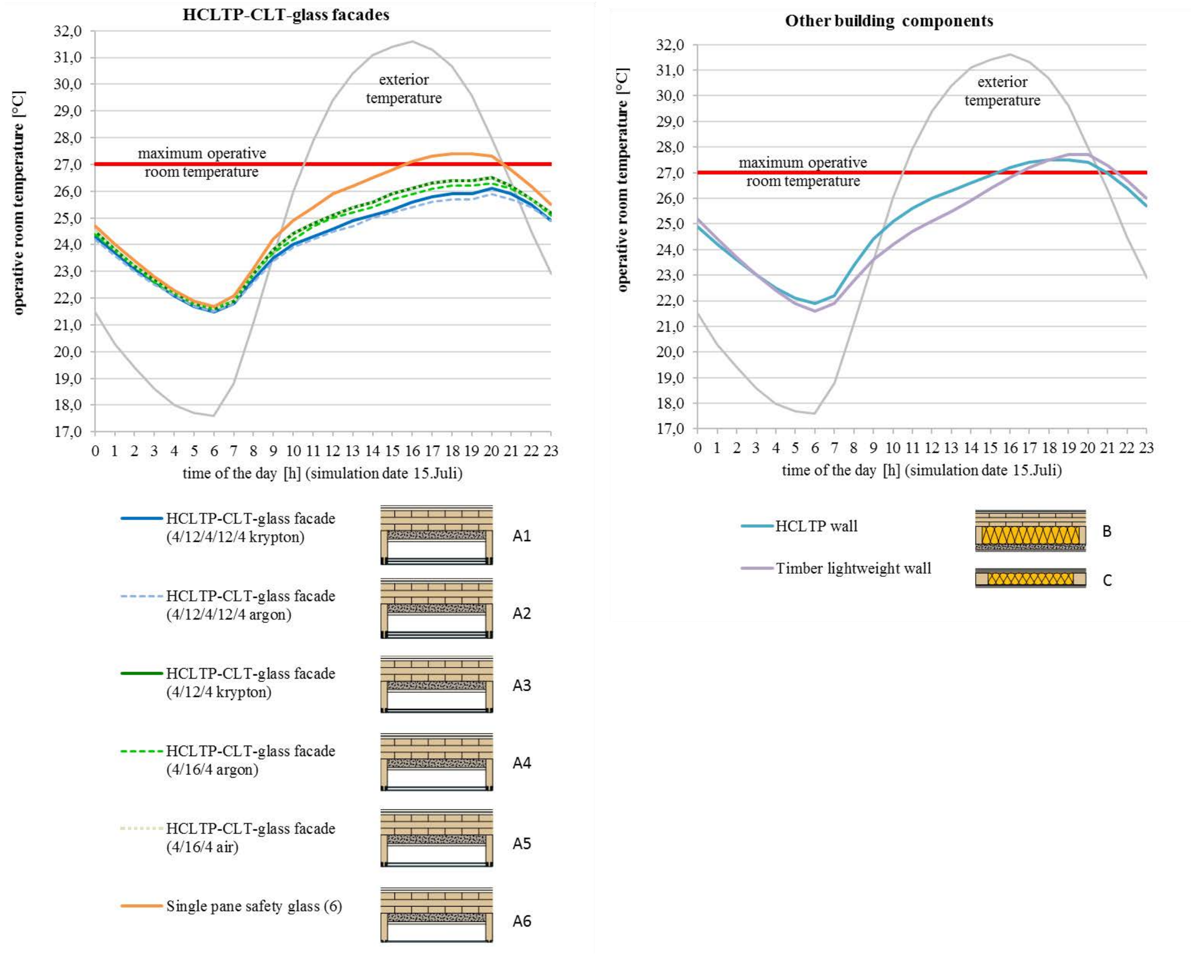


Fig. 5 Operative room temperature of the different components.

The results of the thermal simulations clearly show that by using timber-wood concrete-glass façades, thermally adequate results can be achieved both with regard to annual heating demand and operative temperature in the case of summer overheating. As expected, the thermal quality of the glass elements used represents the decisive main factor for both the heating and the overheating case.

As shown in Fig. 4, it is possible to control or influence the annual energy demand within a relatively wide spectrum by varying the number and properties of the individual glass layers and the buffer spaces between them. By using thermally optimized glass elements (WSG 4/12/4/12/4 krypton), the annual heating demand can be reduced by up to 37% from 2,414 kWh/a to 1,531 kWh/a compared to a version with single-pane safety glass (ESG).

On the basis of these results, a design of timber-wood concrete-glass façades can be considered as quite reasonable in the context of thermal winter suitability. A further thermal optimization of the examined timber-wood concrete-glass façades can only be achieved by an additional insulation layer. By modifying the timber-wood concrete-glass façades to a conventionally insulated construction form with insulated, thermally optimized ribbed spaces (HCLTP wall, U=0.178 W/m²K), it is possible to reduce the annual heating demand by 21% from 1,531kWh/a to 1,207kWh/a compared to a thermally optimized timber-wood concrete-glass façades (WSG 4/12/4 krypton).

As Fig. 5 shows, an explicit analysis of the operative room temperatures of the different timber-wood concrete-glass façades results in characteristically similar proportions as for the annual heating demand. By varying the number and properties of the individual glass layers and the buffer spaces in between, the operative room temperature can be controlled or influenced to a certain extent in case of summer overheating. According to Fig. 5, timber-wood concrete-glass façades meet the requirements for the operative room temperature starting with the use of two- to three-layer thermal insulation glass. Only the construction variant with single-pane safety glass (ESG) exceeds the permissible standard temperature. On the basis of these results, a design of timber-wood concrete-glass façades can consequently be described as highly suitable in the context of thermal summer efficiency.

3.4. Influence of dark and bright walls on the operative room temperature

As a further outcome of the simulation, the results show that the color of the used plaster surface behind the air-filled buffer space of suspended glass façade elements is highly responsible for the operative temperature inside the room. Through the use of a dark plaster instead of a bright finish the operative room temperature increases between 1.4°C and up to 2.9°C, depending on the daytime hour. As seen in Fig. 6 the former discussed timber-wood concrete-glass façades could not fulfill the requirements regarding summerly overheating if using a dark plaster material. For wall structures with additional suspended glass façade elements a bright plaster surface is therefore highly recommended.

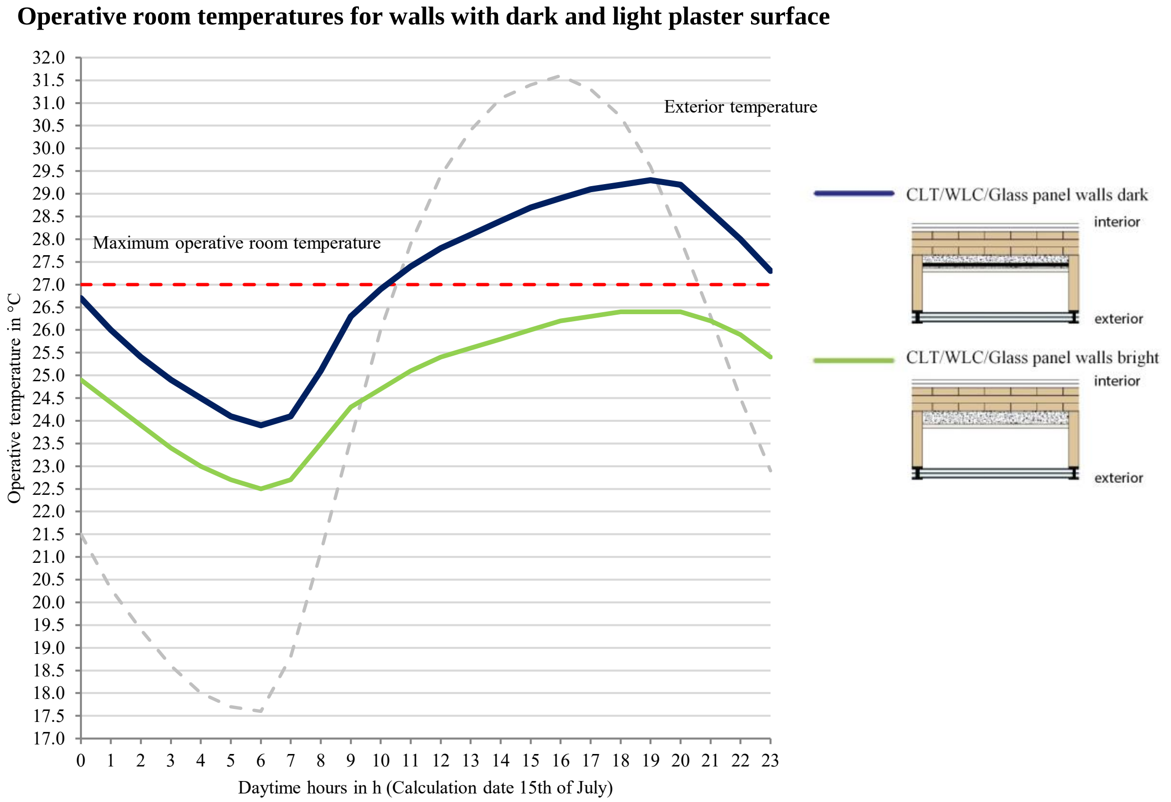


Fig. 6 Operative room temperatures of timber-wood concrete-glass façades with bright and dark plaster surface.

4. Ecological assessment

Life Cycle Assessment (LCA) is a holistic assessment of the environmental impacts associated with a product over its life cycle. The rules of this assessment are defined in OENorm EN ISO 14040 (OENORM EN ISO 14040 2009). and EN 15804 (OENORM EN 15804 2020). To calculate the environmental impacts, an independently validated, comparable life cycle assessment is prepared on the basis of the Environmental Product Declarations (EPD).

First, it is defined to which life cycle phases (production, use, maintenance, renewal and disposal) the life cycle assessment will refer. The ecological assessments consider the manufacturing phase ("cradle-to-gate") and the disposal phase ("cradle-to-grave"). The analysis of the thermal building simulation in considers the "Usage Phase". The functional unit is then defined. This helps to provide a uniform reference value and thus to make the results comparable. Façades are compared which have similar building physics properties, especially a similar heat transfer coefficient (U-value) and load-bearing capacity. The indicators each refer to either one m², m³ or kg.

The focus in the following analysis are on renewable and non-renewable primary energy demand and on the greenhouse potential. The Global Warming Potential (GWP) is a parameter for the potential of a substance to contribute to the heating of air layers near the ground (greenhouse effect). The effect of the substance is compared with the effect of the greenhouse gas carbon dioxide and converted into CO_2 equivalent. The greenhouse potential is expressed in kilograms CO_2 equivalent per functional unit (m² or kg).

4.1. Comparative life cycle analysis, Primary energy demand and CO_2 balance

The environmental effects of the manufacturing phase, the "cradle-to-gate" with option for aluminum-glass façades, wood-aluminum façades and the developed variant of the timber-wood concrete-glass façades are considered. Fig. 7 shows a comparison of the examined façade types.

The ecological balance based on these calculations is derived from an environmental product declaration for construction products according to OENorm EN 15804 (ÖNORM EN 15804 2020), whereby the standardized life cycle phase of production (A1 to A3) and the ecological effects resulting from thermal use are taken into account.

According to EN 15804 (OENORM EN 15804 2020) the manufacturing phase is divided into three parts: A1: Supply of raw materials, A2: Transport of raw materials to the manufacturer and A3: Production. It is investigated which materials and components of the composite have the greatest impact and where the greatest potential for optimization exists. The aim is to be able to make appropriate statements about the design parameters and thus develop timber-wood concrete-glass façades in the most environmentally friendly way possible.

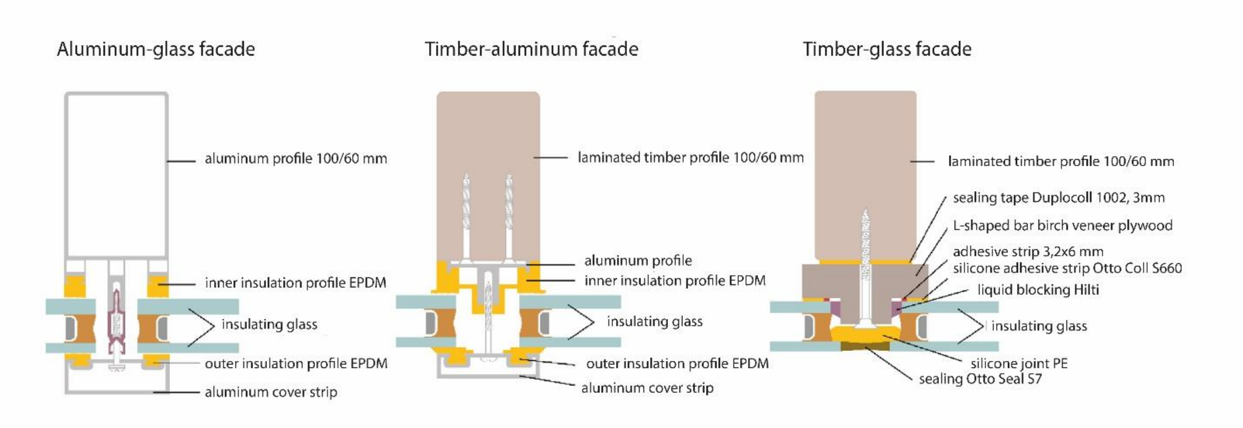


Fig. 7 Overview of the examined façades: aluminum-glass-facades, timber-aluminum- façades and one variant of the timber-wood concrete-glass façades with an L-shaped bar (birch veneer plywood). Own representation based on (Pascha & Winter, 2016).

Due to the fact that the choice of glazing for transparent components has a rather minor influence on the life cycle assessment and that the glazing has very similar specifications for the different facade constructions, the insulating glass unit (IGU) was excluded from the life cycle assessment calculations.

All data for the production and disposal of materials comes from the freely accessible OEKOBAUDAT database, which is provided by the Federal Ministry of the Interior, for Building and Homeland (BMI, Germany). The comparative analysis is carried out for 1 m² reference façade. This is in all cases a post and beam construction with a grid of 1.35m and a height of 3.50m. The reference façade refers to a fully glazed building envelope with maximum transparency.

The production of 1 m² of the aluminum-glass façade releases 1,043.37 MJ of non-renewable primary energy, of which 1,030.47 MJ is due to the production of the building material aluminum. Assuming that this is recycled at the end of its life cycle, approximately 76% of the non-renewable primary energy released can thus be credited again. (Fig. 8) The manufacture of the aluminum-glass façade has a greenhouse effect of 74.97 kg CO_2 equivalent, with a credit of 57.7 kg CO_2 equivalent at the end of the life cycle. (Fig. 8)

Through the use of laminated veneer timber and cross laminated timber in the main structure, as well as the complete exclusion of aluminum, 139.0 MJ of non-renewable primary energy is released during the production of 1m² timber-wood concrete-glass façade (with L-profile including substructure). Compared to the production energy of the aluminum-glass façade, this corresponds to a reduction of 86.7%. The recycling potential amounts to -162.76 MJ. (Fig. 8) The greenhouse potential of the manufacturing phase is even negative for this variant with -0.72 kg CO_2-equivalent, as the wood already absorbs and binds carbon dioxide from the atmosphere during growth. The End-of-Life phase records a credit of -13.92 kg CO_2-equivalent. (Fig. 8)

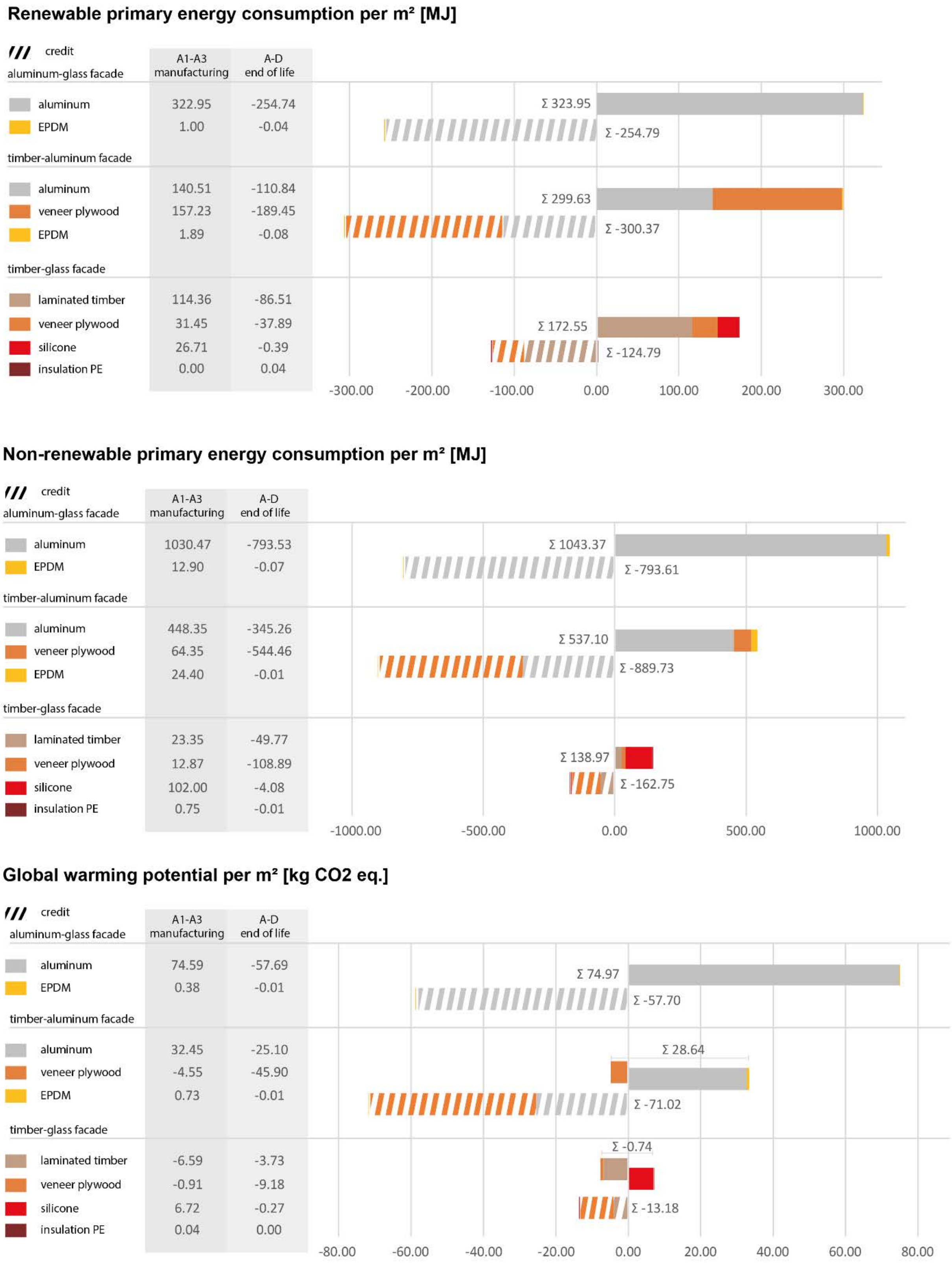


Fig. 8 Primary energy consumption and global warming potential of the three examined facades (as depicted in Fig. 7) (Fadai & Stephan, Ressourceneffiziente Planung großflächiger Holz-Glas-Fassaden, Ökologische und energetische Bewertung (Glasbau 2020), 2019).

5. Conclusion

Consideration of climate-friendly construction should already take place in the design phase, as energy efficiency and sustainability play an increasingly important role in the construction process. The reuse or recycling of building materials is a component of the ecological life cycle analysis. Finished façade elements represent a valuable source of raw materials in this respect. Here it is important to consider the question of subsequent use at an early stage in production or in building planning.

The use of wooden elements, which can be provided with less energy input compared to metallic building materials, is crucial. Above all, the replacement of aluminum profiles with a wooden construction as the main daytime structure for large glass façades can enable a reduction in CO_2 emissions. The focus here is on the choice of materials and ecological evaluations, as well as thermal building simulations. Timber-wood concrete-glass façades are therefore compared to conventional aluminum façades.

Building-physical consequences of timber-wood concrete-glass façades were investigated through several measurements and simulations. The effect of the timber-wood concrete-glass façades to the annual heating demand as well as to the operative room temperature of a typical south-orientated living space were investigated. Not only in the transparent building skin, but also in the opaque sections these façades could be used to reduce the demand for heating energy in the cold period. WLC can then act as thermal storage. An intelligent use of this system is required for not having disadvantages regarding summer comfort inside the building. The differences due to altering the properties of the glass layers, amount of ventilation in the air layer, properties of the WLC, etc. were investigated.

The simulations basically show a competitive building physics behavior of timber-wood concrete-glass façades in comparison to conventional wall constructions. A corresponding suitability for both winter heating and summer overheating can be shown. From the point of view of a resource-efficient use of timber-wood concrete-glass façades, the fundamental ecological relationships between the production and use phases can be examined. As a result, further optimization proposals for the construction of the overall structures can be made. As the ecological balance results show, there is further potential for optimization in both the production and the utilization phase. These aspects, in the form of a further variation of materials and layering of the component structures, as well as the use of photovoltaic laminated glass elements for energy generation in the use phase, should therefore be the contents of a further topic-relevant research.

Optimizing energy efficiency is one of the most crucial challenges of modern architecture. Consequently, timber-wood concrete-glass façades can be used for large-area glass façades and energy-relevant functions can be integrated. The use of efficient timber-wood concrete-glass façades improves the energy efficiency of buildings and thus reduces energy consumption and CO_2 emissions. The lower primary energy requirement of a high-speed rail façade speaks for the future-oriented building material wood. In addition, the architectural aesthetics and increased living comfort are positive effects.

6. References

Alireza Fadai & Wolfgang Winter. (2014, 10). Ressourceneffiziente Konstruktionen in Holzleichtbeton-Verbundbauweise. *Bautechnik 91*, pp. 753-763.

Austrian Institute of building technology OIB-Guidline 3: Hygiene, health and preservation of the environment. (2018). Vienna.

Austrian Institute of building technology OIB-Richtlinie 6: Energy saving and heat insulation. (2015). Vienna.

Austrian Institute of building technology OIB-Richtlinie 6: Energy saving and heat insulation. (2018). Vienna.

Austrian Institute of building technology: OIB-Guidline 3 Hygiene, health and preservation of the environment. (2015). Vienna.

Austrian Standards Institute OIB-Guidline 6, NAT-T13. (2009).

baubook GmbH. (n.d.). Retrieved 11 13, 2018, from www.baubook.info

Bauer, M. (2011). Green Building. Einflüsse auf Planen und Bauen. Vortrag Tagung Glasbau. Dresden,Germany.

Bauer, M., Mösle, P., & Schwarz, M. (2013). *Green Building. Leitfaden für nachhaltiges Bauen.* Stuttgart, Germany: Springer-Verlag.

Christian, S. (2012). *Einfach Bauen Zwei : nachhaltig, kostengünstig, lokal* (Edition Detail ed.). (S. Christian, Ed.) Munich: Institut für internationale Architekturdokumentation.

DIN-Normenausschuss Bauwesen (NABau). (2018). DIN 276: Kosten im Bauwesen. Berlin: DIN Deutsches Institut für Normung e. V.

Edl, T. (2005, 07 06). *Austria Patent No. AT 502 470 B1.*

Edl, T., & Schober, K. (2005). Statisch wirksame Holz-Glas-Verbundkonstruktionen. Vienna: Holzforschung Austria.

Fadai, A., & Stephan, D. (2019). Ressourceneffiziente Planung großflächiger Holz-Glas-Fassaden, Ökologische und energetische Bewertung (Glasbau 2020). Vienna: TU Wien.

Fadai, A., & Winter, W. (2014). Ressourceneffiziente Konstruktionen in Holzleichtbeton-Verbundbauweise. *Bautechnik, Volume 91, Issue 10 (2014)*, pp. 753-763.

Fadai, A., Nicklisch, F., & Rinnhofer, M. (2016). Timber-Glass Composites: Long-term behavior. In *Proceedings of the World Congress of Timber Engineering 2016.* Vienna.

Fadai, A., Rinnhofer, M., & Wagner, D. (2018). Bracing Timber-glass-façade | Feasibility studies, performance assessments and optimization. Dresden: engineered transparency conference.

Fadai, A., Rinnhofer, M., & Winter, W. (2015). Experimentelle Untersuchung des Langzeitverhaltens von verklebten Holz-Glas-Verbundkonstruktionen. In *Glasbau 2015* (pp. 339-349). Dresden: Ernst & Sohn.

Fadai, A., Rinnhofer, M., & Winter, W. (2015). Experimentelle Untersuchung des Langzeitverhaltens von verklebten Holz-Glas-Verbundkonstruktionen. *Stahlbau, 84*((S1)), 339-349.

Fadai, A., Rinnhofer, M., & Winter, W. (2016). Stiffening multi-story timber-glass composites facades in tall building. *Engineered Transparency 2016*, 243-252. Berlin: Ernst & Sohn.

Fadai, A., Rinnhofer, M., & Winter, W. (2017). Holz-Glas-Verbundkonstruktionen: Entwicklung und Anwendung. *Österreichische Ingenieur- und Architekten-Zeitschrift - ÖIAZ, 1-12 (2017)*, pp. 45-54.

Fadai, A., Rinnhofer, M., & Winter, W. (2017). Holz-Glas-Verbundkonstruktionen: Entwicklung und Anwendung". *Österreichische Ingenieur- und Architekten-Zeitschrift ÖIAZ*, pp. 45-54.

Fadai, A., Rinnhofer, M., Schleicher, A., & Winter, W. (2018). Holz-Glas-Verbund-Fassaden / Verhalten im Brandfall / Brandschutzkonzepte für mehrgeschossige Gebäude (Glasbau 2018). Vienna: TU Wien.

Fadai, A., Winter, W., Nackler, J., & Borska, A. (2017). Entwicklung von Holzleichtbeton-Verbundkonstruktionen. *Österreichische Ingenieur- und Architekten-Zeitschrift - ÖIAZ, 1-12 (2017)*, pp. 57-67.

Hilti AG. (2014). Leistungserklärung No. Hilti HIT-RE 500 0756-CPD-0045. Schaan.

Hilti AG. (2014). Leistungserklärung No. Hilti HIT-RE 500 rebar 1343-CPR-M500-4/07.14. Schaan.

Hochhauser et al. (2011). *Holz-Glas-Verbundkonstruktionen: Berechnungs- und Bemessungskonzept.* Vienna: TU Wien.

Hochhauser, W. (2011). Ein Beitrag zur Berechnung und Bemessung von geklebten und geklotzen Holz-Glas-Verbundscheiben. Doctoral Thesis. Vienna: TU Wien.

Hochhauser, W. (2013). *Vienna Patent No. AT 511 373 B1.*

Hochhauser, W., Winter, W., & Kreher, K. (2011). *Holz- Glas- Verbundkonstruktionen. State of the Art, Forschungsbericht, Studentische Arbeiten.* Vienna: TU Wien.

Hochhauser, W., Winter, W., & Kreher, K. (2011). Holz-Glas Verbundkonstruktionen: State of the Art, Forschungsbericht, Studentische Arbeiten; Final report of the research project "Holz-Glas-Verbundkonstruktionen: Berechnung und Bemessungskonzept". Vienna: TU Wien.

Hochhauser, W., Winter, W., & Kreher, K. (2011). Holz-Glas-Verbundkonstruktionen: Berechnung und Bemessungskonzept. Vienna: TU Wien.

Holzforschung Austria. (2008). *Holz-Glas-Verbundkonstruktionen, Weiterentwicklung und Herstellung von Holz-Glas-Verbundkonstruktionen durch statisch wirksames Verkleben von Holz und Glas zum Praxiseinsatz im Holzhausbau, Endbericht.* Wien: Holzforschung Austria.

Nackler, J. (2017). *Sommerlicher Wärmeschutz : Vergleich von Berechnungsansätzen und Entwicklung eines Planungsinstrumentes für Entwurfsfindung und Nachweis.* Wien: Technische Universität wien.

Nackler, J. (2018, 11 15). Retrieved 11 15, 2018, from www.thesim.at

Nolax. (2012). Technisches Datenblatt nolax C44.8505.

OENORM B 6022: Thermal and/or sound insulating products in building construction — Wood splint boards WS, WSD and wood splint composite boards WS-C, WSD-C. (01. 02 2009). Austrian Standards.

OENORM B 8110-3 -Thermal protection in building construction - Part 3: Determination of the operating temperature in summer (Prevention of summerly overheating). (01. 06 2020). Austrian Standards.

OENORM B 8110-6-1 - Thermal insulation in building construction - Part 6-1: Principles and verification methods - Heating demand and cooling demand. (15. 01 2019). Austrian Standards.

OENORM EN 15804 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. (15. 02 2020). Austrian Standards.

OENORM EN 15804: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. (15. 02 2020). Austrian Standards.

OENORM EN ISO 14040: Environmental management — Life cycle assessment — Principles and framework. (01. 11 2009). Austrian Standards.

OENORM EN ISO 8990: Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box (ISO 8990:1994). (1996, 10 01). Austrian Standards.

OIB-Guidline 6, NAT-T13 Energy saving and heat insulation. (2009).

ÖKOBAUDAT. (n.d.). (Bundesministerium des Innern, für Bau und Heimat (BMI)) Retrieved Juli 28, 2019, from https://www.oekobaudat.de

OTTO Chemie. (2013). Technisches Datenblatt OTTOCOLL® S 660. Fridolfing.

Pascha, V., & Winter, W. (2016). A comparative study on ecological impact of timber-glass-facade and conventional facade systems. In *WCTE World Conference on Timber Engineering.* Vienna.

Rinnhofer, M. (2017). Load-bearing timber-glass composites with a special focus on the long-term behaviior of silicone bond lines. Doctoral Thesis. Vienna: TU Wien.

Sustersic et al., I. (2016). Hybrid cross-laminated timber plates (HCLTP)-Numerical optimisation modelling and experimental tests. *World Conference on Timber Engineering (WCTE 2016).* Vienna.

VELOX Werk GesmbH. (2015, Juni). Retrieved from http://www.velox.at

W. Hochhauser, W. Winter, A. Fadai. (2013). Entwicklung von verklebten Holz-Glaskonstruktionen, Bemessung und Anwendung. In *Glasbau* (pp. 186-191). Berlin: Hrsg. Bernhard Weller, Silke Tasche; Ernst & Sohn.

Wagner, A. (2013). *Energieeffiziente Fenster und Verglasungen.* Fraunhofer Irb Stuttgart.

Wuppertal Institut. (2015). Konsistenz und Aussagefähigkeit der Primärenergie-Faktoren für Endenergieträger im Rahmen der EnEV.

www.thesim.at. (2018, 04 29). Retrieved 04 29, 2018

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