Timber-based Façades with Different Connections and Claddings: Assessing Materials' Reusability, Water Use and Global Warming Potential

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Abstract

Timber-based façade technologies have the potential to effectively reduce the carbon footprint, reduce water use in construction, and minimize waste, when their manufacturing process is highly prefabricated. Additionally, avoiding glue parts can enhance the sustainability of the façade as its elements can be replaced (extending the durability of façades and therefore buildings) and separated once that they reach their end of life (to re-use or recycle them). Thus, the connection between materials might have a considerable impact on the façade's sustainability. Moreover, timber-based façades can have different claddings, impacting on the water needed for the technology and their Global Warming Potential (GWP). This paper assesses, through a novel methodological approach, materials' reusability, water use, and GWP for different façade connections and claddings. Four prototypes with different connections (staples, screws, timber nails, and geometrical assembly) were built. Experimental activities representing façade elements' substitution and disassembly provided qualitative and quantitative information about production, extraordinary maintenance, and end-of-life phases. Through these tests, the quantity of material that could be re-used and disposed in such phases was quantified and then inserted in a Life Cycle Analysis (LCA). LCA was conducted using EF v.3.0 impact method and components were modelled with EPD information and Ecoinvent cut-off 3.7 database. According to the results, a timber-based façade with timber nails and wood cladding is the most promising of reusable façade materials, decreasing the water use and GWP.

Keywords

Wood construction, extraordinary maintenance, disassembly, End of Life, Climate Change Potential

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1 INTRODUCTION

According to the Circularity Gap Report of 2022, to keep the planet on a 1.5-degree trajectory, Greenhouse Gas Emissions (GHG) should be reduced by 39% from 2019 levels (Circle Economy, 2022). To reach such an ambitious target is of paramount importance to shrink global material use and extraction by 28%. As highlighted in that report, buildings and construction industry are one of the most impacting sectors in this regard, and thus interventions related to them are critical in reaching the aforementioned reductions. The Circularity Gap Report detected highly impacting interventions involving façade technologies: (i) treating construction materials in a circular way (reusing, recycling, or reducing the quantity), (ii) having resource efficient construction, and (iii) increasing durability of the façade technologies and thus of buildings.

With this evidence, when developing or comparing façade systems, special attention should be paid to (a) the emissions related to the selected technologies during their whole life cycle and water use, a precious resource, (b) the durability of façade elements, and (c) the possibility of reusing the façade materials once they reach their end-of-life. While a well-known method to quantify the emissions and water use exists, i.e. environmental Life Cycle Analysis (Hildebrand, 2014; Pittau et al., 2019), there are few works giving methods to measure the potential re-use of materials (Gubert et al., 2021; Heesbeen et al., 2021) and their application is not widespread. Moreover, end-of-life modelling might heavily impact the overall LCA results, and thus needs to be carefully investigated. LCA methods have already been used to compare a single-use façade against a reusable one (Cruz Rios et al., 2019). Yet, understanding which elements of the façade systems are reusable in a second life is still a difficult task and increases the uncertainty of modelled end-of-life scenarios. To overcome the lack of experience in façade reusability, Cruz Rios et al. (2019) proposed to evaluate the impact of the reusability rate thanks to hybrid LCA approach based on sensitivity analysis.

Façade systems should be designed not only for assembly, but also for their effective disassembly to (i) decrease the disposal of façade materials when their reach their end-of-life and (ii) to lengthen the lifespan of the façade system by substituting and upgrading their elements during their service life. However, the literature on design for assembly and disassembly is scarce. Denis and Dogan (2014) proposed a pioneer methodology to design façade systems with increased deconstruction capacity. According to this work, the connection types of façade systems influence assembly and disassembly sequences, and they suggest simple mechanical and dry jointing connections to allow disassembly without the destruction of adjacent parts. Another research work proposed an end-of-life tool for building product development, structured following the 4Rs of the Circular Economy Concept: Reduce/Reuse/Recycle/Recover (Gubert et al., 2021). This tool establishes a set of indicators to map the impacts of the evaluated building technology. From the technology point of view, Gubert et al. proposed connection systems, lifespan of the components and separability of the elements as the main parameters defining the suitability for the 4Rs .

The sparse literature on design methods boosting detachable façade systems and the lack of practical experience to evaluate replacement, disassembly, and reuse potential, makes it difficult to frame which connection systems and façade features are the optimal ones for the effective separation of the façade elements and future materials reuse. To face this gap of knowledge, the aim of this work was twofold: (i) developing experimental tests and LCA approach to assess façade technologies options' reusability and sustainability; (ii) evaluating the environmental performance of timber-based prefabricated façade systems with different connections among layers thanks to the new approach.

To the state of the art, these kind of assessment methods including prototyping and experimental tests are still uncommon but necessary to understand the disassembly and reusability potential of façade systems, to update façade elements through materials' substitution (increasing the overall façade service life), and to gain knowledge on the possible end-of-life scenarios for the façade elements, thus having more reliable data for the LCA modelling of this phase.

2 METHODOLOGY

This work assesses materials' reusability, water use, and GWP based on two methodological pillars: (i) prototyping and experimental testing of assembly and disassembly activities of different timber-based prefabricated façade options and (ii) LCA assessment of environmental impacts, using the information gathered in the experimental tests for the end-of-life modelling. The assessment compared timber-based prefabricated façade technologies with variations in the two key-features: the connections among façade layers and façade claddings.

The research activity was structured as follows:

1. Prototyping:
    a. Identification of possible connections among the façade layers of a timber-based prefabricated façade system and design of the functional prototypes.
    b. Monitoring the duration of the manufacturing process for each façade prototypes with different connections among layers.
2. Testing maintenance (removing and replacing) and end-of-life disassembly phases:
    a. Installation of the prototypes in the experimental test facility
    b. Monitoring the duration of the on-site partial disassembly, removal and substitution of materials. Visual control to identify damaged and non-reusable materials and quantification (% of the total area).
    c. Monitoring the duration of the off-site disassembly. Visual control to identify damaged and non-reusable materials and quantification (% of the total area).
3. Life Cycle Analysis
    a. Quantification of GWP and water use for the variations of timber-based prefabricated façades with different connections and cladding materials. LCA without and with a window.
    b. Illustrating the benefits of reusing façade materials: merging the impact of their second life with the first life-cycle.

2.1 PROTOTYPING

According to the literature exposed in section 1, different ways of assembling the façade layers impact on the elements' substitution and separation activities. To quantify the impacts of ways of assembling with experimental data, this research compared a state-of-the-art multi-layered timber based prefabricated façade technology (Fig.1) with façade systems with alternative connections. The proposition of the alternative connection system came out from the iterative discussions among the researchers and a timber-based façade manufacturer.

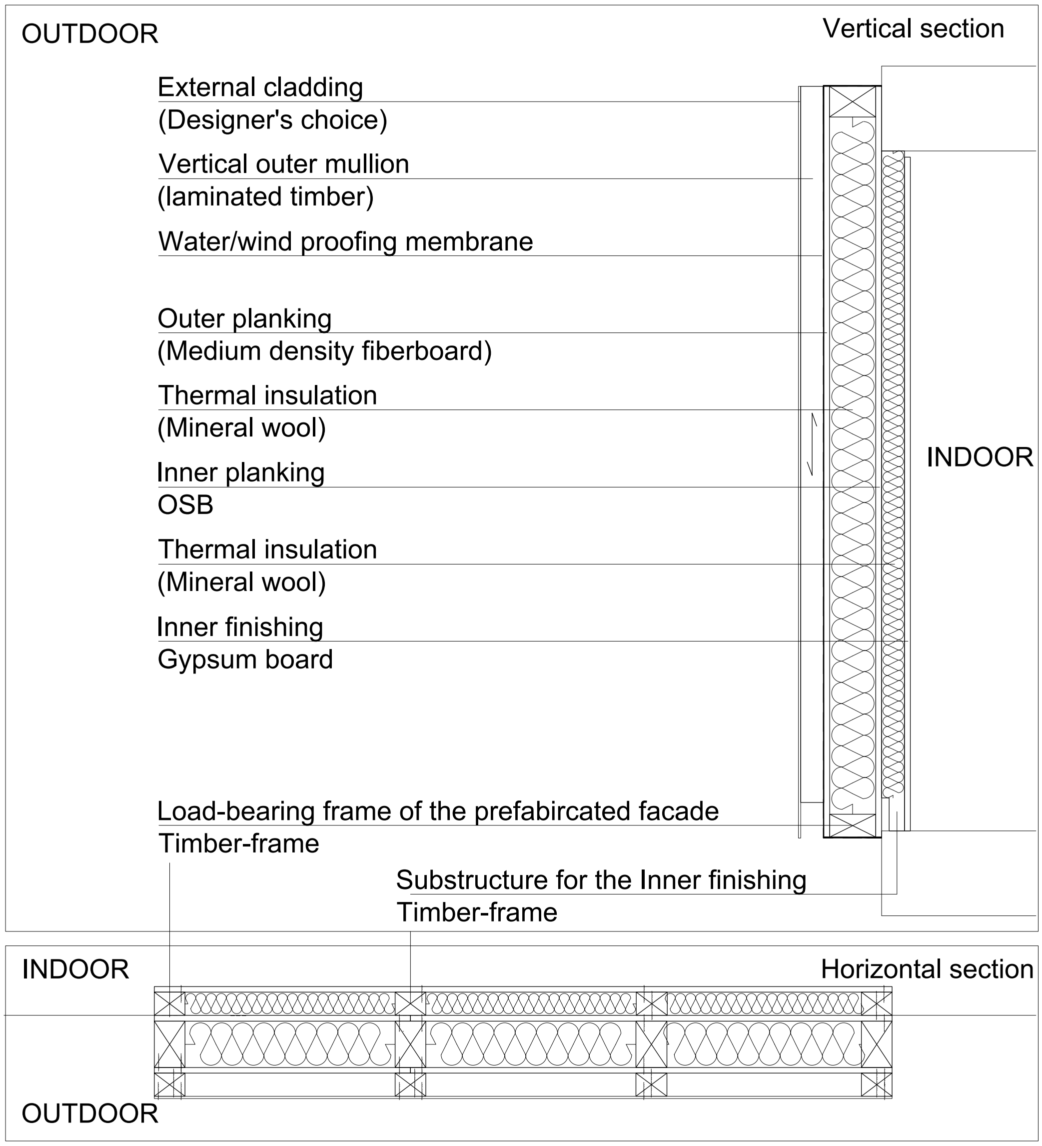
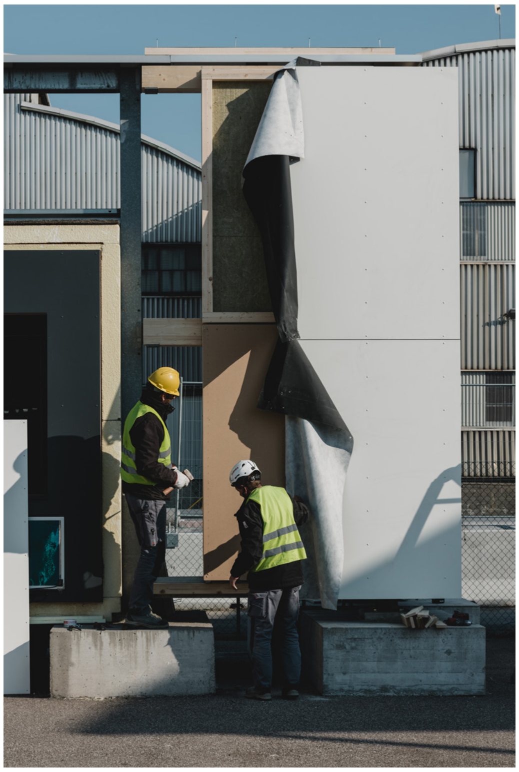


FIG. 1 Prefabricated timber-based muti-layer façade

2.2 TESTING

Four prefabricated timber-based façade prototypes were designed and manufactured as specimen for being tested through a dedicated experimental campaign. The duration of each activity related to the prototypes' manufacturing was monitored to quantitatively compare the differences between the façade connections. The specimens were then installed onto a metallic structure which emulates the slabs of a building, in order to carry out a partial on-site disassembly and insulation materials' substitution (Fig. 2).



a

b

FIG. 2 *Experimental activity to test the replacement of a façade layer. Image by Fiorentino.*

On-site partial disassembly and substitution of materials aimed at emulating a possible extraordinary maintenance activity. Even if nowadays the removal or substitution of the insulation layer is an uncommon maintenance activity, it might be a realistic operation in the future to optimize the façade performance to adapt to changes in boundary conditions or indoor requirements.
For instance, it could happen that the original insulation levels are no longer the optimal ones because of climate change and/or due to a change in the building use. Eventual technology developments could also bring novel insulation systems and replacing the existing static insulation layer could be a good strategy to reduce the energy demand of the buildings (Juaristi et al., 2022).
If the other façade materials are still in good condition, as a result of extraordinary maintenance activity they could be kept until they reach their end-of-life. Thus, this experimental test enabled the understanding of the separability of the different façade layers with different connectors when the façade is installed on the building. It also enabled the identification of the materials that could be re-installed once the insulation panel was replaced.

Afterwards, end-of-life activities were emulated to test the ease of separation of materials and their potential future reuse. For this activity it was assumed that it would not be done on site, but in a dedicated facility. Therefore, the four prototypes were dismantled from the metallic structure (Fig. 3) and the prefabricated façade elements were transported to a shed. There, the four prototypes were completely disassembled by workers, who were asked to separate the majority of the undamaged material in a reasonable amount of time (Fig. 4). The duration of this activity was monitored. Once the façades were disassembled, it was possible to visually check the materials that were damaged and to quantify the % of the area which was damaged by measuring the amount. Thanks to this qualitative and quantitative evaluation, potential reuse of material and the eventual reasons that could lead to a downgrading were established.

FIG. 3 Prefabricated façade elements were disassembled and transported to a shed to separate materials, to realistically emulate an end-of-life scenario.

FIG. 4 PEmulating disassembly activities in the end-of-life phase.

2.3 LIFE CYCLE ANALYSIS: BOUNDARY CONDITIONS & ASSUMPTIONS

To understand if the effective separation of the façade elements and reuse of future materials has a significant impact in the GWP and water use, a LCA must be done. Thus, OpenLCA software was used to quantify the aforementioned impact categories. EF v.3.0 adapted method was implemented along a cradle-to-grave/cradle life cycle and the four façade systems were modelled by using the EPDs of the façade elements, as provided by the supplier to the timber façade manufacturer. When EPDs were not available, Ecoinvent cut-off v.3.7 database was used. The information in this database was also used to model the "standard" processes related to the façade (e.g. transport, disposal activities…). The durability of each façade element was considered thanks to the EPD information and German information portal for sustainable buildings (*Nutzungsdauern von Bauteilen Für Lebenszyklusanalysen Nach Bewertungssystem Nachhaltiges Bauen (BNB)*, n.d.) [Lifespan of building components for Life Cycle Analyses according to the Sustainable Building Assessment System].

Table A, available in the Appendix, summarizes the characteristics of the multi-layered timber-based façade systems and the information used for LCA modelling, and highlights the parameters that were changed for each façade system. When analysing the differences between the connectors, no cladding system was modelled at all. This is because analysed prefabricated façade technologies offer high flexibility in terms of the cladding system. To assess the impact that the selection of the cladding would have, three representative façade claddings were modelled for a timber-based prefabricated panel with state-of-the-art connectors: two options for the ventilated façades, HPL claddings and wood claddings, and plaster claddings with no airgap.

The variations of the timber-based prefabricated façades were modelled for a functional unit of 15 m^2 and a U value of 0.15 W/m^2K. The system boundary considered the following life cycle phases: Production, Construction, Maintenance, and End-of-Life. These phases were modelled according to the following assumptions:

A **Production**: Façade manufacturing site is in Brixen (Italy). All the façade materials are purchased ready to be integrated in the façade systems. The origin of the materials was established based on the current suppliers of the timber-based façade manufacturer. This information was also used to model the transport accordingly (from the selling point to Brixen). EURO 3 transport of different dimensions were modelled according to the material's weight and dimension and the distance never exceed the 500km. On the other hand, the information from providers' EPDs enabled the modelling of the transformation processes from raw materials to façade elements. Specific manufacturing processes to transform façade elements into a timber-based prefabricated façade include cutting these elements to fit the size of the prefabricated module and to connect the different layers. In this phase, some mineral wool and plastic-based waste is generated (from insulation, joint-sealing tapes, water-tightness membrane, and packaging). The energy needed for this transformation included the electricity of the turning table and hand machines. 30% of this electricity comes from the photovoltaic panels installed in the factory, while the remaining 70% comes from a medium voltage electricity grid.

B **Construction**: a hypothetical construction site is located 300km from the factory. Thus, a >32tonnes EURO 3 lorry transport was modelled. In the installation process, the electricity consumed by the crane placing the prefabricated façade and the diesel for the lifting platform was considered, based on the calculations made by the timber-based façade manufacturing company. This phase also included the waste related to the packaging.

C **Maintenance**: according to the EPD, only wood claddings need maintenance activities. Two different analyses were carried out for two possible maintenance scenarios:

- Coating treatment of the wood cladding 7 times during its lifespan. For this activity, the diesel for the lifting platform was considered.
- Deinstallation of the wood cladding at the middle of its lifespan, substituting it with a new wood cladding and incinerating the old one. For this activity, the diesel for the lifting platform was considered. The transport was modelled considering a 16-32 tones EURO 4 lorry, both for the new cladding and old cladding transportation.

D **End-of-Life**: in this phase, it was hypothesized that prefabricated façade panels would be dismounted as a single element to be transported to the manufacturing factory in which disassembly and waste separation are expected to happen. Therefore, this phase includes a >32tonnes EURO 3 lorry transport, the electricity consumed by the crane removing the prefabricated façade, and the diesel for the lifting platform. To determine the way in which separated damaged material needs to be modelled, EPD information regarding disposal and recycling processes was considered. Not all of the materials are disposed or recycled; end-of-life phase was modelled considering the disposal and recycling of the materials that were identified as non-reusable in the experimental tests.

Initial LCA results referred only to the first life cycle of the façade systems and their materials. Re-usable materials were expected to have a second life and therefore, the impacts of using re-used materials instead of virgin materials would be accounted for when modelling their second life cycle. However, this way of illustrating the results did not highlight clearly enough the potential reduction of GWP and water use when the re-use of façade components is boosted. Therefore, the benefits of reusing façade materials were illustrated by merging the impact of their second life into the first life cycle. To do so, the positive impacts of integrating re-used materials in future façade systems were directly subtracted from the total impacts of the first life cycle.

3 RESULTS

3.1 POSSIBLE CONNECTIONS AMONG LAYERS

Currently, staples are used as connectors among layers. However, they do not allow such an effective disassembly of the different façade layers with the minimum harm, which is an essential characteristic of reused materials in their second life. For this reason, three timber-based façade systems with different layers' connections were proposed and compared with a state-of-the-art timber-based multi-layered façade. Proposed alternative connectors were (i) screws, expected to increase the duration of assembly and disassembly phases but causing less harm to materials when separating the façade elements; (ii) timber nails, expected to be similar to staples in terms of assembly and disassembly, but would have a lesser impact when disposing of them, and (iii) geometrical assembly (with milled mullions and no connectors at all), which is a more complex fabrication but the materials are not harmed when disassembling them.

3.2 PROTOTYPING AND EXPERIMENTAL TESTS: DURATION OF EACH PHASE AND ASSESSMENT OF REPLACEMENT, DISASSEMBLY, AND REUSABILITY POTENTIAL

The fabrication of the prototypes and experimental tests enabled the production times to be monitored as well as the validation of the hypothesis with which they were proposed. This production was mainly based on handcraft. Therefore, the results shown in Table 1 could be slightly different if specific automatized machinery was used for each process, adapted to each connection types.

TABLE 1 **Duration differences for fabrication, extraordinary maintenance and disassembly activities (the percentages represent the difference of that façade option respect the fastest solution in each phase)**

Connections	Stapples (1_SA)	Screws (2_S)	Timber Nails (3_TN)	Geometrical assembly (4_NC)
Production time	Best opt	+ 36%	+ 7%	+ 67%
Maintenance (Removing)	+ 500%	+ 125%	+ 50%	Best opt
Maintenance (re-installing)	+ 22%*	+ 111%	+ 44%**	Best opt
End-of-Life Disassembly	+ 98%	+ 35%	**Best opt**	+ 6%

* The same outer planking panel could not be re-placed in the façade again. A new board and staples were needed for the extraordinary maintenance activity
** New timber nails were needed in the extraordinary maintenance activity

The results demonstrate that state-of-the-art connections, the staples, are the fastest options to manufacture. However, as expected, they also are the slowest options when the components of this façade system need to be removed in an extraordinary maintenance activity (Fig. 2) or separated when they reach their end-of-life (Fig. 5 a). Fig. 2b highlights how the outer enclosure panel cannot be replaced if removed in an extraordinary activity because the holes of the staples are too many and too big. If staples are substituted with screws the disassembly time is shortened, and the same holes might be used for re-fixing the layers. Yet, the extraordinary maintenance (removing the insulation layer and re-installing disassembled elements) remains time-consuming. Timber nails showed overall better results, their production time being almost comparable to the staples; they are easily separable when reaching their end-of-life and need a reasonable time in an eventual extraordinary maintenance activity. The best option to ensure a fast and effective extraordinary maintenance was, as expected, the façade with geometrical assembly. However, it was also the most time-consuming in terms of its fabrication and the façade with timber nails had similar disassembly times.

Visual check of the façade components after the substitution and disassembly activities was essential to understand the reusability potential of the different types of connections of the four façades. Fig. 5 illustrates how, when disassembling the façade with the staples, part of the material was lost, such as the internal finishing plasterboard and the borders of the OSB and medium-density wood fibre boards (which were cut for a faster disassembly process). Moreover, part of the plaster remained attached to the wood mullions. On the contrary, when disassembling the façade with no connectors at all, the panels remained complete and free of damage. Only part of the waterproof membrane remained attached to the mullions. Regarding the façade elements with screws and timber nails, they were separated without harming them, except from the holes of the connections (Fig. 6).

a b

FIG. 5 Façade layers after the disassembly activity, for a prefabricated multi-layer timber-based façade joint with (a) 1_SA staples and (b) NC geometrical assembly. Images by Fiorentino.

The outcomes of disassembly activities were a useful input for the Life Cycle Assessment of different timber-based prefabricated façade options, as it enabled the detection of the material quantity that could be reused or recycled in the end-of-life phase. The measurement of the waste from disassembly process stated that for the façade with staple connectors, 75% of the area of the medium-density wood fibre boards and OSB panels could be reused, whereas for the other three connector types 100% would be reusable if the holes were not a problem in their future applications.

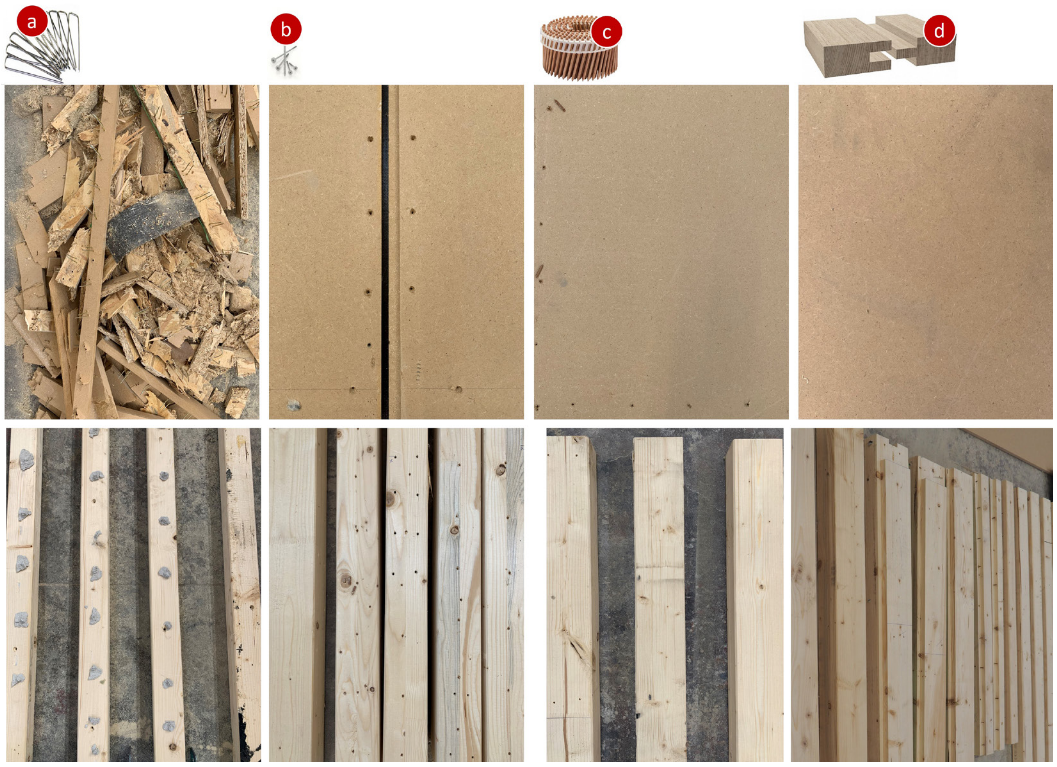
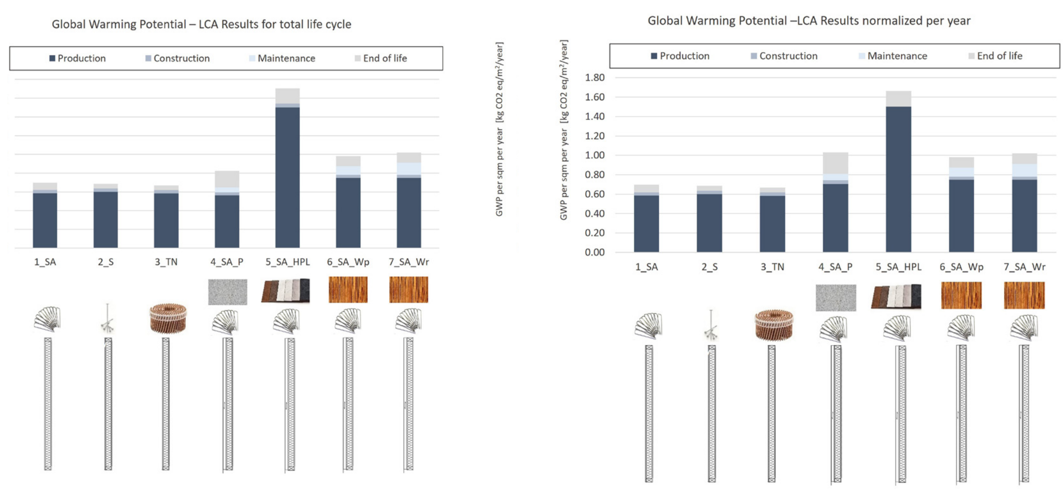


FIG. 6 OSB panels and wood mullions after the disassembly activity. The tests were carried out for four different connections between façade layers (a) staples and nails, (b) screws, (c) timber nails, and (d) interlockings. Images by the author.

3.3 LIFE CYCLE ASSESSMENTS FOR DIFFERENT OPTIONS OF PRE-FABRICATED TIMBER-BASED FAÇADES AND END-OF-LIFE SCENARIOS

Life Cycle Assessment results show the GWP differences of the analysed variations of timber-based prefabricated façades (for different connections and cladding materials). As illustrated in Fig. 7, the production phase is the one with the highest impact in the equivalent kg of CO_2 emissions. Surprisingly, when looking at total GWP results (Fig. 7a), the timber-based prefabricated façade with a plaster cladding (4_SA_P) is the one with the lesser impact during production, even less than the evaluated façade technologies with no cladding at all (1_SA, 2_S and 3_TN). This is because 4_SA_P does not have a medium-density wood fibre board panel as a front enclosure, because it is not commonly used when plaster finishing is adopted. Instead, the insulation layer is closed with wood fibre insulating boards, to which the outer plaster is applied. Thus, this result highlights the significant impact that medium-density wood fibre boards have in the GWP of the studied façades. Regarding the total GWP of the evaluated cladding materials, HPL panels are the most impactful ones. However, it should be noted that, according to the information given by the fabricators in the EPDs and the German information portal for sustainable buildings (*Nutzungsdauern von Bauteilen Für Lebenszyklusanalysen Nach Bewertungssystem Nachhaltiges Bauen (BNB)*, n.d.) [Lifespan of building components for Life Cycle Analyses according to the Sustainable Building Assessment System], the three façade claddings are not expected to have the same lifespan and maintenance requirements. A timber-based prefabricated façade with a plaster cladding (4_SA_P) is expected to last for a maximum of 40 years and coatings are the only expected maintenance activity in that timeframe. HPL can last 50 years, the same duration that is expected for the timber-based prefabricated façade systems. Wood façade claddings can also last up to 50 years if they are regularly painted (6_SA_WP) or if just the cladding is replaced once during the façade system's lifetime (7_SA_Wr). Taking these lifespans, the GWP results were normalized per year. Likewise, a timber-based prefabricated façade with a plaster cladding (4_SA_P) is no longer the façade option with the smallest equivalent emissions of CO2, but that with the timber claddings (Fig. 7b).



a b

FIG. 7 *Global Warming Potential (GWP) per square meter for total life cycle of different prefabricated multilayer opaque façade systems with different connection and cladding materials. 1_SA, 2_S, 3_TN scenarios have no finishing. (a) Total life Cycle Analysis results and (b) Total life Cycle Analysis results normalized per year for 40 years of lifespan (for 4_SA_P) and 50 years (for all other cases).*

Life Cycle Assessment were also done for a calculation unit including a window of 1.2m² in the calculation unit of 15m², and an installation layer (made of insulating material and internal wooden mullions), to better understand the impact of each façade component in the GWP. Furthermore, the obtained results were compared to those in the existing literature (Hildebrand, 2014). The impacts of three opaque façade typologies with a window were used from this research work and re-calculated by increasing their insulation layer to reach the same U-value considered for the timber-based prefabricated façades. The insulation material was estimated to be the same as proposed by Hildebrand in her work and only its thickness was modified to reach a U-value of 0.15W/m²K. To quantify the GWP of the additional insulation, the GWP calculated by Hildebrand for those specific materials was considered.

The results of Fig. 7 report the total GWP, that is not normalized to the expected lifespan. According to these results, the timber-based panel with HPL claddings would have a higher GWP than lightweight concrete façades with a with an External Thermal Insulation Composite System (ETICS) made of extruded polystyrene (XPS). On the other hand, timber-based prefabricated façade systems have lower GWP than a façade made of bricks and EIFS insulated with mineral wool. Its GWP is also lower than for ventilated façades with a concrete core, mineral wool, and aluminium substructure.

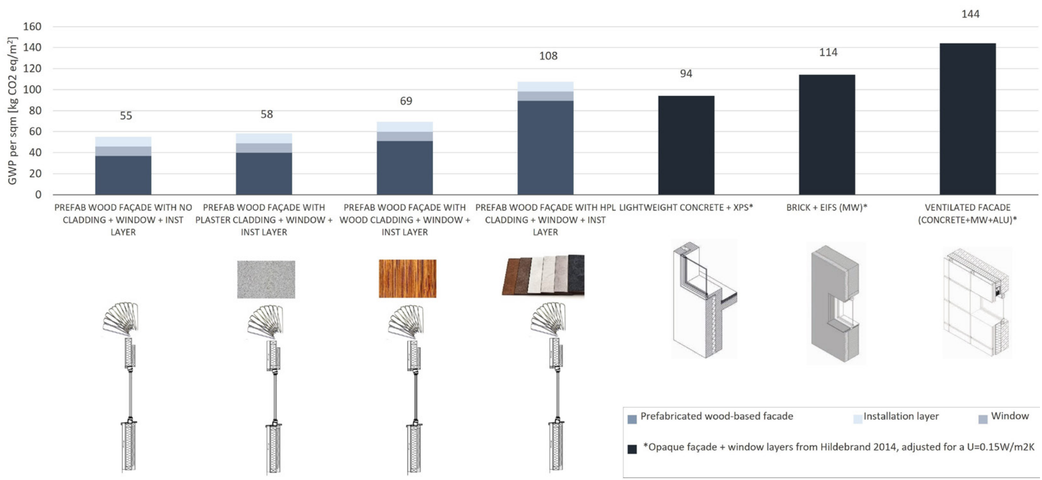


FIG. 8 Global Warming Potential (GWP) per square metre for total life cycle of different multi-layer opaque façade layers (U=0.15W/m2K) which include a window. Total Life Cycle Analysis results for Production, Maintenance, and End of Life Phases.

Fig.7 and Fig. 8 give interesting insights about the GWP of different variations of the timber-based prefabricated façades, but explaining how the reusability of its components could have a significant impact on the GWP and water use is not straightforward. With this aim, further Life Cycle Assessment calculations were done by considering in the analysed life cycle the benefits of reusing the façade components in a second life. The savings from not manufacturing these elements again are illustrated in Fig. 9, which shows the overall GWP and water use for all scenarios and their potential reduction according to the aforementioned method. According to the results of these graphs—which are not normalized to the annual impacts—if HPL cladding panels are reused once they reach their end of life, their GWP use is lower than for wood cladding. However, to do so, business models compatible with reusability should be applied and it is not clear how the HPL could be reused, as, theoretically, they would have reached their lifespan as façade cladding materials. Regarding the results for different façade layer connections, screws (2_S) and timber nails (3_TN) would enable a more significant reduction of the studied environmental parameters compared to the state-of-the-art connections (1_SA).

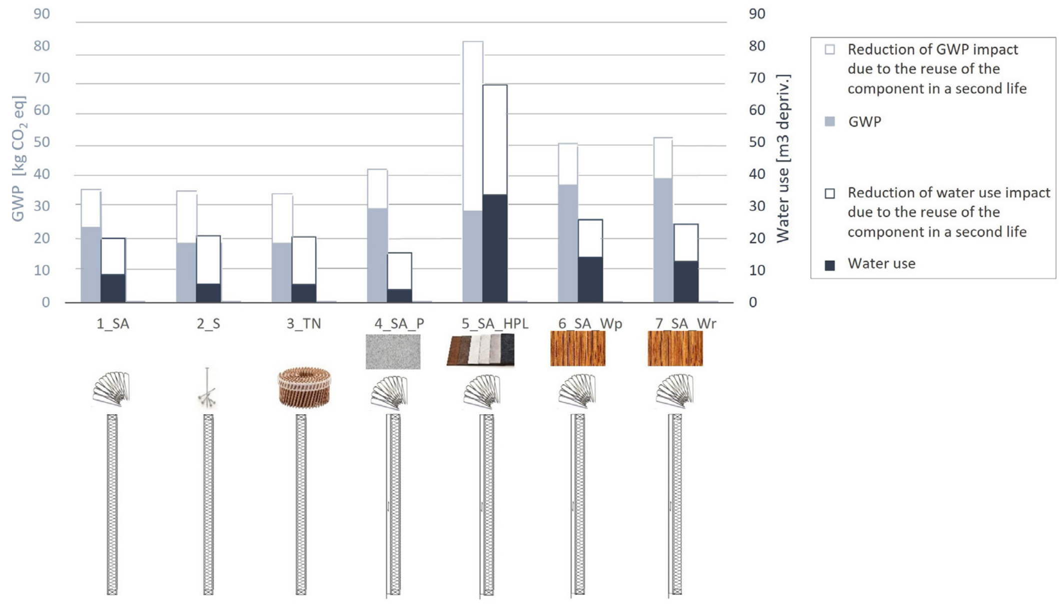


FIG. 9 *Global Warming Potential (GWP) and water use per square metre and its possible reduction if the components are reused in a second material life. Global results for total life cycle of different prefabricated multi-layer opaque façade systems with different connection and cladding materials..*

4 LIMITATIONS AND FUTURE WORKS

One of the biggest limitations of the present work was that façade materials were still new (not aged) when doing experiments for replicate extraordinary maintenance and end-of-life disassembly activities. Future works should find a method to age components of the façade elements before disassembling it, to perform disassembly activities under more realistic conditions. The results of these experiments suggest that timber nail connections might facilitate the disassembly of prefabricated timber-based façades without compromising their fabrication time nor the analysed environmental aspects. However, more detailed static evaluations are needed to guarantee that these connections are also suitable to meet the structural requirements. Similarly, the façade system with geometrical assemblies should be evaluated to test whether it provides enough structural safety against horizontal impact and suction effects in the ventilated chamber.

According to the LCA results, medium-density wood fibre board panels have a significant impact on the GWP. The maintenance of wood cladding with the evaluated coatings also have a substantial impact. Future works should investigate more environmentally friendly coatings for the maintenance of wood claddings. They should also identify cost-effective alternative materials for the front-enclosure of prefabricated timber frames, with the ability to give enough structural stability. Moreover, the emissions related to the transport of prefabricated elements can be reduced if the overall weight of the prefabricated façade element is reduced by optimizing the timber frame substructure and material quantity. Life Cycle Analysis quantified the possible reduction of the GWP and water use if the materials were reused instead of disposed of when they reach the end of their life. However, to reuse these components, the capacity to easily disassemble it is not the only target that must be pursued; the reusability of façade components will be only possible if the market is interested in it. Thus, future works should also focus on the possible business models aligned with the circular economy to sell the materials coming from dismountable timber-based façade systems.

5 CONCLUSIONS

The contribution of the presented work to the research field was a novel methodology to consider crucial aspects of sustainability in the façade system, namely potential façade disassembly for a future re-use of materials and how it impacts on the Global Warming Potential and water use of the façade system. These aspects were evaluated and quantified thanks to the real-scale prototyping activities (production, maintenance-removing and -replacing, and end-of-life disassembly phases) and LCA calculations. The results showed that current state-of-the-art connections (staples) enable a faster fabrication than studied alternative solutions (screws, timber nails, and geometrical assemblies, with milled mullions and no connectors between layers). The fabrication time of timber-based prefabricated façades with timber nail connections was only slightly longer than with staples. Surprisingly, façade systems with timber nail connections were the fastest ones when disassembling them in the end-of-life activity. Disassembled panels, though, remained with the holes where the nails had previously been placed, which could be a problem for some potential reusability, whereas the façade systems with geometrical assembly didn't have this problem. This last system had the best duration considering the extraordinary maintenance activities, but its overall suitability seems limited as its fabrication is more complex and longer in comparison to the other analysed façade systems. Besides, the reusability of the milled mullions could be limited due to its particular geometry.

Overall, according to the results of the present work, timber-based prefabricated façade systems have a lower Global Warming Potential (GWP) than other opaque façade typologies (taken as reference from other scientific studies) regardless the type of connections between layers. However, the selection of the cladding has a big impact on the GWP and water use. Timber-based prefabricated façade systems with HPL cladding have a much higher impact than those with wood claddings or plaster claddings, this last one being the one with the lowest equivalent CO_2 emissions. Timber-based façade with HPL cladding also has a higher GWP than a comparable lightweight concrete façade with an External Thermal Insulation Composite System (ETICS). On the other hand, HPL cladding requires less maintenance than wood and plaster claddings and have a longer lifespan. Indeed, the lifespan of the façade system has a great impact on GWP results. This is why the normalized results, according to the lifespan declared by the fabricators, show how plaster claddings are the less suitable option compared to the wood claddings, in terms of reducing the CO_2 emissions, because of their longer durability if expected maintenance activities are followed. This work also quantified the potential CO_2 emissions and water use reductions if the façade components were re-used in a second life. In such a scenario, timber nail connections and HPL claddings show a great opportunity to reduce environmental impacts if reused, and in this scenario, they would become the timber-based prefabricated façade system with the least equivalent CO_2 emissions.

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Annex

ROLE	ELEMENT	MATERIAL	DURABILITY (years)	SOURCE FOR LCA MODEL
External cladding*	Variable 1 Variable 2 Variable 3	Plaster HPL Wood	40 50 60	EPD-SON-20150247-IBA1-EN** EPD-FMX-2012111-EN
Connection of external cladding and water/wind proofing membrane**	Vertical outer mullion	Solid structural wood	50	EPD-RUB-20180059-IBB1-EN
Water/wind proofing	Foil-Membrane	Polyester and acrylic coating	50	Modelled by the authors with database's flows
Closing layer of the insulation, rigidity	Outer planking	Medium Density Fibreboard **, ρ=615 kg/m3,	50	EPD-EGG-20140196-IBA1-DE
Thermal performance	Thermal insulation	Mineral Wool, density ρ=60kg/m3	50	EPD-RUB-20180059-IBB1-EN
Load-bearing frame of the prefabricated façade	Timber-frame	Solid structural wood	50	EPD-RUB-20180059-IBB1-EN
Closing layer of the insulation and vapour barrier, rigidity	Inner planking	Wood based panels	50	EPD-EGG-20180107-IBD1-EN
Fastening of the inner insulation and connection of the inner cladding***	Vertical inner mullion	Solid structural wood	50	EPD-RUB-20180059-IBB1-EN
Inner finishing***	Gypsum	Gypsum	50	EPD-FER-20160218-CAD1-EN
Daylight, ventilation***	Window (transparent part, U=1.1 W/m2K, frame U=1.5W/m2K)	Glass and wood (frame)	**25**	Database

*For the supporting board. Plaster layer was modelled by the authors with database's flows.

** The EPD to model plaster cladding refers to the supporting board. Plaster layer was modelled by the authors with database's flows. Moreover, the façade system with the plaster cladding does not include vertical outer mullions nor an outer planking made of medium-density wood fibre board .

***Installation layers and windows were a variable parameter; thus they were not always modelled.