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Advancing Timber for the Future Built Environment

THE INTERLOCKING DOWEL SYSTEM - ECOBALANCE AND SCOPE OF APPLICATION

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ABSTRACT: This research examines manufacturing parameters for a novel, material-saving timber wall construction concept based on serial robotic fabrication and evaluates its assemblability using the Design for Assembly Index. By comparing specific wall construction methods, it identifies necessary process improvements for an efficient production line. Assembly, durability, and load-bearing experiments assess the feasibility of the new design and quantify its production efforts within a competitive threshold. The findings define its application range and compare its ecological and economic impact to timber frame and massive timber constructions. The study concludes that the innovative use of interlocking dowel joints can create a balance between resource and automation efficiency and that the resulting construction design is a viable solution for quickly manufactured adaptive buildings with a low wood consumption.

KEYWORDS: beech dowels, robotic manufacturing, dfma, mono-material construction, interlocking joints

1 – INTRODUCTION

Due to the high structural and physical requirements on buildings in Central and Northern Europe timber constructions of exterior walls are multi-layered and require complex production processes. Exterior walls have been largely prefabricated here for decades and are therefore highly standardized and systematized. Still there exist over a hundred different designs of Timber Frame Construction (TFC) and over ten designs of Mass Timber Construction (MTC) plus a handful of innovative timber wall systems such as LEKO and RIPA [1]. To choose the right wall construction type for a certain building one must consider the necessary design flexibility and the desired level of automation (LoA) and production setup of possible manufacturers, which is hardly possible within public tendering.

Compared to wall construction methods using steel or minerals, the processing times for the partially or fully automated production of exterior walls made of wood are particularly high [2], [3]. This is not due to a lack of dedication on the part of the craft-based timber construction industry towards technical aids, as the timber construction industry has been relying on partial automation in the prefabrication of building elements for decades [4]. It is rather due to the geometry of trees and properties of wood itself, which inevitably requires lots of joints to produce larger building components like walls. The high degree of complexity and the number of layers of most timber wall structures result in a relatively high manufacturing and assembly effort [5].

Due to the high structural requirements placed on them, particularly lightweight or non-solid, material saving exterior walls made of wood, involve a high level of production effort. The production and assembly of the walls therefore offer the most important starting point for evaluating the efficiency of a construction concept and for shortening throughput times, reducing costs and positively influencing the competitiveness of the executing companies. There are two approaches to achieve this:

(a) increasing the level of automation in production
(b) adapting a novel wall construction design laid out for automated manufacture and assembly

Using a new type of construction method (Fig. 1), this research aims to examine how a fabrication aware design of a timber wall system (b) can help reducing the number of components and individual parts in resource efficient timber construction and lead to a reduction in the number of production steps. The resulting design consequences are then analysed in their ecological context.

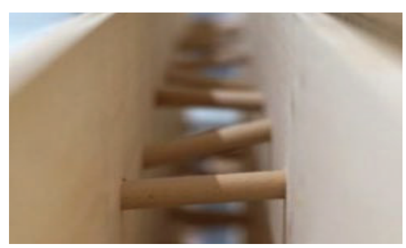

Figure 1. *interior of a hollow IDS wall prototype*

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1.1 THE INTERLOCKING DOWEL SYSTEM

The project builds upon a novel wall design that is easily manufactured (without the need for two sided operations or turning the elements) while reducing the mass of the wall through a double-layered approach with a non-solid core (see Fig. 2), filled with insulation. Inclined tight-fitting dowels connect the shell parts to make use of load redistribution effects. Due to the oblique positioning of the dowels, the whole structure is interlocked. Therefore, it does not require screws nor additional manufacturing steps that would otherwise be required to fasten the structure. The result is a relatively simple composition of laminated veneer lumber (LVL) as shell, soft wood fibre insulation as core, and reinforcing beech dowels, called Interlocking dowel System (IDS) [6].

Figure 2. *Mounting of a hollow IDS Wall Prototype (left) and finished installation (right)*

Robotic manufacturing Setup

The IDS emerged from a production- and assembly-oriented design that is geared towards a robotic production line with serial kinematics. Robots with serial kinematics can execute complex trajectories and allow a high number of degrees of freedom (DoF) during production. They are not a specialized solution for one consistent task, such as a framing station or a nailing bridge, but a flexible platform for placing individual effectors for individual operations. Due to their comparatively low investment costs and spatial requirements, they also represent an easy-access opportunity for the efficient production of individual components, once the generating of the production data is working autonomously.

The bottom-up design approach of the IDS reflects the constraint spaces of a low-cost industrial robot (Kuka HA60). It can be used for drilling the holes with a self-build aggregate for deep hole drilling as well as inserting the dowels with a gripper and (where appropriate) anchoring the dowel heads with a nail gun for wooden nails, all at one comparably small workspace using a tool changing system (Fig. 3).

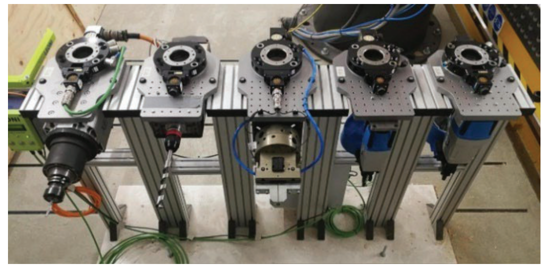

Figure 3. *Tool station for the automatic swapping of effectors, from left to right: high frequency milling tool, drilling aggregate, gripper, nail gun (F60) and (F44)*

It was shown that the necessary production steps can all be automated and that the production time can be held very low due to the production-oriented design [7]. Due to the fitting of the dowels in blind holes, there is no turning process needed, and the number of connection points compared to the TFC and MTC can be reduced drastically. The positioning of window and door openings within the wall is not bound to the axis-centre distance of the studs. Possible users for the IDS are therefore companies in the prefabricated single family housing sector that want to meet high design standards and individuality requirements but equally save material.

Relative Manufacturing and Assembly Complexity of Dowel Connections

We distinguish between the following groups of manufacturing processes: Primary forming, forming, cutting, joining, coating, material property modification [8]. Due to their tectonic nature, the two primarily manufacturing operations required in the manufacture of timber walls, are cutting and joining. Regarding the competitiveness of the innovative fabrication-aware light weight timber wall design it is necessary to analyse the time needed for the cutting and preparing of single parts such as dowels (referred here as manufacturing) and for joining them with the LVL (referred here as assembly).

When comparing the manufacturing and assembly time of different dowel connection types (adhesive bond, mechanical, friction based and enhanced friction based), a divergence between the resulting manufacturing and the assembly effort becomes apparent. They are either easily manufactured or easily assembled.

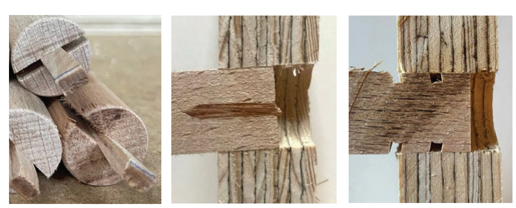

Figure 4. *Slit and mechanically anchored dowel end (left and middle), ridged dowel ends for enhanced friction-based approach (right),*

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The implementation of different test specimens with different connection types has shown that the manufacturing and assembly time for the respective variants varies greatly. The relative manufacturing complexity of these four connection types is not proportional to their relative assembly complexity. Although glued dowel connections are easy to produce because no additional physical preparations must be made to the dowel or bored holes, attention must be paid to the contact pressure, size of the glue joint and the open gluing time, as well as temperature and cleanliness (no dust) during installation.

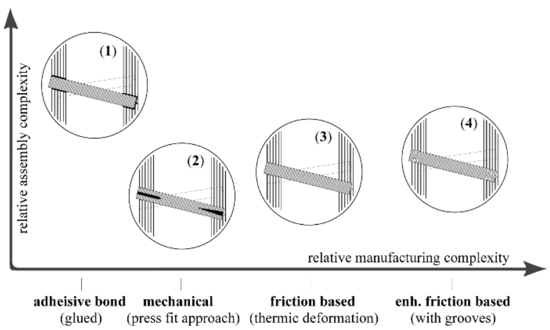

Figure 5. *Intersections of different dowel connection types and comparison of their relative manufacturing and assembly complexity*

From a manufacturing point of view, the glued (adhesive based) connection would be advantageous, but from an assembly point of view, mechanical anchoring (force-based) would be preferable. Measured in terms of overall production time and structural capacities, the glued variant is nevertheless the most promising and easiest to automate.

1.2 AUTOMATION IN THE PRODUCTION OF TIMBER-BASED WALL SYSTEMS

Unlike physical automation, cognitive automation in the building industry is always limited. Decisions cannot be made without human interaction as the manufactured walls underlay an obligatory security check and must be approved by a representative of the company.

When it comes to the construction of IDS walls both the planning process and the robotic production process are automated to a certain point. An ensemble of algorithms allows for cognitive automation by distributing the points of origin of the dowel connections over the corresponding individual wall geometries (shapes) in a load-reflecting manner, generate trajectories for the manufacturing and assembly operations, sort them according to production requirements and convert them into G-code without the need for human interaction. Regarding a scale of ten levels of automation this corresponds with a cognitive LoA of five.

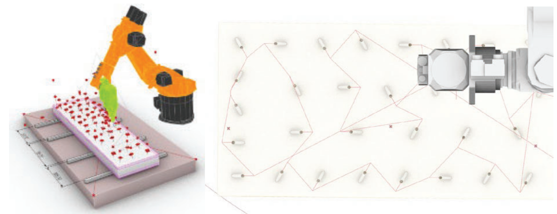

Figure 6*. Simulation and automated processing of production data*

At the physical level, the LoA of the production of IDS remains at the same stage. This is due to the prototypical level of the research laboratory where IDS specimen where build in, as no (external) sensors were used here to enable autonomous robotic manufacturing. However, it is foreseeable that a higher LoA could be achieved with the appropriate equipment.

In comparison, the automated production and assembly of TFCs already applies a relatively high LoA (between 6 and 9) both cognitive and physical [5]. However, a high LoA does not only bring advantages.

With regard to the automation of manufacturing processes, it is stated that the competitiveness of a production line is linked to a medium LoA (6-8) and that a higher LoA can even have negative effects [9]. If the LoA is too high, there is a risk of "overautomation". This is associated with loss of expertise, increased investment and maintenance costs, as well as high lead and operating times. This gives reason to assume that not every wall design has the same optimum LoA.

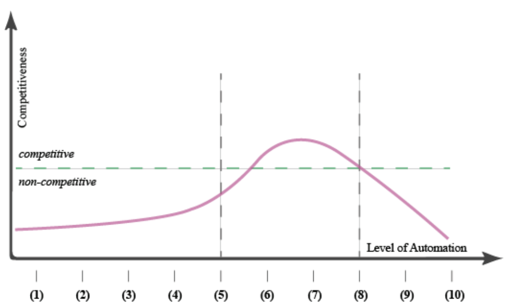

Figure 7. *Adequate Level of Automation for the manufacturing of timber walls, based on Säfsten (2007)*

Automation vs. Flexibility

Flexibility and design variety prevent a high degree of automation (LoA) on both a physical and cognitive level [10] [11].To implement individual wall geometries in a highly automated approach, production and assembly processes are simulated beforehand to check buildability right from the design stage. For this purpose the production line must be precisely known and as flexible as possible an adequate LoA must be defined.

A high LoA is not helping with higher productivity as such. Boothroyd observed that the design of a product can have a greater influence on the productivity of the production line where it is manufactured, than the LoA of the production line itself [12]. He therefore developed the Design for Assembly (DFA) Method, which is a tool that helps redesigning products in a way that makes them aware of the associated manufacturing efforts. This can be considered in the manufacturing and automation strategy for the efficient implementation of corresponding IDS wall elements as well.

Thus, compared to TFC and other non-solid wall designs, the IDS aims to reduce the number of connections and assembly operations overall. At the same time, the already very low material consumption of the referenced TFC wall sample (0,075 m³/m²) may not be exceeded.

2 – COMPARING TIMBER WALLS

The comparison of the manufacturing and assembly complexity of the here shown five different timber wall types is based on 20 m² wall samples, designed for the load-bearing capacity of three-storey residential buildings and to comply with a thermal transmission coefficient of λ = 0,035 W/(m²K). The operations needed for the installation of the facade layers are not considered. Only the production of the load-bearing section is analysed. Reports from German and Luxembourgish timber construction companies were used to validate the data. The fabrication set-up varies between robot-based (serial kinematics) for LEKO- and IDS-Walls as well as semi-automated linear production lines (parallel kinematics) for MTC-, TFC- and RIPA-Walls.

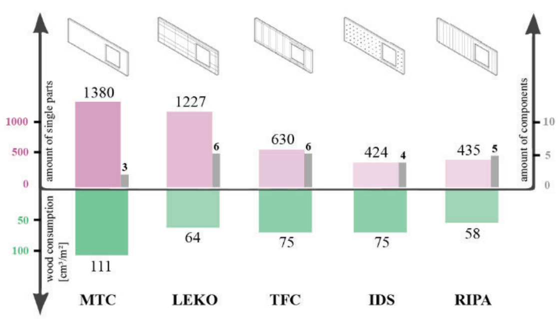

Figure 8. *Number of components and single parts needed for the construction vs. wood consumption of different wood based wall types*

While other robotically manufactured individual timber-based panelised wall systems such as the LEKO system or fully automatically manufactured standardized wall systems such as the RIPA wall from Metsä consume even less wood, the IDS stands out in terms of extremely low part counts and number of involved components. Within the group of material-saving, light-weight timber wall systems (TFC, RIPA) however it shows reasonable values concerning possible automation strategies (Fig. 5). Next to TFC and RIPA it seems to be competitive, especially if it undertakes the advantages of adhesives in its dowel connections instead of additional mechanical fasteners.

2.1 ASSEMBLABILITY EVALUATION

The effort required during the assembly of a certain construction design depends on various countable and not countable factors. The comparison shown here focuses on the number of different components, the total number of parts, the number of tool changes required for the operations and the number of consecutive work steps.

As part of automating joining processes in manufacturing, high-volume product designs must be improved to reduce operation time. Several methods have been developed to facilitate the evaluation of semi-automated and fully automated manufacturing processes. The different approaches can either help to develop fundamentally new design concepts that are designed for a specific production line or aim to improve an existing design as done here.

To compare the ease of assembly of automated prefabricated timber wall types, the shown analysis uses the DFA index. This indicator is strongly focused on the number of individual parts required and the associated assembly time. Unlike comparable methods, it is based on a simple calculation and not on fixed score values within an evaluation matrix based on keywords. It is calculated by multiplying the number of necessary parts by the assembly time per part and dividing the result by the total assembly time.

When applying the concept of DFA on the offsite assembly of timber walls, we only look at assembly times this means, the joining of components as well as the assembly and the setting and preparation of individual components, not the preparation time needed for the single parts.

Table 1 displays the varying number of operations of the studied timber walls and their associated assemblability. On average, the wall designs based on robotic manufacturing require fewer work steps than MTC and TFC. Comparing the most time-consuming operations it becomes apparent, that within solid construction it is the placement of the lumber, while in non-solid construction it is the installation of the connections that stick out.

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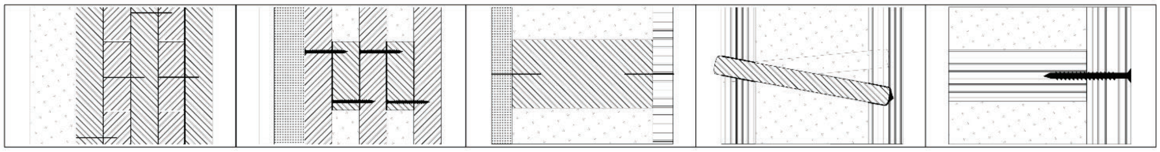
***Table 1**. Design for Assembly Index of MTC, LEKO, TFC, IDS and RIPA Walls*



MTC Wall (semi-automated linear prod. line)		**LEKO Wall** (robot based vertical prod. line)		**TFC Wall** (semi-automated linear prod. line)		**IDS Wall** (robot based vertical prod. line)		**RIPA Wall** (semi-automated linear prod. line)	
assembly operations	DFA Ind.	assembly operations	DFA Ind.	assembly operations	DFA Ind.	assembly operations	DFA Ind.	assembly operations	DFA Ind.
1. place lumber	0,33	1. place lumber	**0,05**	1. framing and stud fitting	**0,19**	1. place sheeting and insulation	**0,22**	1. place studs	0,31
2. apply adhesive	**0,12**	2. fasten screws	0,64	2. bring down sheeting	**0,11**	2. drill oblique holes	0,42	2. apply adhesive	**0,11**
3. fasten structure with nails	**0,31**	3. apply adhesive	**0,16**	3. insert nails	0,25	3. insert glue	**0,13**	3. place sheeting	**0,05**
4. place insulation panels	**0,12**	4. place insulation strips	**0,15**	4. turning the wall	**0,06**	4. insert beech dowels	**0,23**	4. fasten structure with screws	**0,29**
5. fasten insulation panels wirh nails	**0,22**			5. bring down insulation and second sheeting	**0,14**			5. turning the wall	**0,06**
				6. insert nails	0,25			6. bring down insulation	**0,18**
								7. insert nails	

3 – ECOBALANCE OF TIMBER WALLS

Life cycle assessment (LCA) is a method for quantifying the environmental damage associated with a product. In the case of a wooden wall, the analysis covers the production including upstream processes (A1-5), the use phase (B1-7) and disposal (C1-4). Raw, auxiliary and operating materials are considered [13], [14]. When looking at the building level, the actual measured emissions over the entire life cycle are not specified, as aspects such as maintenance, disposal and dismantling are often far in the future. Instead, model-based assumptions are used as the basis for the assessment. The preparation and process of the assessment is regulated in different standards (ISO, EN and DIN).

3.1 TIMBER WALLS AS A CARBON SINK

Wood as a building material offers the possibility of showing negative CO_2 emissions in the production phase, as the carbon is stored in the material in the long term. This way most timber products can be declared as low-emission or even carbon-negative.

Resource-saving construction methods are less relevant in this consideration, as they do not serve as quick solutions for the long-time fixation of carbon. For example, solid construction based on CLT is generally used in the comparison of mineral construction and timber construction [15]. But even though wood is renewable many countries buy wood from abroad to cover their current per capita wood consumption. If this wood comes from less strictly regulated forests or virgin forests in which cleared areas are left behind, this can lead to a spreading drought, which in turn favours forest fires that further reduce the remaining forest areas [16]. In addition to this, cheap timber products and construction methods, which often make a profit possible in the first place, go hand in hand with extreme emissions in production or long transport routes.

A less error-prone approach for environment friendly constructions would be preferring a material saving construction method over mass timber solutions.

Controling Construction

Prominent voices from political bodies such as the Federal Ministry of the Interior and Community in Germany or the International Institute for Applied Systems Analysis lay their focus on resource-intensive timber construction by perceiving it as a carbon storage and recommending a targeted selection of low-emission building products [15], [17].

A result of this logic are certificates, like the QNG seal, which is a prerequisite for federal funding for efficient buildings. It evaluates the efficiency of a building project based on the material used. This can indirectly create a competitive advantage for resource-intensive over resource-saving timber construction elements [14] and result in needlessly high wood consumption. To give a broader view of the ecological impact of timber walls we oppose the ΔOI3 indicator, the carbon storage potential and the wood consumption in the following comparison.

3.2 CARBON STORAGE, DELTA ECO INDICATOR AND WOOD CONSUMPTION OF TIMBER WALLS

The following comparison of the ecological effects of different wall constructions is based on the Delta Eco-Indicator 3 (ΔOI3). The advantage of this method lies in the simple handling and the comparability of the numerical values in contrast to the complex data profiles of a complete LCA. In the assessment, the individual layers of the wall constructions are analysed and given a score that reflects the environmental impact of the respective component layers. Among other things, the primary energy consumption from non-renewable sources, the global warming potential and the acidification factor are assessed. This covers the main environmental impacts of production. The lower the score, the lower the environmental impact of the production of a component layer.

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This evaluation system can be used to evaluate individual component layers as well as complete constructions and buildings. To compare the different wall constructions, their component-specific eco-indicator is calculated (ΔOI3BS), which is also known as the delta value. The ΔOI3BS values facilitate the identification of "ecological heavyweights" within the construction.

The environmental product declarations (EPD) of the materials used in the shown walls are depending on the respective energy mix flowing into their production. This can have a negative impact on the life cycle assessment of the materials used. To achieve a fair comparison of IDS with other timber walls, materials with EPDs from the same country of origin and based on equal technical standards had to be used. The referenced data originates from current studies on the *Schuhmacherquartier* [18].

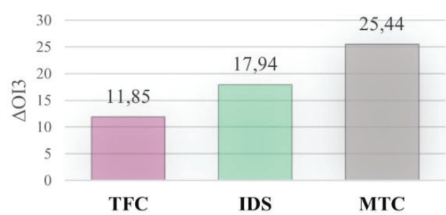

Figure 9. *Eco-indicators (ΔOI3) of the different wall types*

It was found that particularly the energy required to produce the soft wood fibre has a negative impact on the ΔOI3 indicator of timber wall structures. Even though soft wood fibre insulation has twice the carbon storage potential per m² of wall surface as cellulose insulation its ΔOI3 indicator deteriorates because the production consequences (non-renewable primary energy) are so high. Overall, this accounts for approx. 20% of the delta value (module A) (17.94 to 23.72), whereby it accounts for 50% of the storage potential.

For this reason, cellulose insulation was chosen for the IDS structure, as it is used originally in the compared TFC structure as well.

Also, the heat transfer coefficient of the wall structures had to meet the same requirements to maintain comparability. The compared structures from the assemblability analysis above (IDS, TFC and MTC) are here extended with individual external insulation layers so that they comply with the same insulation values (0,16 W/m²K).

For evaluating the thermal building envelope, the balance limit BG0 was defined. This means that the assessment is only carried out up to the rear ventilation level, which implies that the façade system is not taken into account. Likewise, foils such as vapor barriers and wind seals are not included in the assessment. (IBO, 2023, P. 18) [19]. The varying individual external cladding of the walls under consideration was also not considered when comparing the wall thicknesses.

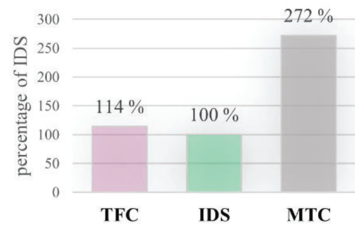

Figure 10. *Carbon storage potential in different wall types*

In terms of the eco-indicator criteria (ΔOI3), the IDS does not perform better than the established timber construction methods. However, a look at the pure raw material requirements and timber requirements shows that the IDS (with additional insulation layer) has the lowest material consumption with comparable building physics performance and at the same time requires a lower wall cross-section than MTC and TFC, resulting in a larger usable floor area.

One aspect that is not considered in the comparison of the different wall types, is the reduction of metallic connectors in IDS components. Due to the purity of the materials involved, it can be assumed that the probability of reusing IDS elements (instead of thermal recycling) is significantly higher than with the competing construction methods.

For the comparison of wood consumption, the different specific densities of the used timber products was deducted. With the highest wood consumption of around 0,11 m³ timber per square meter wall surface [18], MTC serves as reference in the comparison of the potential wood consumption of the analyzed walls. Compared to TFC the IDS uses a similarly low amount of solid wood per square meter wall element.

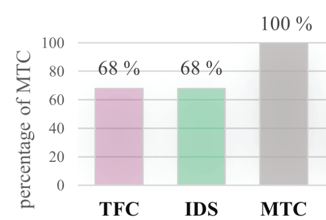

Figure 11*. Potential wood consumption of different wall types*

3.3 LOAD BEARING CAPACITY OF MONO-MATERIAL DOWEL CONNECTIONS

Calculations on the FE model have shown that the stiffness of the dowel connection is decisive for the performance of the overall construction of an IDS Wall [7]. Exploratory tests with mechanical (press-fit), friction based (thermal deformation) or glued (adhesive-bond) connections of beech dowels (d = 20 mm) and laminated veneer lumber panels (d = 27 mm) made it possible to determine the respective stiffnesses. When comparing the test results, it was evident that the polyurethane-based glued test specimens had the highest pull-out resistance (4-6 kN).

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The enhanced friction-based dowel connections based on the shrinkage and swelling effects of the beech wood after a drying process, with additionally increased friction due to vertical slots (grooves), achieved higher pull-out resistances (4-5 kN) than mechanically anchored dowels (2-3 kN) and are not far behind the values of materially bonded (glued) dowels overall. With thermally or mechanically anchored dowels, however, there is concern that the relaxation effects in the joint pose a considerable risk over the service life. This risk must be observed and defined more precisely with the help of thermal simulations and endurance tests over one or more annual cycles.

These observations go hand in hand with Hu et al. (2022), who demonstrated in a similar scenario that glued dowels can double the load-bearing capacity compared to plugged (friction-based) dowel connections [20]. In addition, recent studies by Fraunhofer IFAM have demonstrated that bio-based glutin glues have an adhesive strength comparable to commercially available synthetic petrochemical adhesives [21], [22]. This could help to drastically lower the threshold and environmental concerns for the use of adhesives in timber products.

Even though wall specimen (2,5m x 0,65 m x 0,2 m) with glued dowels reached a similar vertical load-bearing capacity as those with mechanically anchored dowels (195 kN), from a practitioner’s point of view the preparation and spreading of the dowels is more time consuming and therefore less functional. When focusing on mono-material structures with the potential of disassembly and reuse, the enhanced friction-based variation would be preferable.

4 – OUTCOMES AND REFLECTIONS

The function of the dowels as connectors and spacers at the same time (and thus enlarging the load-bearing wall cross-section) makes the IDS a particularly production-friendly wall structure (design) compared to TFC and MTC constructions. In comparison, it requires the lowest count of individual parts and assembly operations.

The experimental load tests of IDS walls samples showed that automatically assembled IDS walls (with low-resource cross-sections), and glued connections could potentially be used in three to six-storey buildings. This also includes roof extensions, interior walls and small-scale architecture like temporary structures and stages. The minimal manufacturing constraints when arranging window- and door openings and the low wall thickness, offer planning advantages and greater design freedom.

When evaluating the environmental impact of individual component layers using the Delta Eco-Indicator 3, it becomes clear that the degree of processing of the building materials plays a decisive role. Each production step causes environmental impacts that are reflected in the impact indicators. A manufacturer has several options for improving these ratings, for example by using modern exhaust filters, switching to green electricity or converting production to more efficient manufacturing technologies. However, a much more immediate solution is to choose a resource-saving, easily automatable construction method.

To notably fall below the ΔOI3 value of MTC, IDS must work with more ecological insulation than soft wood fibre. Therefore, the production strategy of the IDS must be adapted in a way that the insulation does not also have to act as a spacer between the LVL panels during drilling. This way the IDS construction method can retain the advantage of robotic manufacturing and still offer a valuable balance of resource efficiency and automation.

5 – CONCLUSION

This research demonstrates that the degree of automation and production speed in wooden wall construction are closely tied to its core design principles. Identifying and addressing production bottlenecks is crucial to improve economic efficiency. With the applied approach for evaluating and comparing the assemblability of exterior timber walls, alongside material consumption, storage potential, and eco-indicators, a novel evaluation method is given at hand, that highlights possible correlations between wood consumption and assemblability, enabling practitioners to determine the most suitable wall structure for their application.

The findings indicate that the ecological impact of the IDS and its manufacturing affordances are relatively low, compared to conventional wall designs. It offers a resource-efficient solution for the rapid production of adaptive buildings up to six-story height. However, further research is needed to assess key aspects such as mechanical performance, durability and fire safety.

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