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MONO-MATERIAL TIMBER CONSTRUCTION RE-INVENTION OF PRESS-FIT TIMBER CONSTRUCTIONS

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ABSTRACT: The paper presents the development of a building system made from solid timber that fulfils the requirements of modern buildings while expanding the design possibilities through re-inventing traditional timber techniques. Press-fit-timber connections, which were the basis of centuries-long building traditions all over the world, can be cost-efficiently used in contemporary buildings using modern manufacturing techniques.
The main goals of the research are:

- Develop a building system with mono-material timber structures (in contrast to hybridization with concrete and steel)
- Optimize the recyclability of building structures: Design to disassemble (on the level of the building and components)
- Improve cost-efficiency by industrial manufacturing methods for mono-material timber constructions.

KEYWORDS: Mono-material timber construction; building system; adaptability; recycling; design to dissemble;

1 INTRODUCTION

Before the advent of industrialization, timber was one of the essential construction materials due to its local availability, easy workability, good load bearing, and overall structural properties. For centuries, carpenters built impressive timber constructions without metal fasteners. Europe and Asia have a wealth of historical examples of timber joints for the widest variety of load cases and construction designs. Multi-story, large, and complex buildings were constructed with purely timber-based methods and only press-fit timber joints.

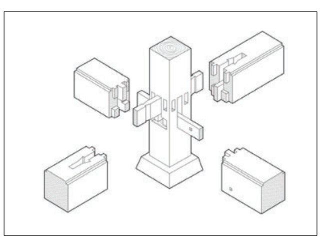

Figure 1: *Yatoi-Hozo-Sashi, three-dimensional joint of the Ashikatame post (main post), graphic: DGJ Architektur, based on Sato Hideo and colleagues [1].*

But this tradition fell into disuse in the wake of industrialization. Not only were such joints – made by highly skilled craftsmen in a time-consuming and thus wage-intensive manner – replaced by cheaper metal fasteners such as nails, screws, and bolts, but even timber itself was displaced as a primary construction material by new materials such as cast iron, steel, and concrete. To this day, these materials are sold at lower prices because they can be produced in higher volumes, and their external costs, especially environmental costs, are left out of the pricing equation. And even though solid timber has many advantages compared to other construction materials. Timber requires less energy than concrete or steel for its production. As a renewable resource, it stores atmospheric carbon during the lifespan of the building. Timber is central in the current discourse on carbon-neutral, energy- and resource-efficient construction [2]. The ecological and economic advantages make mono-material timber systems an interesting alternative for efficient and sustainable buildings.
In order to make the most efficient use of these opportunities, this research operates on two levels. On a first technological level, it offers transferable solutions for the local and the global structure of multistorey residential buildings, which are accompanied by an easy-to-use Excel tool for estimating the dimensions of the primary structural components. On a second architectural level, the research explores how the building system called '*Open Architecture*' [3] can be used to design a wide variety of flexible and adaptable residential buildings. It enables flexible, sustainable, and cost-effective construction with press-fit timber joints that can be easily recycled, and a design that adapts to the respective circumstances without sacrificing design quality and living comfort.

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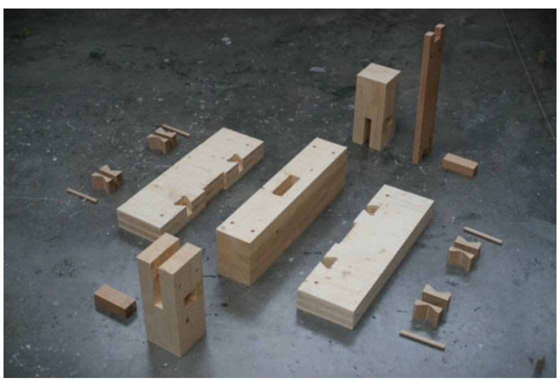
2 PRESS-FIT TIMBER CONSTRUCTION SYSTEM

Thanks to advancements in digital design and production technology, it is now possible with computer-controlled machines to produce perfectly fitting joints economically, regardless of the geometry's complexity.
New computational design and digital fabrication promise to enable different access to traditional construction materials. Digital timber fabrication (CNC-milling machines) allows for the precise and efficient milling of solid timber with very low tolerances. In addition, computational design strategies enable the development of adaptive and integrative design tools with a direct transfer of fabrication data, ultimately opening new potentials for design and production.

In two research projects, *DGJ Architektur* with *Pirmin Jung Ingenieure GmbH* has developed a timber construction system in which the entire load-bearing structure and all joints are press-fit without metal connectors [4]. Part of the research is a complete set of construction details so that the system fulfils today's regulatory requirements regarding fire protection, acoustic insulation, structural calculation, and industrial construction standards.



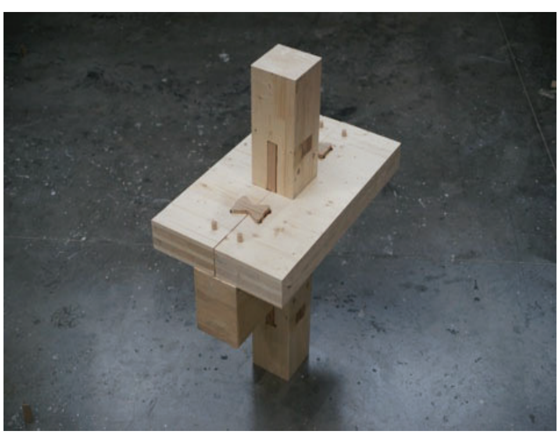


Figure 2 and 3: *Prototype of the construction detail: Intersection of column, beam, and ceiling, Photograph: Hans Drexler, DGJ Architektur, 2018.*

The construction system is based on readily available materials, technologies, and processes at all levels so that the system can be applied by all larger carpentry companies. Standardized materials, such as structural timber and CLT, can be used. The structural analysis of the load-bearing structure and the joints are based on the current Eurocode; in principle, any engineer can calculate and dimension them.
Thus, the innovative part is not newly developed materials or machines but the more intelligent and smart use of existing methods, technologies and materials and combining them into a system.
As part of our research project [4] an Excel-based design tool was developed that enables our system to be pre-dimensioned and costs and performance to be evaluated. It allows the designer to estimate the inputs (timber volume, costs) and performance (living space, efficiency (gross floor area/living space). The joints are designed using modern, three-dimensional CAD systems widely used by architects and engineers. Fabrication data can be generated in the design phase with little extra effort. The system, including press-fit joints, can be produced with widely available timber CNC milling machinery. In this way, traditional knowledge is translated into contemporary building technologies and materials.

3 STRUCTURAL SYSTEMS

Different structural systems for the building system were explored in developing the load-bearing structure: skeleton, hybrid, or solid timber. An essential part of the research is concerned with describing and evaluating the advantages and disadvantages of the various structural systems. A key parameter is the amount of timber required for the load-bearing systems. Other parameters that were examined included the usability and flexibility of the building, but also fire protection, acoustic insulation, and thermal construction physics as mentioned above.

3.1 SKELETON CONSTRUCTION

Timber – produced from tree trunks – is initially a linear, rod-shaped construction material, which lends itself to building skeletal constructions [5]. Given, for example, the high prices for timber and difficulties in the supply in 2022, the structure's efficiency is an important criterion, which was investigated by comparing different articulations of the building system. For non-load-bearing walls and facades, timber-panel and timber-frame constructions are used, which can be produced inexpensively, using less timber.

Another advantage of the skeleton system is flexibility. Taking Steven Groák's definition of flexible housing [6], i.e., a physically and structurally changeable structure, the skeleton construction offers the best opportunities to create flexible housing by separating space creation and load-bearing functions. As a result, the load-bearing skeleton allows both external and internal walls to be moved and altered. If one considers the rapid changes in lifestyles, resulting social structures and demographics (e.g., the declining number of families with the typical, traditional family structure and shrinking household

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sizes), then inflexible housing layouts are not sustainable in the long term.

3.2 HYBRID SOLUTIONS: COMBINING SKELETON AND SOLID CONSTRUCTION

In the mid-1990s, a solid timber construction known as cross-laminated timber (CLT) came onto the market, which offered key advantages, especially for taller buildings, because solid wall panels perform better in terms of vertical load transfer and cross bracing of the global load-bearing structure. When developing this press-fit construction system, a combination of the advantages of the two construction methods was explored: parts of the skeleton structure are replaced by load bearing and bracing cross-laminated timber elements, which allow for an efficient transfer of the horizontal loads. Thus, a part of the walls enclosing the bathrooms, which are in the same vertical line on all floors, and a part of the party walls are designed to replace posts as load-bearing wall segments. The horizontal bracing is achieved by means of bracing walls of solid timber (cross-laminated timber) that are connected to the posts by means of tenons.

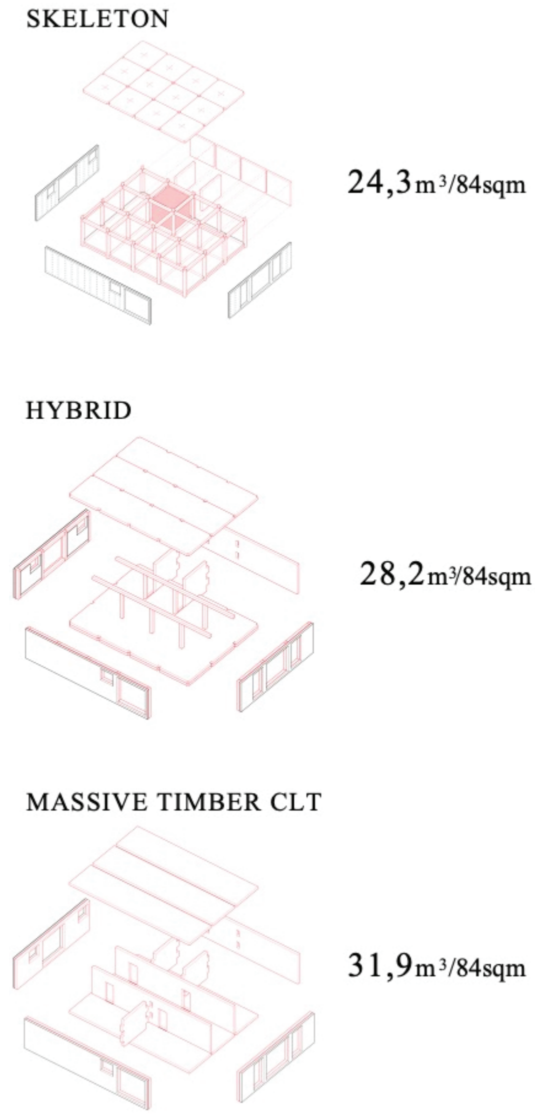

Figure 4: *Axonometric drawings of structure / Comparison of wood volume necessary in different construction methods for a typical apartment of 84 sqm. Designed by DGJ Architektur, Illustration: DGJ Architektur.*

Figure 4 shows a comparison of the consumption of wood in different construction methods. For the hybrid construction, consisting in part of solid walls, the amount of timber used in Case-Study 1 (*Collegium Academicum*), with a load-bearing timber skeleton, a bracing core, and ceilings of cross-laminated timber (CLT), totals 28,2 cubic-meter or 14% more timber than the skeleton construction.

3.3 SOLID TIMBER CONSTRUCTIONS

During the development of the system, it emerged that the introduction of cross-laminated timber resulted in a construction that combined aspects of a skeleton construction (i.e., only linear load-bearing elements) with aspects of a solid construction for ceilings and bracing walls. This led to redundancies at the intersections. The bracing wall could take all loads vertically and thus replace not only the column but the beam as well. Thus, based on the grid, this system could be implemented as a solid timber construction. The disadvantage of solid interior walls is their low adjustability.

The solid construction for ceilings and bracing walls is more material-intensive, although the strength of the individual walls can be reduced by the uniform load transfer.

3.4 LOCAL STRUCTURES AND JOINTS

Given the wide variety of traditional timber joints such as tenon and mortise, lap joints, dovetails etc., the research examined which joints can easily be applied to modern production in real-life practice. Here two different approaches were examined and compared: integrated or differentiated joints.

The integrated joints are cut so that the elements fit into the geometric space of the adjacent elements and guarantee a press-fit joint via the interlocking of the elements' geometries. The initial idea of our construction approach was to produce geometrical locking and press-fit joints when cutting and sizing the elements, thus making fasteners unnecessary. Our reference point was a Japanese "Yatoi-Hozo-Sashi" joint, which fits two main beams into the geometric space of the post to form beam-to-post joints, but also forms a lapped end-to-end connection from beam to the beam by means of rod tenons, which are secured in place with wedges or cross tenons. The load of the beams is transferred not only via the rod tenons but, above all, via a parapet from beam to post, into which the beam is precisely fit. The principle of this joint is that the geometric spaces overlap, and the members are joined with comparably complex geometries.

Differentiated joints separate the geometric spaces of the components, which are then connected via secondary elements.

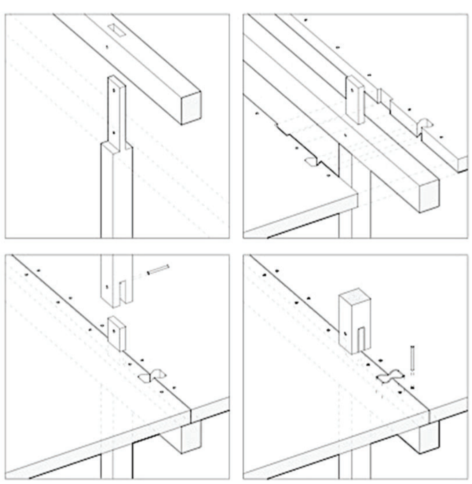

Figure 5: *DGJ Architektur, 3D model of the construction system's beam to post joints, DGJ, 2016.*

The combination of timber components is an advantage of the differentiated local system. The solid ceiling elements are joined to the post with dovetail joints made from hardwood. This type of joint is complicated to build on-site but allows for the transfer of shearing, compressive, and tensile forces. Beech dowels are used for the shearing forces between the ceilings and the beams. The final detail, the vertical connection between the two columns above and below the ceiling, is produced from hardwood (beech wood LVL), which allows for the transfer of the vertical forces through a smaller cross-section.

In this context, discussing the weakening of the supporting beams by such geometric joints is interesting. At first glance, the beams and columns sections increase the timber volume necessary for structural performance. But it became apparent during the development that there is a system synergy between fire protection and structural performance. When measuring the load-bearing capacity of the beams under fire conditions, the entire timber volume is not applied to the load transfer. Still, it is assumed in the case of fire that the outer layer of the beam burns away slowly, ensuring the remaining beam's stability for the required time. In the case of the press-fit joints, this layer is also part of the structural elements used for the joints, which serve as an integrated fire-resistant layer.

In the first case study (see Case Study 1: *Collegium Academicum*), the connections between posts and beams and beams and ceilings were increasingly simplified during the design process, i.e., separated into their own geometric spaces. Vertically, the forces are achieved by lapping the elements, which are secured in position with beech wood dowels. The stable plate effect of the ceiling elements is achieved by lap-joining ceiling elements with dovetail joints. This differentiated construction has two advantages: first, it makes the timber trimming process for the individual elements easier because the elements lie above and next to each other. The geometry of the components is more straightforward, and the production is cheaper. Second, the differentiated construction of the components allows the dimensional tolerance of the individual parts to be compensated across the load-bearing structure, as the horizontal accuracy of the fit is initially not decisive for the load transfer. The vertical inaccuracy can be compensated locally. The disadvantage of joining in this way is that the connections with beech wood dowels can only be released by drilling out the dowels, which makes dismantling more difficult.

3.5 DESIGN TO DISSASEMBLE

An essential aim of the research was to develop a mono-material construction system based on renewable materials. Since all parts of the structure are made from timber, the system is also easy to dismantle later. The disadvantage is that putting it together requires high precision and leaves little room for dimensional tolerance.

In the real-life buildings so far designed and studied, the idea of mono-material timber construction is only applied to the primary structure of the building. Therefore, secondary systems for facades and fit-outs would still use screws and other metal fasteners. Even though comparable automated methods for fixing panels using timber nails are readily available, the necessary

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certificates are not. Also, timber nails do not offer the same performance as metal screws.

Figure 6: *Timber Prototype House, Photographs: Thomas Mueller, 2018.*

In a small-scale prototype building, the idea of mono-material timber construction was demonstrated comprehensively: The '*Timber Prototype House*', which is part of the international building exhibition IBA Thüringen, is made from timber (and glass for the windows), joined by press-fit timber construction. The building still fulfils all technical requirements, including thermal insulation [5]. But the design and production processes are still too complicated and costly to allow for use in affordable buildings.

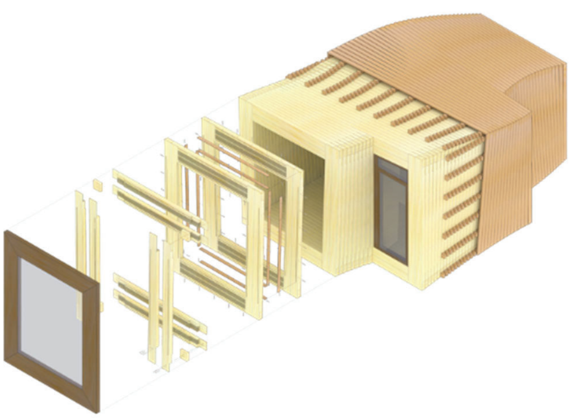

Figure 7: *Timber Prototype House, Graphics: ICD Stuttgart, 2018.*

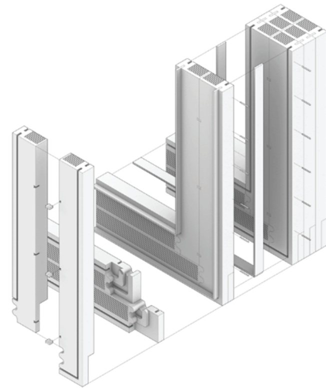

Figure 8: *Timber Prototype House, Graphics: ICD Stuttgart, 2018.*

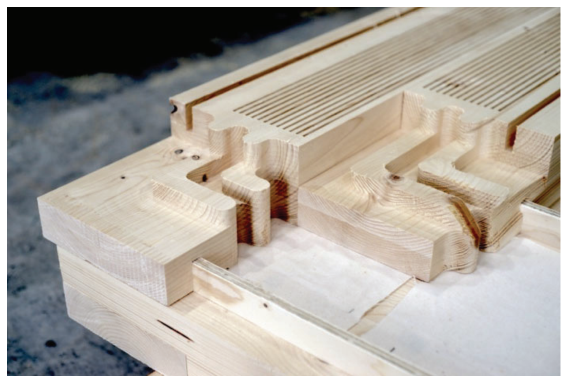

Figure 9: *Timber Prototype House construction detail, Photograph: Hans Drexler, 2018.*

4 RESEARCH BY DESIGN

The development of *'Open Architecture'* [3] as a building system was as much about exploring the architectural potential as the technical solutions. A series of case studies were used to incrementally improve the building system, using a set of criteria for sustainability, efficiency, and usability. The system was developed in 2015 through several 15 case studies [3]. During the research, the development of the system (planning and design methodology) was combined with analysis (evaluation and optimization). This has brought to light an essential aspect of explorative applied construction research: Design has both creative and analytical aspects, which interact with each other in iterations and recursions. In the day-to-day designing and planning process, iterations, parameters, criteria, and decision paths are seldom explicit, and as such, they are not transparent. They take place in numerous sketches, drawings, models, and discussions. In the research and development project, the analytical parts are made explicit and operative, thus complementing the design. From these analyses, tools were developed with which the construction system can be adapted to different locations and functions. In developing this system, the levels of research and parameters for a given object are evaluated and optimized.

The case studies are vehicles and research objects at the same time. The transferability and usability of the construction system are identified. Through the systematic research of the application parameters, load cases and characteristics, an estimate of the dimensions of the structure can be calculated for each application. To study the possibilities in terms of building typology, we first defined a series of design parameters, the permutations, which can be expressed as a matrix. The matrix is a parametric design tool for the performance and dimensions of the system, depending on the building-typological characteristics of the respective permutation. In the matrix, all three analysis levels – design, structure, and performance – are interlinked and influence each other.

4.1 CASE STUDY 1: *COLLEGIUM ACADEMICUM*

Animation: https://vimeo.com/459124025

Figure 10: *Case Study 1: Collegium Academicum in Heidelberg, Germany, designed by DGJ Architektur, Photographs: Copyright Thilo Ross Urh. Nr. 4026999.*

One of the first case studies was the *Collegium Academicum, a* project of the International Building Exhibition (IBA Heidelberg). It is a student residence with 176 units. A new housing typology was developed, which enables residents to change and adapt their apartments to various spatial configurations.

Figure 11: *Construction detail, Collegium Academicum. DGJ Architektur, and photograph: Hans Drexler, DGJ Architektur, 2018.*

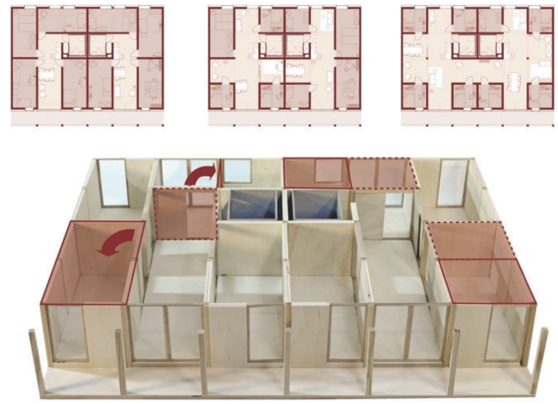

Figure 12: *Three possible floor plan configurations (top), physical model of the construction system, model scale 1:25, DGJ Architektur, and photograph: Hans Drexler, DGJ Architektur, 2018.*

The residents can quickly and easily reposition partition walls within the apartments, thereby changing the size of the rooms. The individual rooms consist of two sections: a core area of seven square meters and a flexible area of seven square meters, which can be used as personal space or be part of the apartment's shared space. Depending on individual preferences, the flexible area can remain completely open, partially separated by dividing elements (table, shelving), or partitioned off entirely by placing the wall between the core area and the flexible zone. Thus the building becomes an adaptable space where the individual inhabitants and housing communities can reconfigure and negotiate the space requirements.
The project is part of the program "Variowohnungen" of the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) in the Federal Office for Building and Regional Planning (BBR) and is additionally funded by the program "Holz Innovativ" of the state of Baden-Württemberg. "Holz Innovativ" is financed with the European Regional Development Fund (ERDF) funds.

Figure 13: *Model apartment, Collegium Academicum. DGJ Architektur, Photographs: Copyright Thilo Ross Urh. Nr. 4026999, Source: DGJ Architektur.*

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4.2 CASE STUDY 2: *GEMEINSAM SUFFIZIENT LEBEN* (LIVING TOGETHER SUFFICIENTLY)

Figure 14: *'living together sufficiently', physical model of the construction system, model scale 1:50, DGJ Architektur, and photograph: Hans Drexler, DGJ Architektur, 2016.*

This building is designed for a small housing cooperative: a group of families and individuals who asked for a variety of apartment types and sizes within a comparatively small building. The design offers a wide range of different apartments that are suitable for families, senior citizens, couples, and individuals. However, due to the basic concept (*'living together sufficiently'*), the individual rooms are relatively small for the respective use and therefore offer little scope for other uses. The common areas and central facilities offer an advantage for long-term usability and the adaptability of the building. Different divisions and apartments on the floors can be realized, from a small two-room studio to a five-room family apartment. The building is planned as a skeleton structure with a stiffening core. The concentration of bracing around the access gives a high degree of freedom for the design of the floor plans. The flexible but clearly structured system has proven to be a suitable means of planning. The structure allows for individual requests and long-term customization without jeopardizing the integrity of the overall system.

Several types of apartments for different living needs were developed for dialogue with the living group. Ultimately, no variant is implemented similarly but redesigned in dialogue with future users. The large 4-room apartment was redesigned into a 5-room apartment, which was chosen together with the smaller 3-room apartment on almost all floors.

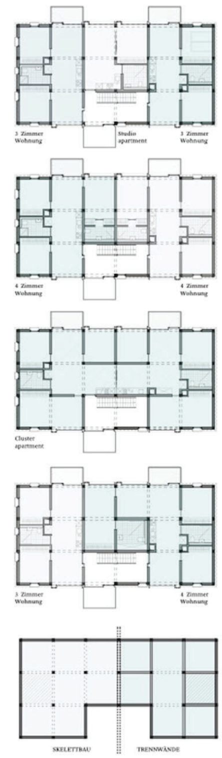

Figure 15: *Case Study 2: 'sufficiently living together', apartment layouts, graphics DGJ Architektur, 2016.*

The square grid permits different apartment layouts adapted to individual needs and wishes and flexibly combined. At the same time, the layouts of the apartments remain flexible/adjustable for future changes.

4.3 CASE STUDY 3: ARRIVAL CITY 4.0

Animation: https://vimeo.com/240369724/0d8d1520a6

Figure 16: *Case Study 3: Arrival City 4.0, model and photograph by DGJ Architektur, 2016.*

Arrival City 4.0 was designed to respond to the so-called refugee crisis at the end of 2015 in Europe. The project was intended to demonstrate how spatial and social structures can contribute to the creation of affordable housing and integration. The building system '*Open Architecture*' [3] was used to provide people not only a place to live in the short term but also to give them a long-term perspective. *Arrival City 4.0* is an expandable design representing a general low-investment approach to housing shortages. The primary structure and a basic building envelope made from polycarbonate panels can be built with minimal investment in a short period of time. This basic shelter would gradually be transformed into a permanent building by the inhabitants by adding internal walls, technical systems, and more advanced façade panels.

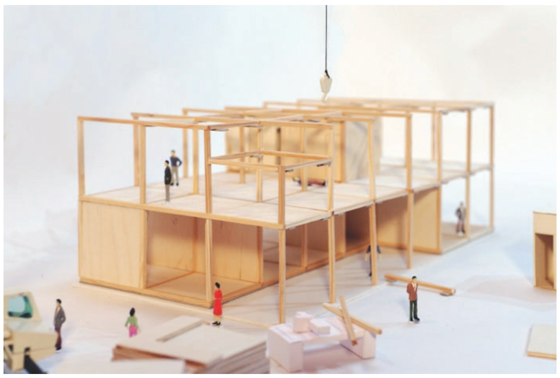

Figure 17: *Case Study 1: Arrival City 4.0, model and photograph by DGJ Architektur, 2016.*

5 FINDINGS: CHALLENGES AND OPPORTUNITIES FOR PRESS-FIT TIMBER CONSTRUCTION

5.1 RE-USE AND RE-CYCLING

Due to the widespread use of non-renewable construction materials and given that most construction materials are rarely reused or recycled (only downcycled), the construction industry is responsible for a large share of waste that is generated today. This building practice also results in the high use of resources. Sustainable buildings must be built differently: The individual construction elements should be joined to be taken apart again. The shearing layers of construction should be joined to maintain, repair, or replace individually since they have different life spans.
For the primary structure, the developed mono-material timber constructions offer an alternative that can be reused and recycled into engineered wood products, such as OSB boards. The constructions' simplicity promotes sorting, an essential prerequisite for recycling materials.

The system is designed to allow components and materials to be dismantled and reused, but implementation is limited to the primary construction in the first use cases. Looking at the building, further potential for recycling needs to be raised. The ability to be dismantled, the reuse of components and the recycling of building materials are essential criteria for a holistically sustainable building design. Ideally, the buildings of the future will consist of components and materials that can either be reused as such elsewhere or that can be easily broken down into components suitable for reuse. The principles of circular construction should be applied systematically at all construction levels. Optimizing the construction system regarding a circular economy and closed material cycles is the most crucial technical optimization that must be addressed within the system. Even more, than in conventional construction, the system presented is suitable for meeting this requirement regarding flexibility and the construction hierarchy. These include in particular:

- Hierarchy of construction according to life expectancy and subsystems.
- Simple, removable, and self-explanatory constructions that favor dismantling.
- Use of renewable building materials.
- Use of materials that can be easily recycled.
- If possible, define parts and components that can be reused as a whole unit.

More precise planning and analysis of the assembly and disassembly processes and the subsequent recycling of the disassembled parts are required here. Analysis, evaluation, and optimization of all building materials installed in the system are necessary.

5.2 HIERARCHY OF CONSTRUCTION

The primary structure determines the basic structure of the building to a large extent. In today's construction, where a whole range of requirements and technology must be met, many other components and layers are added to this primary construction. The question of how these are structured and interconnected has received little attention from research. For example, no terms and definitions are introduced for the different hierarchies, which can be used to distinguish between different types of construction. In the following, such terms are developed to be able to categorize the other construction methods.
Within the construction, subsystems can be identified that are analogous to the 'Shearing Layers of Change' [7]:

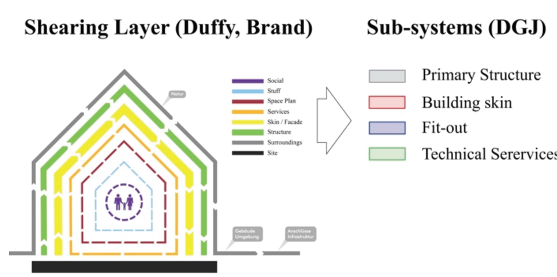

Figure 18: *Shearing Layers introduced by Frank Duffy, further elaborated by Stewart Brand [7], sub-systems for constructions graphics by DGJ Architektur, 2020.*

Structure: All primarily load-bearing and stiffening components of the skeleton structure fall into the subsystem of the supporting system.
Façade / building envelope: The subsystem of the building envelope includes all structural elements that form the primary external space closure. The corresponding components fulfil the basic functions of fire protection, heat, and weather protection.

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Fit-out: Both fundamental components and individual component layers, which are necessary to meet the requirements for interior room closures, can be assigned to the subsystem of the interior design (e.g., for apartment partition walls and floor constructions).
Technical building equipment: Technical systems form a separate subsystem since interchangeability and flexibility should be guaranteed to an exceptionally high degree.

The definition of the subsystems was developed in the project to analyse buildings. The four subsystems can be viewed on three hierarchical levels because the interior and building services subsystems are arranged on the same hierarchical level [8]. Regarding the separability of materials, efficient assembly and the dismantling of components, a strategy for structuring the system should be selected that provides for a clear hierarchical structure in constructive-functional and temporal dimensions as well as the flexibility of the components. As part of the research, a series of constructions were developed and analysed, allowing the identification of categories of timber constructions. Depending on the degree of differentiation and/or overlap between the sub-systems, the constructions are more or less flexible and/or suitable for recycling.

The definition of the hierarchical levels is primarily linked to the expected life span of the individual materials and components. On the one hand, this should ensure flexibility in the assembly process since the components can be prefabricated together as larger modules or installed successively on-site. The system should, therefore, also be adaptable for project-specific circumstances and restrictions (transport, accessibility of the property, possibility of prefabrication, etc.). On the other hand, the service life is crucial, especially the ability to overhaul, exchange, convert, dismantle, and recycle the components. The clear separation of the hierarchical levels should, therefore, also be reflected physically, i.e., concretely in the components' constructive connection and geometric arrangement, to ensure that they can be separated according to type. For the assessment, the individual subsystems are assessed separately regarding accessibility and the possibility of adaptation.

5.3 SUSTAINABILITY

As a domestic, renewable resource, timber is the most sustainable construction material available since it is the only construction material that can be used for all construction tasks in large volumes and is not based on limited resources (fossil fuels, sand, iron ore …). Thanks to Germany's established, sustainable forestry industry, timber can serve indefinitely as a renewable raw material. Model computations indicate that the timber needed for the country's total construction activity can be covered by just one-third of its annual timber output [9]. Using timber as a renewable resource, our construction system has ecological advantages; improving the reusability of the construction elements can increase these advantages even further. The production and processing of timber require significantly less primary energy. Wood absorbs carbon dioxide from the atmosphere and thus stores it over the lifetime of the building. In the hybrid construction variant, the reduction of CO^2 emissions by wood is partially offset by high emissions related to secondary materials, like cement or steel.

5.4 COST EFFICIENCY

Regarding commercial viability, timber-only joints may have advantages over constructions using metal fasteners. The fasteners by themselves are high-quality and expensive construction elements, especially given the current high prices for metals and energy. Moreover, mounting the fasteners represents a considerable expenditure of time in the production and assembly at the construction site. When processing times are minimized, costs are also reduced. The high complexity of timber-trimming processes means longer processing times at the milling machine but reduced time for fasteners on site.
The building system's first real-life applications did not show a significantly lower price than conventional timber constructions. This could be because, in both buildings, the manufacturer used the press-fit structure for the first time and could not calculate prices more aggressively.

5.5 PRECISION

Press-fit joints require a high degree of precision in production and assembly. Especially in the case of larger buildings, where imprecision in construction elements and their fitting can add up, joining with press-fit elements is a challenge. In both real-life applications, the construction on site was faster than expected due to the higher precision achieved with the system. Within the press-fit construction, building components fit together as 3D puzzle, constantly eliminating impressions in the assembly process.

5.6 SOUND PROOFING

Timber constructions, in general, are comparatively lightweight and can, therefore, absorb sounds less efficiently than heavier materials such as concrete or bricks.
In press-fit timber constructions, an additional conflict of objectives is found: The press-fit connections should be as tight as possible for structural integrity. For soundproofing, decoupling of the elements would be preferable when building components continue through sound barriers, such as ceilings or walls between apartments. Two strategies can be used to minimize the problem: decoupling and stiffening. The sound transmission is minimal when the construction is decoupled using vibration isolation (high-density foam materials). For example, partition walls between apartments are designed as double walls and decoupled. The ceilings are equipped with sound insulation, which decouples them from the primary structure and the rooms below. Beams and load-bearing walls must be individually assessed as secondary noise transmission channels. Here the strategy was to stiffen the connection between the column and the beams, as well as between the walls and the ceilings, respectively, to a point where all components acted as a unified system. Due to the

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increased mass, they absorb more sound energy, which will not be transmitted.

5.7 FIRE PROTECTION

Given the combustibility of the primary construction material, special care must be given to fire protection. In the simplest scenario, timber can protect itself from combustion. Timber forms a relatively stable charcoal coating in a fire, which in turn delays full destruction by fire. This effect is included in the dimensioning of the construction elements for fire conditions, in that the beams are sized larger than what they need to be to meet their load capacity requirements so that in case of fire, the remaining beams assure the stability of the building for the prescribed amount of time. Press-fit joints can, as a rule, be considered homogenous construction elements. In practice, however, care should be given that the joints are so tight that fire cannot penetrate them.

Supporting and bracing parts of the structure are generally not reached by a fire for five to ten minutes due to the low combustibility of a closed timber surface. In most cases, fires are fueled initially by furniture and fixtures so that houses have been evacuated by the time the fire reaches the supporting and bracing elements. This, in turn, means that the primary fire protection goal would be met. If added fire protection of the supporting and bracing elements is required, e.g. because it is prescribed by regulations and/or due to increased evacuation risks (higher buildings, more complex layout), the primary timber load-bearing structure can be additionally protected from fire by encasing it with cladding so that the combustible elements can be protected from the fire for a defined period of time (30 min., 60 min., 90 min.).

6 CONCLUSIONS AND OUTLOOK

6.1 CONCLUSIONS

The building system '*Open Architecture'* has so far been used for three residential buildings in Germany, which are constructed in Frankfurt, Heidelberg, and Mannheim. This indicates that the system fulfils all technical and legal requirements.

Given the technological advances in automated cutting and milling of timber, mono-material timber construction is a plausible solution for solving the problem of higher costs and carbon emissions caused by metal components and improving the recycling potential of timber buildings.

6.2 OUTLOOK: SIMPLICITY AS DESIGN PARAMETER

Mono-material timber construction's high ecological and economic potential needs a comprehensive approach. Most parts and all sub-systems of the building should be mono-material and/or designed to disassemble. Given the many requirements a contemporary building must fulfil, like structural performance, insulation against heat and cold, fire protection, soundproofing and many others, most building designs tend to translate each into discrete layers or components. This strategy adds to an enormous complexity in the construction, making the design and building process challenging and re-use or recycling almost impossible. To make extensive use of the simple and effective idea of press-fit timber construction, the complexity of the building construction must be dramatically reduced. At the same time, the hierarchy of the constructions, according to life span and functional sub-systems (or shearing layers), can be used as a design strategy.

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