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Increase in Efficicency and Quality Control of Construction Processes through Off-Site Fabrication

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Summary

This paper compares and assesses modular prefabricated building systems according to material use, process efficiency, ecological potential, i. e. sustainability of construction processes, and market relevance. To provide a holistic overview of the current market situation, two best practice examples are examined and evaluated. Covering favourable materials and prefabrication methods essential for the development of sustainable, cost-efficient housing, selected projects comply with current and future energy efficiency standards in construction. Due to systemized planning strategies and optimized utilization of materials, recyclability properties of buildings and their parts enhance significantly. Furthermore, prefabrication processes contribute to the reduction of waste. Beyond achieving ecologically and economically advanced processes, prefabrication enables technical improvement of manufacture by simultaneously increasing the quality buildings and their parts.

Keywords: Off-Site Construction Processes, Prefabrication, Integrative Planning, Resource Efficient Fabrication

1. Introduction

Rising global population growth and urban migration rates are indicators of a continuously increasing demand for housing. Higher building densities and compact building designs are essential to reduce associated land use as much as possible. This paper describes how current building production techniques must rapidly change in order to accommodate these factors.
Examining methods of the prefabrication industry, key aspects of modular building processes for residential construction are conveyed and highlighted. Serial manufacturing methods and automated processes are assessed and evaluated to categorise indicative workflows. Thus, transfer strategies of technological analogies for industrial construction are defined.

3.1 Background

Studies conducted by the United Nations Organisation (UNO) show that urban migration rates will increase with about 75 % of the world population living in cities by 2050. Therefore, today’s building concepts need to allow for both, higher densities within the urban environment and institute environmentally friendly construction methods. [1] A holistic sustainable design approach requires the consideration of fabrication and construction processes as well as materialization of buildings and components. In order to achieve resource efficient manufacturing methods, planning strategies have to consider and evaluate the distribution of on- and off-site processes. Beyond increasing control of work sequences and quality of execution, procedures contribute to ecological advancements and the enhancement of cost- and time efficective project realisation.

3.1.1 Housing Situation and Market Overview

The German prefab industry is one of the leading global manufacturers in the segment of prefabricated housing. The industry's main focus remains the single-family and low-rise housing segment. Representing about 15 % of the German housing market, the popularity of prefabricated residential construction, particularly located in suburban areas, has grown about 2.5 % within the past 20 years. [2] In intra-urban areas, conventionally built multi-storey structures dominate the built environment. The following paper evaluates modular prefabrication and associated construction technologies based on

- Material use
- Integrative design approach
- Applicability in multi-storey building structures

The majority of prefabricated, residential building stock remains the single-family home segment in timber construction. As shown in Figure 1, conventional, wet construction methods using brick, building stones or concrete cover approx. 84 % of the materials used for housing. The amount of 0.01 % buildings in steel is negligible. To generate a thorough and fundamental comparison of building materials and systems, fabrication and construction processes need to be evaluated. Validated statements regarding ecological, economical and technical qualities allow for direct transfer regarding manufacture and assembly of buildings and their components, thus contributing to the optimisation of building construction.

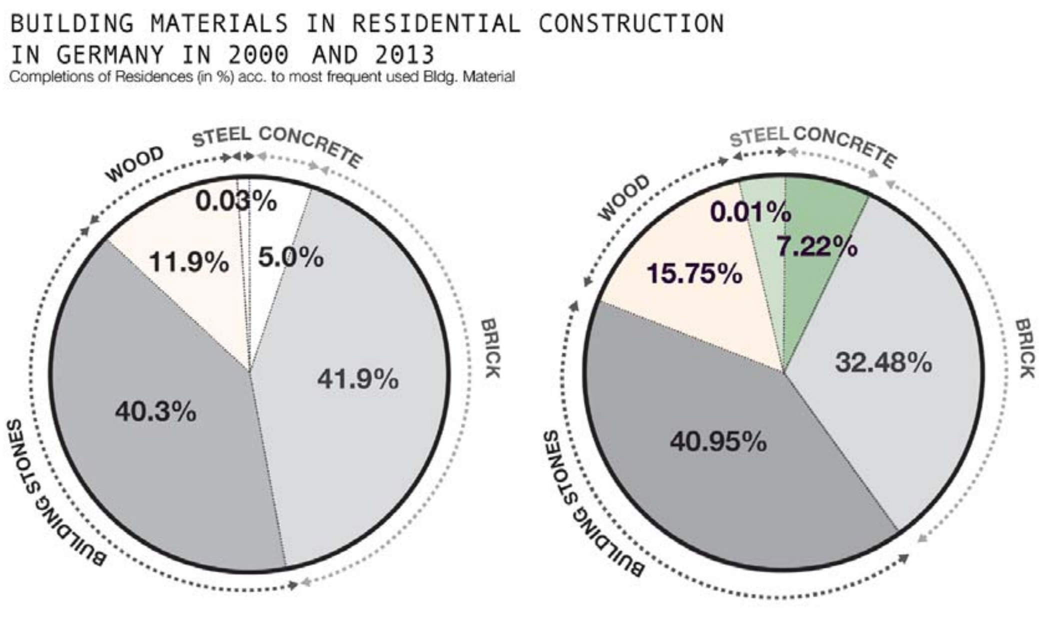

Fig. 1 Building Materials in Residential Construction in Germany in (a) 2000 and (b) 2013

3.1.2 Manufacturing Methods Using Wood Based Systems

The construction of an average sized prefabricated 140 m^2 single-family home takes about 15 tons of wood used for load-bearing elements, nonstructural components, and finishes. According to industry research, a CO_2 relief for the atmosphere of up to 27 tons can be accomplished. [3]
During the past decades, a predominant use of timber frame building systems for multi-storey housing becomes apparent. Requiring lightweight construction methods, systems developed continuously, and technological innovations regarding material build-ups and the integration of subsystems enabled enhanced assembly and installation sequences. More recently, new wood products, i. e. cross-laminated timber (CLT), were introduced into the market, contributing to advanced structural solutions and building typologies.
Compared to solid construction methods, the lightweight wood-based systems improve a building's carbon footprint. On the one hand, the amount of energy required for material production and processing is comparatively small. Furthermore, the material enables to store large quantities of CO_2. In comparison to industrially produced building materials, wood extracts CO_2 rather than emitting it, hence eco-balance and GWP-values improve (Fig. 2). Due to sustainable forest management, the availability of the material will remain sufficient.
Compared to conventionally built dwellings of brick, stones, or concrete, buildings made of wood are 10 to 15 % higher in cost. However, a project's economical efficiency can be improved by accelerated construction cycles, achieving shorter manufacture and assembly times. Furthermore, the use of lean element sections provides an increase of net floor area, benefitting the economical status. Additionally, a high quality of elements can be achieved.

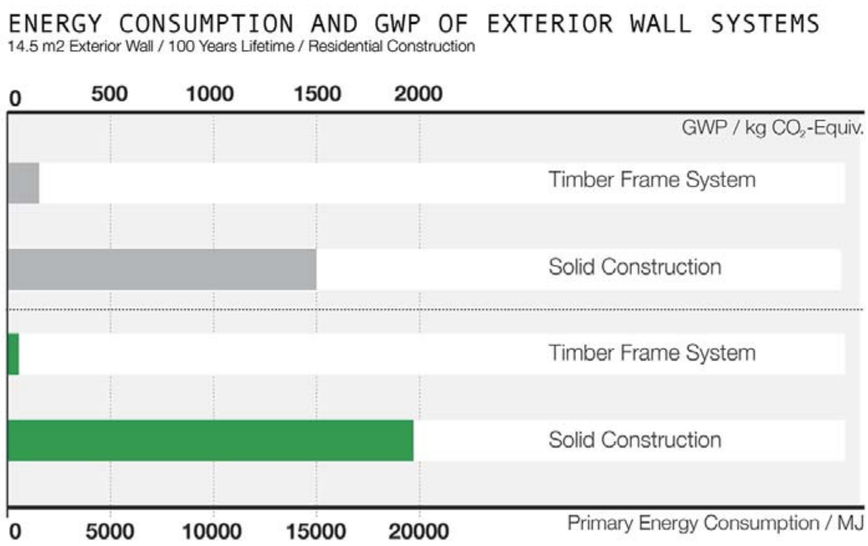

Fig 2 Energy Consumption and GWP of Exterior Wall Systems (14.5 m^2)

3.1.3 Potential of Precast Concrete Modules for Multi-Storey Housing

This paper evaluates the prefabrication potential of concrete and its applicability in multi-storey buildings. This material proves to be economically efficient, easy to produce and maintain, and precast elements are fast to assemble. Subsequently, advanced construction technologies and implementation methods emphasise considerable advantages for fabrication.

Nevertheless, resource efficiency aspects as well as limitations through fabrication and transport have to be considered when chosing the material and associated methods of construction.

2. Methodology

The following research compares two modular building systems. For a boarding house in Neuhausen (Germany), construction methods combine in-situ concrete and modular timber prefabrication. For the student housing block in Sant-Cugat (Spain), precast concrete cells are used to generate a two-storey building structure.
This paper focuses on the assessment of construction systems and material performances. Technical properties, behavioural aspects, and manufacturing and assembly processes of buildings and components are essential for the ecological, economical, and technological optimisation of buildings and their design. In the analysis, joints and transition areas of structure, building envelope and technical services are identified and exemplified based on outlined projects in modular construction. The manufacture of building components, following smart assembly and disassembly strategies, contributes to an efficient enhancement of building and construction processes.
Furthermore, the paper evaluates current methods of manufacture to generate advanced solutions for future building construction. Outlining the coherence of materiality and building structure, the material-specific case studies introduce industrial construction methods, highlighting prefabrication potential and applicability for multi-storey structures.

3. Results

3.1 THW-Bundesschule in Neuhausen (DE) 2014, Project Development: Bundesbau Baden-Württemberg rep. by Hochbauamt Reutlingen

The two-story boarding house of the THW-Bundesschule, an extension to an existing 1950 building ensemble, is located on a hillside in Neuhausen, near Stuttgart.
The original scheme proposes a combination of conventional in-situ concrete construction and precast cavity wall elements. Due to time and cost related deficiencies, a redevelopment of planning and building process was required. The resulting comparison between construction methods lead to increase the amount of prefabrication, introducing modular CLT-room cells in the scheme.

3.1.1 Building Information

Table 1 shows an overview of construction cycles and building data, relevant for the comparison of systems and the distinction between design approaches. On-site processes are divided into conventional work sequences, including site preparation and in-situ construction, and on-site assembly and installation of prefabricated parts, in this case the completed room modules.

Table 1: Construction Data

Construction Times	Duration Periods
On-Site Conventional	29/01/2013 - 29/02/2015, 24 Months
Off-Site Prefabrication	02-04/2014 Plg., 04-05/2014 Fabr. (5 wks.)
On-Site Prefab (Assembly)	02-08/06/2014, 6 Days

The following table shows general information regarding building dimensions, areas and mass, and construction costs. Furthermore, energy performance values, based on DIN 18599 and EnEV 2009 are shown. Energy values refer to the project’s total net floor area (NFA).

Table 2: Building Data

Building Data	Dimensions/Costs/Energy Performance
Building Dimensions (w*l*h)	13.4 x 41.5 x 10.4 m
GFA (Gross Floor Area)	2109 m^2
NFA (Net Floor Area)	1535 m^2
GBV (Gross-Building Volume)	7173 m^3
No. Levels	4 (L-01/00/01/02)
No. Units	30
Costs Modular	1 180 179 €
Costs Total	5 400 000 €
Annual Operating Energy	245 kWh/ m^2a
Primary Energy Consumption	306 kWh/ m^2a

3.1.2 Structural Concept and Assembly Strategies

The building bends along its centered axis, enabling an optimised orientation of the rooms. Each of the 14 m^2 bedrooms includes a bathroom, cabinet, storage and desk space each, and is laid out on a 3.65 m planning grid. Due to the modular structure, the bearing crosswalls consist of two 0.12 m CLT-layers and reach a fire resistance rating of F 30. Figures 3 a, 3 b, 3 c and 3 d show the rapid on-site assembly and installation sequence of the prefabricated units, which were finalised within six days.

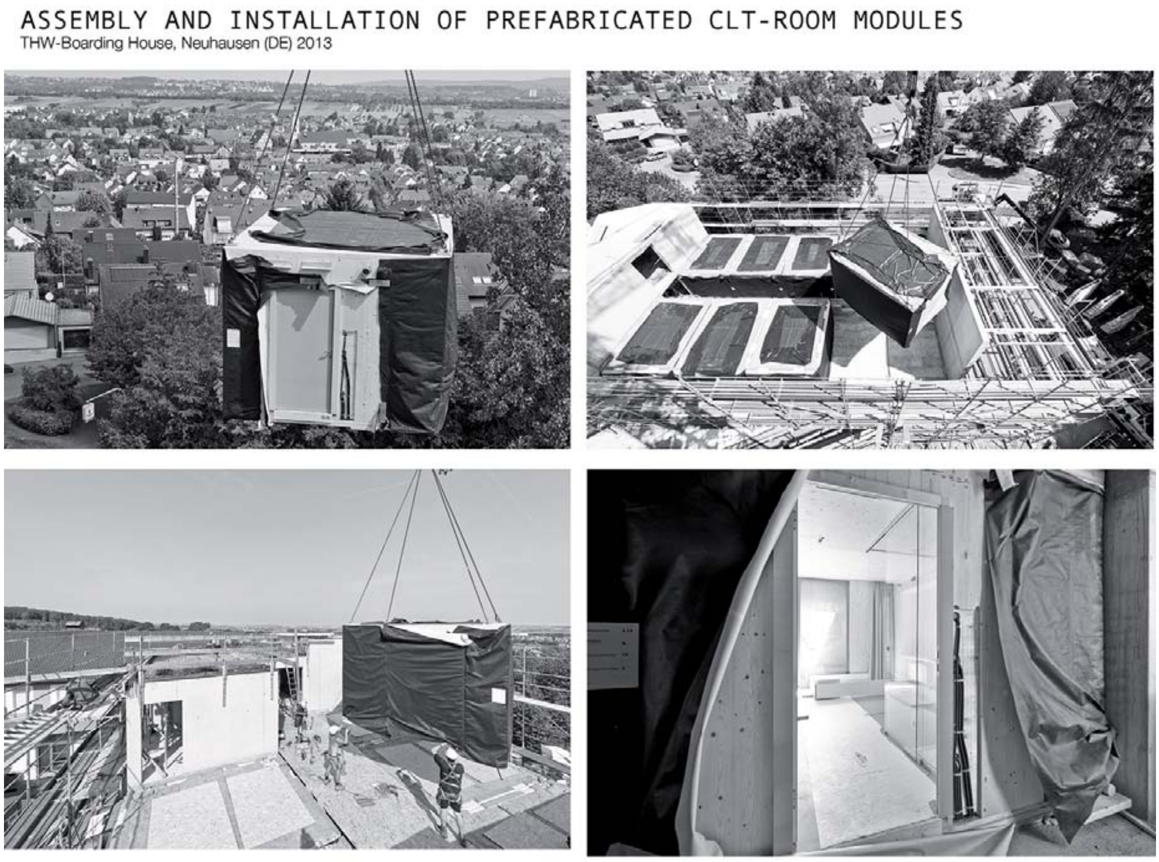

Fig 3 a – d Assembly and Installation Sequences of CLT-Room Modules

The structural concept combines in-situ concrete construction for core, bearing walls, and ceilings with prefabricated, structurally independent modular cells for the bedrooms. All technical supply rooms, recreation and sanitary facilities, a lobby, the restaurants including cafeteria, canteen, and a large kitchen are located on basement and ground floor level, while the 30 rooms of the boarding house are on first and second floor. The modular prefabrication of the hotel rooms not only bears economical and technical advantages, but also contributes to a resource efficient manufacture. However, energy use values for building operation increase significantly due to consumption of the ground floor facilities.

Fabricated and equipped off-site, the modules contain mechanical and technical supplies, the substructure of the facade, and internal partitions. Cladding and final external layer were subsequently applied on-site. All required connections for final on-site installation were provided.
Similar to the behavioural performance of solid components, the cross-laminated timber slabs of walls and floors enable sufficient bracing of the modules during transport and assembly. According to fire-protection standards, four to five cm filling above the structural plate is required, adding mass and further improving sound insulation qualities. Therefore, the final weight results at approx. 5 tons for each room module of the boarding house.

3.1.3 Summary

The application of modular timber construction has enabled significant advantages for the project. According to comprehensive cost estimates, the implementation of prefabricated bedroom units led to a reduction of total building costs, and allowed for saving of time and associated costs for rent paid to third parties. In comparison to the initially proposed precast slabs, the use of massive wood elements improved the ecological footprint of the building and contributed to interior comfort.

In contrast to the modular wood project in Neuhausen, a student housing project in Sant Cugat, Spain uses concrete cells to generate the double-storey buildings. Besides rewarding design and planning strategies, the project provides excellent ecological performance values.

3.2 Student Housing Campus Sant Cugat, Barcelona (ES) 2013 Architecture: N-Arquitectes, Project Development: Compact Habit

Organised within two opposite building blocks, the 57 student residences are located in Sant Cugat del Vallées, a town in the suburban area of Barcelona. The two-storey apartment buildings are arranged around an open courtyard. The precast concrete modules cover 3013.50 m^2 of the total 3101 m^2 GFA. These 62 prefabricated units include a few cells for common space, and are completely manufactured off-site. For delivery and final on-site assembly, the room modules were transported from the plant facility on-site using heavy load and special freight movements.

3.2.1 Building Information

Table 1 gives an overview of construction cycles and building data, relevant for the comparison of systems and the distinction between design approaches. On-site processes are divided into conventional work sequences including site preparation and in-situ construction and on-site assembly and installation of prefabricated parts.

Table 3: Construction Data

Construction Times	Duration Periods
On-Site Conventional	12/2008 – 08/2009, 8 Months
Off-Site Prefabrication	NN Planning, 04-05/0209 Fabr. (6 wks.)
On-Site Prefab (Assembly)	10 Days

The following table shows general information regarding building dimensions, areas and mass, and construction costs. Here, energy performance values are based on Swiss Minergie standards and refer to the building's total GFA (Gross Floor Area).

Table 4: Building Data

Building Data	Dimensions/Costs/Energy Performance
Building Dimensions (w*l*h)	28 x 75 x 6.5 m
GFA (Gross Floor Area)	3101 m^2
NFA (Net Floor Area)	2480 m^2
GBV (Gross-Building Volume)	9920 m^3
No. Levels	2 (L00/01)
No. Units	62
Costs Modular (incl.adj. buildg. pts.)	1 872 752 €
Costs Total	2 784 739 €
Annual Operating Energy	82 kWh/ m^2a
Primary Energy Consumption	88 kWh/ m^2a

The 57 apartments, consisting of reinforced concrete modules, each measuring 11.20 x 5.00 x 3.18 m and 39.95 m^2, include bathroom pod and balcony space. They were fabricated within 6 weeks using an indoor assembly line. Standardised dimensions, fixed widths and heights but alternating lengths enable resource and time efficient production sequences. Off-site manufacturing contributes to process control and improvement of a construction's energy management. The reuse of formwork provides significant economical advantages.

3.2.2 Structural Concept and Assembly Strategy

The structural framework of the modules is based on a planning grid of 0.90 m for each unit. Concrete ribs transfer vertical and horizontal loads. The tubular structure provides easy stacking of units without further support. The decoupling through flexible elements, that are located at the bearings between the cells, impedes direct sound transmissions.

Figure 4 a shows the structural framework of a concrete cell, highlighting maximum span dimensions. Figure 4 b illustrates the stacked units, emphasising the double build-up of wall and floor slabs and the gap inbetween units to locate the flexible sound barriers. Due to the structural performance, no additional bracing of the building block is required. The lifting of an apartment module during assembly is shown in Figure 4 c. For on-site works, heavy-duty equipment to manoeuvre the 45 ton units is required.

Mechanical and technical supply systems are preinstalled on defined routes and connected to the main installations on-site.

The construction method enables rapid on-site assembly, enhanced cost and time management, the reduction of risk and noise, and controlled waste management. Furthermore, disassembly of the modules does not require demolition. The system permits building relocations with minimal effort and guarantees for easy modernisation or modifications of cells. However, the weight of the container-shaped units varies between 25 and 45 tons depending on dimensions and size. [4] Constraints due to transport and logistics need to be considered.

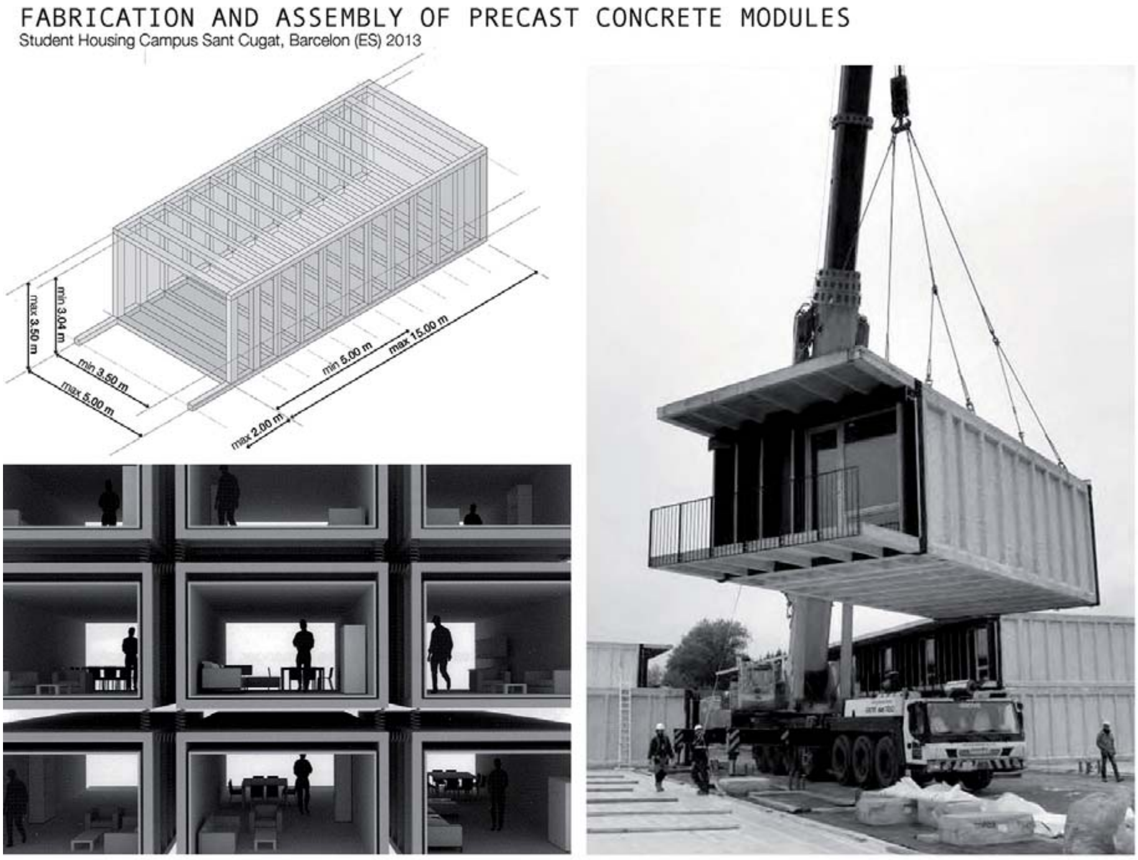

Fig 4 a – b Structural Corpus of Concrete Modules, Fig 4 c Assembly of Apartment Unit

3.2.3 Summary

Due to the double built-up of wall and floor components, the modular concrete system provides excellent insulation values allowing for energy certification ‘A’ for buildings. Depending on materialisation and built-up, an acoustical insulation of 55 dB for walls and 56 to 57 dB for floors and ceilings can be achieved. Furthermore, U-values for thermal transmittance of the building envelope are at 0.30 W/m^{2}K and range between 0.22 W/m^{2}K and 0.30 W/m^{2}K for roofs depending on configuration and material use. Contributing to its life cycle balance, construction process and building operation allow for energy savings and a reduction of CO_2. Compared to conventionally built architectures, savings of up to 60 % are expected. [5]
However, for a comprehensive life cycle analysis, logistical dependencies and transport distances between off-site manufacture and building site play a major role and need to be considered.

4. Discussion

The best practice examples prove the economical and ecological improvement of construction through prefabrication. For both projects, significant cost and time effective advantages were achieved, playing a major role for the developer's estimations. Material dependencies and regional preferences influenced the choice of building system opposite modular wood or concrete. In both cases, the familiarity with selected materials and systems prevailed.

Current processing methods and engineering technologies allow for improved durability of wood and its high performance as structural component. On the one hand, glue and cross laminated systems enable advanced structural solutions. Especially in the field of high-rise buildings, innovative structural technologies allow for energy efficient material use contributing to reducing the embodied carbon footprint. [6] On the other hand, for the development of intra-urban high-rise structures, however, fire-safety regulations and resulting constraints need to be considered.
A comprehensive design approach to solve material shortcomings is the use of hybrid-components, i. e. wood composites.

Considering the material's life cycle, concrete requires enormous amounts of energy for production and processing. Emissions make 85 to 90 % of the material's primary energy consumption and contribute significantly to an increase of the GWP values. Furthermore, the amount of rebar in reinforced concrete affects energy values and ecological properties. For a resource efficient manufacture of the material, the use of rain- and grey water, recycled granulates and break-off materials become eminently important. Additionally, high-performance concrete composites allow for innovative structural solutions, raising its applicability for resource efficient construction.

5. Conclusion and Outlook

5.1.1 Comparison of Methods

The coherence of materiality and building structure remains significant for the valid evaluation of current construction methods. The optimisation of buildings regarding fabrication process and structural systems requires an integrative approach to architectural design. The interrelation of building systems, technologies, and functional and environmental aspects is significant to define valid statements for the development of progressive architectures.

The modular design approaches enable high efficiency of production and assembly, and lead to significant time and cost savings. Controlled operations and monitoring of workflows contribute to to increased security on site, and at the same time reduce waste and water consumption. Finally, the modular structures enable easy exchange and removal of individual components; thus straightforward restoration and changes regarding future building modernization are provided.

Due to shifting the majority of processes from the construction site into the production hall environment, time and cost savings are achieved. Compared with the conventional construction in-situ concrete or masonry savings of up to 60% are expected. As a consequence, the overall energetic optimization of processes is provided.

Yet, the comprehensive assessment requires consideration of the structural materials, significantly influencing a building's ecological performance and technical properties. Compared to the use of wood products, concrete affects the primary energy balance, and leads to substantial limitations regarding the weight of the modules. Depending on size and dimensions, the units weigh up to 45 tons, requiring heavy-duty transport and special equipment for on site works. Ranging between 5 to 6 tons, the timber modules facilitate assembly and installation procedures, as well as transport and logistics.

5.1.2 Capacities of Building Systems

Representing novel manufacture and assembly processes, the above examination demonstrates material shortcomings due to single or mono material use. Hybrid solutions, e. g. wood-concrete composites, widen the fields of application, enhancing the performance of elements. Thus, contributing to an increase of ecological, technical and economical aspects, improved flexibility to today's manifold and diverse building requirements can be provided.

On the other hand, the combination of materials into composite elements affects later material separation, decreasing the recyclability potential. Furthermore, the correlation of varying properties needs to be considered, causing behavioral discrepancies.

6. Acknowledgements

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