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TOWARDS DESIGN FLEXIBILITY AND FREEDOM IN MULTI-STOREY TIMBER CONSTRUCTION: ARCHITECTURAL APPLICATIONS OF A NOVEL, ADAPTIVE HOLLOW SLAB BUILDING SYSTEM

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ABSTRACT: This paper discusses the architectural design potentials of a novel hollow timber slab building system for flexible and adaptive multi-storey timber building typologies. Current timber building systems are defined by their standardized nature, which limits most structures to unidirectional, rigid grids and limits designs to rectilinear layouts. At the same time, recent developments in computational design and digital fabrication open new possibilities to overcome these limitations. In this paper we present four building design applications of a new multi-directional slab building system that allows for a greater level of spatial flexibility and adaptability with free column placement and a tuned network of internal shear webs. These examples expand on previous work through the co-development of building design, skin, building system, and building service integration strategies for a long lifespan and changeable building program. The design applications illustrate open, reprogrammable floor plates that can support three different program states: office, residential, and mixed-use. Furthermore, the novel conceptual approaches to building service integration and the resulting slabs are compared to approaches more common in mass timber construction. Finally, we contextualize the study with related developments and discuss how computational and integrated design thinking could lead to a greater level of design freedom in timber construction and an increased applicability to more complex site conditions than in conventional mass timber construction.

KEYWORDS: multi-storey timber buildings, flexibility, adaptability, multi-directional timber slab, digital design

1 INTRODUCTION

Since the early 2000's, there has been an increase in worldwide construction of multi-storey timber projects [1]–[3]. This is in part due to environmental issues [4], the urbanization and densification of cities [5], [6], and material and building system developments [7], as well as to policy changes that allow taller timber buildings [8]. Although current projections show is a global demand for more building area [9], there is ongoing stagnation in the building industry [10], [11]. Additionally, there is a contradictory situation in which usable buildings are being prematurely demolished when they are considered to no longer be valuable [12]. Adaptable buildings are increasingly important in the face of changing economic incentives, rising material costs that make reuse more economically viable, and climate change [13].

Housing in some Asian countries has always had a shorter life expectancy than in the West, with an average demolition age of about 30 years versus 50-70 [14]. However, studies have shown that in some European countries the average demolition age is between 30 and 60 regardless of the building's program [15]. Furthermore, future demolitions will include buildings constructed only fifty years ago due to current methods of renovation and changing energy performance requirements [16]. In addition, changes in building layers are not made due to elements being obsolete but mostly due to external factors, such as economic or business-models [17]. This may be not only due to buildings being difficult to adapt, but also not designed for longevity or to accommodate future needs.

Timber is suitable for tackling challenges related to stagnation in the building industry because it is a digital material that is easily machinable and highly suitable for prefabrication [8], [18]. It also has a good stiffness to weight ratio [19], making it relatively lightweight for

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transportation, and can address challenges related to decarbonization thanks to its great potential for carbon storage [20]–[23]. While timber construction allows for relatively easy building component and process modification compared to concrete and steel, its flexibility is limited by shorter spans and limited architectural typologies [3].

1.1 FLEXIBILITY IN ARCHITECTURE

In literature, the terms adaptability and flexibility have multiple definitions and characteristics attached to them, often with overlapping meanings, such as expandability, polyvalence, or partitionability [24]–[27]. Perhaps the most widely accepted concept is that of separating, or shearing, building layers by their rate of change [17], [28]–[30], because the "longevity of buildings is often determined by how well they can absorb new services technology" [31]. The authors distinguish between two terms: (i) design for flexibility, which refers to the manipulation of design factors that affect the building's adaptability to change [32], and (ii) process flexibility, or flexible planning, which can refer to the ability of a (design) process or a system to adjust to and accommodate change and disruption [33], [34]. Both of these are needed for adaptable buildings and building systems [13].

1.1.1 Approaches to flexible design

There have been many approaches to flexible design throughout history, including, recently, Open Building projects [35]. In general, flexibility has been achieved through the use of an open area as a universal floor plan that can be subdivided into spaces based on need [17]. Therefore, homogeneous spaces and a "generality" of space [36] define the modern concept of flexibility, as opposed to heterogeneous spaces, which exhibit a more diverse range of spatial qualities. Conversely, interchanging and removing components is important for building use conversion [29], [37] as can be seen in projects such as the Multifunk building, whose networks of services and shafts to handle transformation, or the CiWoCo building, which separates service layers and partition walls from the structure [38].

1.1.2 State of the Art flexible projects in timber

While there are many concrete projects with large open floorplates, there are still relatively few flexible projects in timber construction. One of the more flexible projects is Patch 22 in Netherlands, a mass-timber frame project with 9m spans. Its general layout is enabled by a Slimline floor, a concrete slab that rests on timber beams with integrated steel profiles that provide cavities for installations in the raised floor [39]. This floor enables the residents to swap technical systems themselves [40]. Together with hollow floors, no vertical structure in the apartment interiors, a central service core, a tall stories and a high floor load, this produces a flexible and durable design. Another proposal for flexibility in timber construction is the Kiubo construction system, where prefabricated timber modules can be inserted into a concrete skeleton structure [41]. They can be swapped or connected to extend or change the interior requirements. While modular construction is developed at an industrial level, research is also being conducted on future-oriented timber buildings. The project "Convertible wood hybrid for differentiated expansion stages" tested a seven-storey timber frame structure for the use of parking, living, and working [42]. The design aimed for a neutrality of use and utilized recyclable materials at the building, assembly, and material levels. This was achieved through load bearing and window elements that could be reused or had reversible connections, enabling the non-destructive dismantling of components. It had a grid of 5.4m x 7.9m in the beam direction.

1.2 FLEXIBLE TIMBER DESIGN CHALLENGES

Engineered wood products, such as CLT have enabled increased structural performance and new heights of construction. At the same time, studies show that multi-storey timber construction has so far been limited to grid-based and mostly orthogonal and rectangular designs [3], [43]. Although timber construction offers the advantages of automation and prefabrication in terms of speed and cost-effectiveness, current wood building systems are defined by their modular and standardized nature. Even though elements of almost unlimited size and shape can be fabricated out of engineered wood, transport and assembly requirements greatly limit the complexity and scale of these systems and the resulting buildings. This is also partly due to the lack of suitable load transferring connections in timber [44]. In contrast, conventional reinforced concrete or steel structures allow can have larger spans and be more adaptable to site constraints or design intent. Therefore, timber building systems with spans competitive to concrete construction are mostly post-and-beam structures with a comparatively greater structural depth. Beams and girders impact the placement of partition walls, reducing options for interior partitioning and compromising the building's adaptability for future changes of use and therefore its life span.

Timber construction faces additional challenges in terms of flammability and acoustics. Building service integration is therefore often problematic, as services and any openings must be pre-planned and prefabricated.

1.2.1 Building services in mass-timber construction

In mass-timber frame structures, services are most often hung below beneath slabs or integrated between beams to increase flexibility and because they are easier to place and access. Services can also be placed above the structure either as an accessible layer, such as in a raised access floor, or as a permanently embedded layer of the structure, in conduits that run through the concrete topping of the slab. In exposed timber post-and-beam structures, services can be even more integrated, and run through and between structural elements, either through cut outs in timber beams, by staggering the heights of the beams, or by providing gaps in the structure, such as indents in the assembly of the structural elements. Table 1 shows how these service integration strategies, which can have different impacts on accessibility and freedom of placement of services, can be layered, embedded, or integrated into the building system.

Table 1: *Common horizontal building service integration strategies in post-and-beam mass-timber construction and type of integration based on accessibility.*

Service location	Integration type
Below structure	Layered
Above structure	Layered / Embedded
Through structure	Layered / Integrated

The structural system can inform or inhibit the way the building service systems appear and perform [45]. While the direction of beams can inform service paths, the structural grid can also intersect with MEP (mechanical, electrical, plumbing) paths, resulting in non-systematic overlaps. Additionally, current MEP systems, such as air ducting, are ill-suited to frequent changes of fit outs to adapt to new program or tenant requirements. Finally, the rectangular geometries and 90-degree corners of existing ductwork and mechanical systems are optimized for manufacturing and not for efficient air movement or distribution [46].

To allow timber construction to break free from current limitations and for its architectural possibilities to be competitive with concrete and steel construction, it is necessary to innovate on multiple levels, from design to fabrication processes, including service integration.

1.3 AIM AND SCOPE

This work investigates novel possibilities for multi-storey timber building designs. It showcases both a robust building design process and an adaptive building system capable of greater column spacing, lower structural ceiling depth, and an integrated approach to building services for greater adaptability in multi-storey timber construction. It will describe and compare four design applications of a novel building system as case studies to explore novel design possibilities and changes of building use. It will focus specifically on change in different operations cycles and building service requirements for different programs, and their impact on the design of the building system.

The authors define adaptability as the ability of the building to accommodate different programs throughout its lifetime with minimal costs or changes to the structure, as well as the ability of the building system to adapt to site and design intent. This paper asks the following questions. (I) How can digital fabrication and computational design methods enable novel multi-storey timber building typologies with innovative building service integration, and (II) what overarching, and timber specific design strategies are needed for a building that will change its program over a 100-year building life span.

The resulting case studies will address these questions as conceptual studies and integrative design proposals.

2 BACKGROUND

The research in this paper was conducted as an extension of that done on a resource efficient timber building system within the Cluster of Excellence on Integrative Computational Design and Construction for Architecture (IntCDC). This mono-material building system prioritizes timber over steel for its elements and joints, in contrast to the conventional mass-timber construction. The research included the development of new design, simulation, and fabrication workflows for this building system, as well as the Co-Design of a robotic prefabrication platform for its construction.

The development builds on top of the overarching methodology of Co-Design pursued within the IntCDC [47], and the integrative design workflows of the Institute of Computational Design and Construction (ICD) and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart. These have previously been used in the design of resource-efficient high-performance fibre [48] and segmented timber shell structures [49], [50], and have now been extended to multi-storey timber construction. The design application case studies presented in the paper were developed within the "Integrative Technologies and Architectural Design Research" (ITECH) master's programme 20/21 design studio.

2.1 BUILDING SYSTEM DESCRIPTION

The building system is based on a hollow slab consisting of thin upper and lower cross-laminated timber plates connected by internal shear webs tuned to a column layout and allowing for greater flexibility through multi-directional spans (Figure 1).

This level of customization is possible due to direct feedback via an integrated computational design and engineering workflow, resulting in a differentiated web layout, slab segmentation and joint distribution. Several papers already present the following aspects of the system: conceptual development of two previous hollow and solid slab system iterations [51], structural development and integration of structural principles in a computational design methodology [44], different design and simulation methods for internal web reinforcement placement [52], and agent-based methods for column, plate, and web placement [53].

As described by Krtschil et al. [44], the system consists of a hollow slab, columns, and their connections. The slab itself consists of three layers: a top and bottom CLT plate with shear force transferring webs also made of CLT in the middle layer. The webs are oriented by the flow of forces in the slab. The slabs are connected with a glued, stepped edge connection [44]. The column-to-column and

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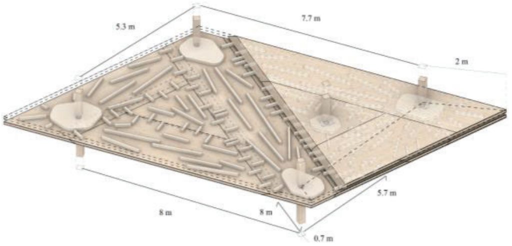

Figure 1: *Multi-directional hollow slab timber building system with internal shear webs.*

column-to-plate connections are reinforced with beech LVL. The columns are connected by a beech LVL pin that transfers the loads through the slab. The column-to-plate connections consist of a solid CLT column crown that brings the high moment and shear forces into the column. The columns can be placed freely inside the slab segments. The system is mono material as it requires no steel connectors.

2.2 STRUCTURAL CAPABILITIES

This first iteration of this building system enables spans up to 8 m and cantilevers up to 1.7 m with a 32 cm deep slab [44]. Further iterations may enable greater spans with only small adjustments in the overall slab depth.

The primary features of the novel system are: (i) large spans with a relatively shallow slab depth, (ii) cantilevers from 0.7 up to 2 m, (iii) corners that can meet at a variety of different angles, and (iv) irregular column placement with varying relations between them.

2.3 ARCHITECTURAL CAPABILITIES

Flat slabs are more flexible than those with beams because they allow greater freedom in partition wall placement. The building system enables design features currently not possible in flat slab timber construction. This includes aspects such as free slab edges, open corners, overhangs, greater freedom and variations in slab outline design and slab openings, non-orthogonal layouts, and large open floors (Figure 2). As such, in contrast to conventional mass timer construction, this building system can adapt to, rather than dictate, the design intent. The hollow cavity within the slab could also be enlarged, to either integrate services or be filled to improve the acoustic behaviour of the slab. The acoustic damping effect would be particularly notable for spans 12 m and above.

3 METHODS

The methods build on top of previous research and explore the application of the proto-architectural timber post and slab building system concept at an architectural scale. They are based on the integrated co-development of the overall building design, building system and building service integration strategies. This process considered robotic fabrication and assembly processes, alongside computational design and engineering methods for multi-storey timber construction.

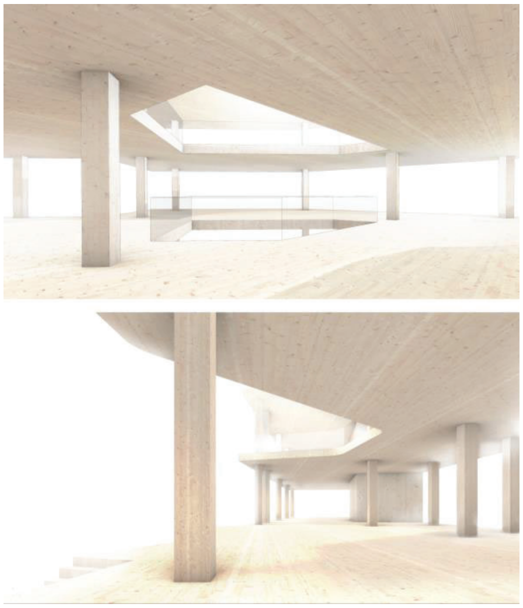

Figure 2: *Interior views of Case Studies 2 (above) and 3 (below).*

3.1 BUILDING DESIGN AND BRIEF

The design brief for the interdisciplinary design studio has been focusing on designing and developing a building system suitable for a long lifespan and change of building program; a "non-programmed" building with a minimum 100-year life span enabling a more flexible and multi-purpose use of space. Therefore, the main interest lies on the exploration of current technical possibilities in timber design and construction rather than on strict adherence to locally applied building codes and regulations.

The four Case Studies are two different architectural building designs on each of two different sites. As Figure 3 shows, the sites were selected due to constraints that typical mass-timber construction would have difficulty adapting to, such as a relatively irregular non-rectangular

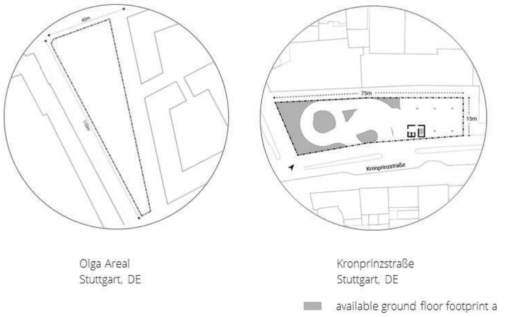

Figure 3: *Sites in Stuttgart, Germany: Olga Areal (left), and Kronprinzstraße (right).*

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site form, proximity to neighbouring buildings, and limited footing for construction due to pre-existing construction on site (underground parking).

Within each Case Study the hollow slab building system was extended by considering lateral bracing strategies for the overall structure, building façade design, and an integrated building service distribution strategy.

Each Case Study was then tested in four use cases: (0) the “non-programmed” state, (1) office, (2) residential, and (3) mixed-use program combining commercial with residential, such as a hotel.

3.2 Building System Components and Lifespan

Within this research relative lifespans were established for different building layers or components: permanent structure, semi-permanent building skin and façade elements, and temporary building services frequently adjustable to program changes. Table 2 shows the conceptualized average life span in years.

Table 2: *Relative building elements rate of change*

Building layer	Lifespan (years)
Structure	100+
Building skin	25
Building services	5-15

3.2.1 Structure and Hollow Slab Building System

The focus of the structural system development was to increase lateral stability of the building. Each of the four building designs had their own concepts towards this aim. These included cores, an exoskeleton, shear walls, and timber bracing. Another focus of the building system development was the optimisation of structural timber use, rather than maximising its overall use, with the goal of replacing metal connections whenever possible. The slab system was also reconceptualised to integrate building services, which required new slab segmentation, web placement, and assembly strategy concepts.

3.2.2 Building Skin

The building skin was developed to a conceptual level only, as a semi-permanent substructure that would change minimally regardless of program and service requirements. As detail development was out of scope, this included only aspects such as materiality and modularity. Structural supports are aligned with the façade segmentation and further panel subdivisions are done with future program distribution in mind, as façade subdivision is closely related to internal layout.

3.2.3 Building Services

The following MEP services were considered in the development of the design application case studies: heating, cooling, ventilation, and air conditioning (HVAC), electrical wiring, and plumbing. The focus was on developing overall horizontal and vertical service distribution concepts that would work for all programs despite their different technical needs. Table 3 shows a short overview of these needs. As can be seen, the main challenges were the opposing requirements for quantity of wet spaces, and for centralised versus decentralized HVAC systems, between Office and Residential uses.

Table 3: *Overview of service needs for the programs*

Service type	Office	Residential	Hotel*
Mechanical	centralized	decentralized	both
Plumbing	low	high	high
Electric	exposed	concealed	both

*mixed-use commercial program

3.3 Case Study Comparison

Finally, the four resulting hollow slab building systems are compared from two perspectives: (i) structural, considering slab depth, maximum span, and span directionality, and (ii) building service integration strategy and accessibility concepts in relation to the hollow slab and horizontal distribution of services.

4 Results & Discussion

Figure 4 shows four building designs with different horizontal and vertical building service distribution strategies. Case Study 1 and 2 were designed for an empty wedge-shaped plot. Case Studies 3 and 4 were designed to be built on top of a pre-existing parking lot and to adapt to the car entry and the existing structural grid (Figure 3).

4.1 Case Studies Description

4.1.1 Case Study 1

Case Study 1 relies on its service distribution strategies to create flexibly programmable spaces. This includes cores and temporary shafts for vertical service distribution and a distributed network of services integrated into the hollow slab. The cores’ hollow shear walls contain embedded service channels. The temporary vertical shaft locations provide a guideline for partition wall placement, but also act as access points for services in the slab when program change needs horizontal duct rerouting (Figure 4 -I). The partition walls can also provide additional horizontal service distribution. This has several implications on the slab system. One of the most relevant factors determining the possible service locations are the column locations as well as the slab segmentation, as openings for service accessibility need to be carefully considered for structural purposes. The service channels are placed inverse to the column location, which means that the slab openings are located mid span, away from areas with high shear forces, minimizing the structural impact (Figure 5).

The building façade was designed with a varying modular rhythm that matches possible future locations of partition walls. Movable shading modules allow for the enclosing and glazing aspects of the façade to be reconfigured,

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reducing the need to disassemble façade panels during use changes. Figure 5 shows how each program can use a different combination of service distribution strategies based on its needs. In the open plan office state wet spaces can be organized around the core with minimal horizontal runs. Electricity can be hung from the ceiling, and HVAC systems can use the core for vertical distribution and the slab for horizontal distribution with ceiling vents at slab access panels. In the residential state, a combination of cores and temporary shafts for vertical distribution and partition walls for horizontal distribution would increase the number of possible wet spaces in the floorplan. HVAC systems would only need to vent kitchens and restrooms, which could be done through the façade by way of partition walls. Electricity could also be integrated in the partition walls. The mixed-use state, such as a hotel, would use the residential strategy for rooms and the office distribution strategy for communal spaces.

4.1.2 Case Study 2

The design of Case Study 2 consists of integrated service channels in the slab for horizontal distribution, and cores and temporary shafts for vertical distribution (Figure 4 - II). Temporary shafts can be deployed when necessary and placed where services from the cores' shear walls cannot reach. Horizontal service lines are branching pathways that run from the cores and cut across the main direction of the webs with access openings carefully positioned between columns. They are arranged based on the shortest path needed to optimize their distribution. The service pathways are envisioned as encased metal ducts ensuring fire and moisture protection. Therefore, in the office state (1), wet spaces are limited to the areas next to the core, while in the residential (2) and mixed-use (3) states the wet space locations can be extended by use of deployable shafts and horizontal plumbing limited to partition walls (Figure 5). HVAC ducts are planned within the slab with venting along the slab edge, while electrical lines are planned within walls and floors. The facade design concept uses a limited number of modular dimensions for easy replacement and maintenance. Only a few custom elements are used, for specific corner conditions, that are expected to have a longer life-span.

4.1.3 Case Study 3

Case Study 3 leverages its site constraints to provide maximum daylighting for both itself and its neighbouring buildings by using terraces and an atrium. The design of the massing, in particular the relatively shallow floorplate depth, enables a thin slab with no integrated services. Services are instead distributed through the cores, while a limited number of temporary shafts link not to the ground but to a service transfer level below the first floor (Figure 4 - III). Wet program placement is therefore limited to the areas within the maximum horizontal run within partition walls from the core and shafts. As such, in the open office scenario (1), plumbing is constrained to areas around the cores, while HVAC systems and electrics are suspended below the ceiling. In contrast, the residential scenario (2)

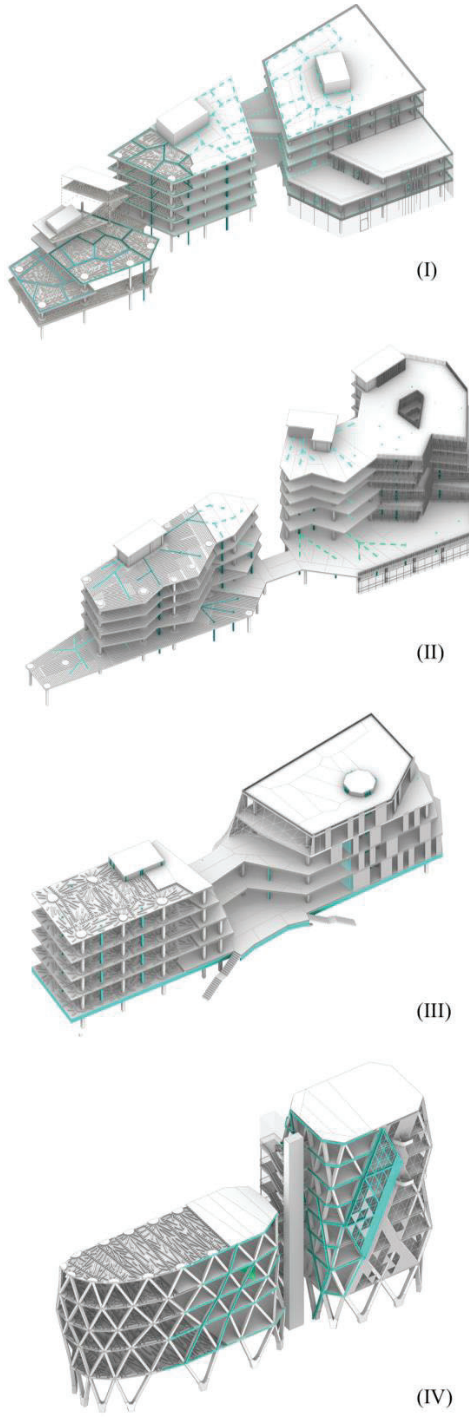

Figure 4: *Case Studies massings and exposed building system with highlighted service integration strategy and building skin design concept.*

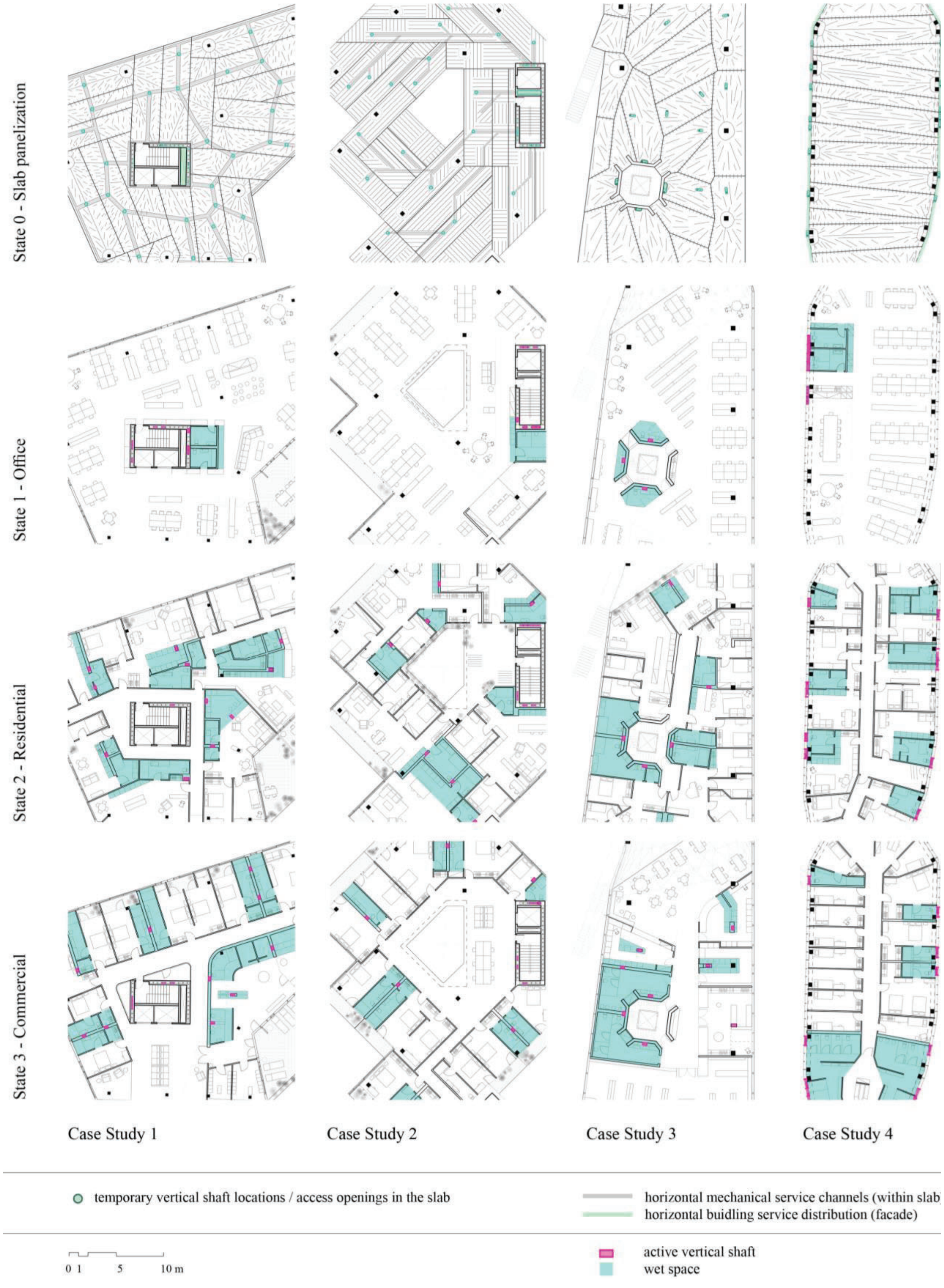

Figure 5: *Case Studies plans by different program*

uses a decentralized ventilation strategy in partition walls with exchange vents integrated into the façade. Similarly, electricity and plumbing are mostly integrated into the partition walls. As in other case studies, a mixed-use scenario (3) uses a combination of the two approaches (Figure 5). The façade concept relies on modular segments that can be replaced and swapped over time. The facade provides transparent and opaque modules, and the same system could also integrate new technologies, such as solar panels, as façade elements.

4.1.4 Case Study 4

Case Study 4 is based on the idea of relieving interior space of structural supports for a maximum amount of flexibility and adaptation. Adaptability to the different technical requirements of various programs is achieved through an integrated exoskeleton: the façade, services, and structural supports are organized along the floorplate boundary. Figure 4 - IV show how the façade contains all vertical service distribution channels, while the edge of slab houses the horizontal service runs. From there, partition walls take and distribute the services within the floor plan. As this Case Study's structural core is not within the floor plate, all services are distributed either i) from the façade via partition walls, or ii) as exposed cabling or HVAC ductwork beneath the slab, as is commonly seen in open plan offices, regardless of program. Figure 5 provides an overview of the vertical shafts in the different program states.

The façade is designed to follow the supports, creating areas that are triangulated and subdivided into smaller panels which can be either transparent, for view, or opaque, to conceal services and provide enclosure. The façade frames are perforated to allow (future) services to run freely. The façade layer therefore dictates service placement, level of enclosure needed for the program (transparent or opaque panel), and the rhythm of the partition wall placement.

4.2 Case Study Comparison

4.2.1 Building structure and building system

The Case Studies utilize the circulation core and facades as their primary vertical load-bearing system, with the aim of minimizing the number of internal columns. In Case Study 1, there is only one column placed internally due to span limitations. In Case Studies 2 and 3, column spacing and placement adapt due to design of atriums, terraces, or openings in the slab for increased daylighting. These three studies all use the internal cores for lateral stability. Conversely, Case Study 4 only has structural supports along the façade with no internal columns due to its exoskeleton structure. This choice necessitated longer spans, up to 13.5 m, and therefore also a deeper slab. The case studies all maintained the 110mm dimensions of the top and bottom plates from the previously developed hollow slab system [44] but increased the height of the cavity and therefore the structural depth and the maximum spans (**Feil! Fant ikke referansekilden.**).

Internal web reinforcement and slab segmentation strategies were another factor that varied between Case Studies due to different horizontal service distribution strategies. As can be seen in Figure 5, Case Study 1 has three categories of internal webs based to their structural and service related functions: (i) webs forming closed internal channels to carry ducts for HVAC or electrical cables (plumbing was excluded due to the risk of water damage), (ii) longer span webs which act as internal beams, and (iii) shorter webs that connect different slab panels as well as fill the remaining slab space.

Case Study 2, meanwhile, aims to increase possible cantilevers by placing most webs orthogonal to the direction of the segmented slab. This orientation changes based on stiffness allocation in the slab but is limited to 90° or 45° rotations within the panel (Figure 5). In other Case Studies, slab segmentation and internal web placement are not constrained by service channels. The arrangement of webs is instead governed by the principal moment vectors at their position in the slab, and the slab segmentation is primarily governed by the spanning axis within the floorplate. In Case Study 3 this means a more irregular arrangement of panels, while in Case Study 4 this results in mostly rectangular panels with transitional trapezoidal panels due to the uneven distribution of vertical supports (Figure 5).

4.2.2 Service Integration Strategies

As mentioned in the comparison of internal web reinforcements, the Case Studies show several different approaches for horizontal service distribution within the slab (Figure 6). Case Studies 1-3 all utilize the core as the primary vertical distributor, along with temporary shafts that get utilized based on program needs (Figure 5). These slabs have openings that either are filled by the temporary shafts or act as access panels for maintenance. Whereas Case Studies 1 and 2 concepts embedded both their mechanical and electrical services within the slab, respectively, Case Study 3 relies completely on suspended

Table 4: *Structural depth and maximum span values of the Case Studies.*

Case Study	Structural depth (mm)	Internal cavity (mm)	Maximum span (m)	Service integration	mechanical	electric	plumbing
CS1	420	200	12	within	x	x	n/a
CS2	420	200	12	within	x	x	n/a
CS3	320	100	8	n/a	n/a	x	n/a
CS4	520	300	13.5	slab edge	x	x	x

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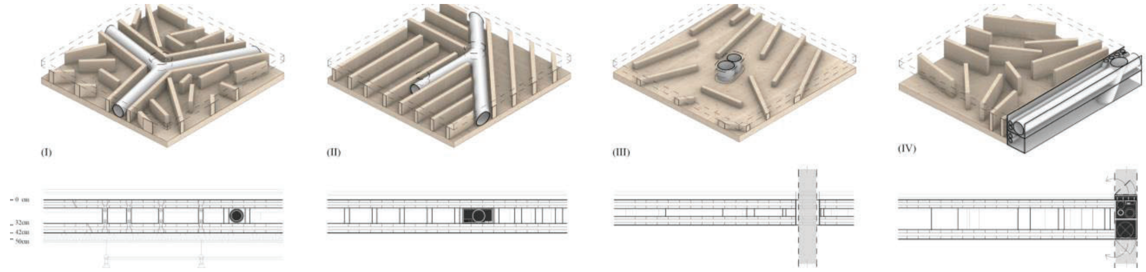

Figure 6: *Case Studies slab comparison with highlighted building service distribution strategies within the slab.*

suspended services or services integrated into partition walls for horizontal distribution. Although Case Study 3 does not integrate any services within the slab, the 100mm shallow cavity could theoretically allow electric cables to pass through. Similarly, Case Study 4 relies on services being integrated into partition walls or suspended below the ceiling. However, due to the façade based vertical distribution strategy, the slab still incorporates full MEP horizontal service distribution along its edge. While other concepts are more embedded or integrated into the slab, services are most separated from the slab in Case Study 4.

5 DISCUSSION

The developed multi-storey timber building system results in multi-directional spans with irregular point support layouts by creating a semi-monolithic slab out of segmented hollow slab plates. Embedding services inside the cavities of these plates results in a smaller overall floor depth, including services and floor and ceiling build-ups, when compared to typical mass-timber construction. This has two effects: the cavity could simultaneously contribute to better acoustic performance; and the system is more complex to fabricate than a solid CLT slab.

5.1 Comparison to common timber systems

As can be seen in Table 5, we compared the performance of some of the timber slab building system products on the market to the performance of the hollow slab system. Although there are products available that offer large spans, they either have greater structural depth, a composite or ribbed structure or offer only uni-directional spans. The most similar product in performance would be the TS3 flat timber slab system which offers bi-directional spanning up to 8x8m grid [54], but further research is being done on TS3 GridBox, a hollow box with a girder grid to reduce costs and save building material [55]. The building system showcased in this study may be more suitable for larger spans of up to 12 m due to increased fabrication complexity and lack of available solid flat slab systems with similar depth and spanning capabilities on the market.

Another aspect gleaned from the comparison is that most systems do not integrate building services in the building system development. This also shows that most building systems today are mainly developed without considering services. As a result, additional height and build-up are needed compared to the case studies of the hollow system where the increased structural height can save overall floor to ceiling height.

Table 5: *Structural depth and maximum spans designed for office use, spanning directionality values of common market slab system products, and potential for service integration (marked with "x" for possible integration within the element)*

Product	Depth (mm)	Max. span (m)	Span. directionality	Service integration	Slab system description
Research slab	310	8	Multi-	n/a	Hollow slab with internal webs [R]
Case Studies 1-2	410	12	Multi-	x	Hollow slab with internal webs
TS3*	400	8	Bi-	n/a	point supported solid CLT plate [57]
ThomaHolz100	212	5	Uni-	n/a	DLT slab [59]
StoraEnso rib panel	580	13	Uni-	n/a	CLT rib panel open R30 [60]
Kerto-Ripa	660	14.7	Uni-	x	LVL 5-rib floor [61]
Lignotrend	410	8	Uni-	x	Box slab [62]
Lignatur	440	10	Uni-	x	Hollow box-slab [63]
Kielsteg	380	13	Uni-	n/a	Flat hollow slab [64]
CREE	400	9	Uni-	x	Timber drop beams with concrete [65]

* Depth and max. span for a 5 kN/m² Live Load

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5.2 Limitations of the work

The developed case studies are primarily of a conceptual character. They explore novel possibilities for design and construction while considering design, building service, structural, and fabrication limitations. However, they do not provide comprehensive or definitive solutions.

The case studies lack a specific consideration of fire code relating to building class, integration of services and exposure of timber elements. The integration of different elements, such as façade, its' substructure, even partition walls, and their interface with the building system, is also left open.

Our observation is that there are great potentials in integrating service within the structural layer of the slab. However, this development cannot be achieved only by automating service placement and installation in prefabrication. New innovative methods for service rerouting, replacement and maintenance or damage detection with new technologies are needed.

One future promising trajectory of research to address this would be mobile robot service installation or service extrusion. This could expand the possibilities of the timber slab design and make the suggested integration strategies more competitive with systems designed based on and operating on manual serviceability and accessibility. Additionally, it is important to acknowledge that it is very difficult to predict the dimensional, operational, and other requirements of future technologies. Questions about the minimum sizes for internal cavities and access panels for future requirements need to be balanced against structural considerations, particularly spanning performance.

Moreover, there is a trend away from use of suspended ceilings and towards exposed ductworks and services in office environments to gain room height. While in timber construction the use of beams and grid-based design can work in favour of typical ductwork, with a flat ceiling use of conventional service distribution strategies might lead to poor aesthetic quality. Already, enabled by computational design, novel airduct geometries are being developed that enhance air distribution and aesthetic quality [46].

This paper only presents a design proposal and a façade concept. Further analysis is needed on how to integrate lateral supporting structures — such as cores, walls, façade systems, or pre-existing structural elements in other materials — into the building system.

6 CONCLUSION

The presented research shows integrative development of four design applications, and therefore also timber building system variations, of a hollow multi-directional slab for multi-storey construction with structural and building service considerations. The studies showcase novel possibilities for design in timber construction, adapting to conventionally complex site conditions, creating interior spatial situations not currently possible in pure timber construction and change of use during the building life cycle, as well as initial conceptual strategies for building scale application. Compared to typical mass timber systems, the system allows for higher resource efficiency and decreased of wood use due to structurally informed placement of internal reinforcement within a cavity. One of the clear perspectives for new developments in terms of increasing flexibility relates to considering the full life cycle of the system past end of use. The current state of research focused on preventing the necessity of disassembly, however demountability of elements or their reusability were not considered.

The designs leverage complex timber elements that must be prefabricated with strict tolerances. The inherent advantages of integrated design have been used in the design of both the building and the building system. Integrating different phases of program use into the design planning enhances the outcomes of the project and is only possible through an adaptive building system and an adaptive planning process.

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