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ADAPTABILITY IN MULTI-STOREY TIMBER BUILDINGS – TOWARDS DIFFERENTIATED DURABILITY LAYERS IN ARCHITECTURE

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ABSTRACT: The rise of multi-storey timber architecture has been recognized by multiple actors in the field. Most contributors discuss new timber buildings made with engineered wood products (EWP) almost entirely technologically, neglecting both spatial-architectural and organisational-functional aspects within buildings. Furthermore, even though today's timber structures are designed for longevity, studies show that more than half of all buildings are demolished not because of technical deficiencies but because of vacancy. This suggests that most buildings have an insufficient potential for adaptation.

This paper critically discusses current approaches of adaptability in timber construction and examine their relevance and effectivity within the larger theoretical framework of architectural adaptability. For this purpose, both areas are discussed based on existing literature and compared in their central aspects. Based upon three case studies in Europe, the principles of adaptability for timber buildings are visually traced and analysed.

In conclusion, precise demands for zones of changeability and permanence within the building can be predicted and timber components can be applied accordingly in a targeted manner. The paper proposes strategies for designing a timber construction that is differentiated according to the functional layers and designed to be able to adapt over time.

KEYWORDS: Circularity, Adaptability, Flexibility, Timber Engineering, Structural Design

1 INTRODUCTION

Thanks to new technology and advances in material research, wood is experiencing a renaissance as a modern building material. The ground-breaking improvements in engineered wood products (EWP) in the last decades have fundamentally changed timber architecture. Moreover, the rise of multi-storey timber architecture has been recognised by multiple actors in the field, i.e., architects, engineers, manufacturers and academics alike. However, most contributors discuss new timber buildings with four storeys or more almost entirely technologically, neglecting both spatial-architectural and organisational-functional aspects within buildings. [1] In general, studies show that more than half of all buildings are demolished not because of technical deficiencies but because of lying empty. [2, p. 421] Therefore, even though today timber structures made with EWP are designed for longevity, most buildings most have an insufficient potential for adaptation. As Geldermans (2016) notes, adaptability is a prerequisite for circularity, as it generates quality and added value.[3] This raises questions about the current discourse of adaptability in timber architecture regarding the actual circularity of a modern timber construction beyond the promising role of the biomaterial.

In recent years, a certain amount of important work have addressed the circularity of timber buildings. In general, Ellen MacArthur Foundation's definition of the circular economy as an 'economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles' is accepted in architectural and timber engineering literature. [4, p. 5] In this respect, the six ReSOLVE Framework actions for the implementation of circular economy (Regenerate, Share, Optimise, Loop,

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Virtualise, Exchange) are too broad to be directly applied as guidelines for the design of circular buildings. [5] Instead,, Cheshire outlines five design principles for applying circular economics: building in layers, designing out waste, design for adaptability, design for disassembly and selecting materials. [6] Similarly, in structural engineering, design for robustness, design for durability and design for repairability can be added as circularity strategies. [7] In this paper, we focus on adaptability following the findings of previous studies that 14% of the embodied greenhouse gas emissions can be prevented if a structure is reused instead of recycling its materials. [8, p. 9] Although referred to as ‘flexibility’ in several publications, [9], [10] we accept Schmidt and Austin’s definition of adaptability as a capacity of a building to accommodate the evolving demands of its users and environment effectively, thus maximising value through life. [11]

While research on adaptability in architecture has developed a nuanced understanding of the gradual permanence of building layers throughout the lifespan of a building, the discussion on adaptable timber buildings mainly considers general technical aspects such as those of the building elements and connections. Besides these aspects, most literature neglects social and economic indicators. [12, p. 18] Hence, the architectural discourse can expand the technical discourse of adaptability of multi-storey timber architecture by taking into account social, cultural and economic indicators. In so doing, it can reveal strategies for designing a timber construction that is differentiated according to the functional layers and designed to evolve over time. In this way, building adaptability brings an overarching coordination layer to the design process, in which material and constructability decisions can then be coordinated explicitly concerning overall long-term goals. As consumer expectations, technological progress and competitiveness are increasing, the need for adaptability is likely to increase as well. [13]

The aim of this paper is to critically discuss the current approaches of adaptability in timber construction and examine their relevance and effectivity within the larger theoretical framework of adaptability in architecture. For this purpose, adaptability in timber engineering and architecture are discussed based on existing literature and compared in their central aspects. Subsequently, they are brought together in spatial diagrams in which the potentials and conflicting goals are described.

2 METHODOLOGY

For the purposes of this paper, the particular features of ‘circularity’ and ‘adaptability’ in timber engineering are analysed through a comprehensive literature review. Previous research on the topic of adaptability and circularity in timber engineering is searched for in the online databases Scopus, Jstor and Web of Science. The searches conducted in April 2022 requested the key words: timber AND engineering AND circular OR circularity OR adaptable OR adaptability, and was repeated in November 2023. Based upon these findings, the list of circularity facilitators in section 3 is distilled. These themes are examined with a focus on their inherent environmental goals and circular strategies.
Similarly, in section 4 the most significant approaches to adaptability in architecture are discussed. The canonical work of Schmidt and Austin, and Leupen and their references are taken as a starting point for the definition of adaptability. Additionally, the data-driven study of Ross (2016) and its preliminary results are a basis for a theoretical framework of adaptability enablers, complemented with the references of the theory of adaptability. This is followed by a critical positioning of the technical engineering approaches therein.
In section 5, the insights from key papers and books discussed here are supplemented by applications in practice that have been discussed and referred to by scholars. The most recent literature on the rise of timber architecture (from 2020 onwards) is taken as a base for the analysis of the trends and the identified indicators. These indicators are evaluated against three cases, chosen for their variety and exemplarity of the current trends. The case studies in Europe are multi-storey buildings of various sizes and functions which are illustrative of the circularity and adaptability approaches found in the literature. The analysis of the cases is based upon the published plans and sources cited. As visual feedback is important for experts in the field [14, p. 10], the principles of adaptability are visually traced, modelled and analysed. This diagrammatic approach is based on Leupen's visual studies and Rinke and Pacquée's concept of structural porosity. [15] The method proposed here illustrates the sustainability potential of EWP and their contributions to adaptability discussed from the literature and relates them to the permanence layers of adaptability in architecture.

3 TIMBER ENGINEERING ON CIRCULARITY

Since wood is part of the biological cycle of the circular economy, structural timber has a high inherent circularity potential. Other inherent environmental benefits associated with structural timber are carbon storage, renewability, lower energy demand, malleability, durability, visual quality, thermal conductivity, lightness and recyclability. [16, p. 141], [17, p. 3] This is proven by multiple life cycle assessments comparing mass timber structures with similar variants in other materials. Even though carbon sequestration could suggest that maximising the use of timber is the most sustainable, this renewable natural resource should be applied efficiently: reduce, reuse, recycle. [18, p. 25]

Nowadays, sustainability objectives generate many incentives for larger timber construction, supported by subsidies and a growing expertise. However, circularity in

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timber buildings is faced with several threats, organisable in three categories: market forces, regulations, and physical conditions. First, due to resources running out, the competitiveness for forest products plead for intelligent use of timber. [16, p. 145], [19, p. 8] Also, the low material cost gives little incentive for recycling [16, p. 149], [19, p. 7]. Studies focus on the environmental impact of reusing or reprocessing salvaged timber in mass timber products or (non-)structural applications. [12, p. 18], [20, p. 9] However, there are very few examples in practice where structural timber has actually been recovered and reused, and just like other materials, timber has been downcycled or recuperated for bioenergy in Europe. [21]

Second, national regulations are inconsistent relative to timber building construction. The absence of adequate guidelines in the current edition of The European Standard Eurocode 5: Design of timber structures is particularly pointed out, although a new version is in the making. [17, p. 7], [22]

Third, some technological risks are also to be considered. The assessment of the structural performance of elements for reuse is difficult. [19, p. 7] Seismic resistance, acoustics, moisture performance and fire resistance are yet to have universal solutions with predictable behaviour and efficiency. [1, p. 103] The overall costs and risks of this relatively new mode of construction can be higher than standard structure, leaving little room for circularity. [1, p. 134].

This newness also provides an opportunity for establishing the regulations and expertise with a circular viewpoint from the start.

To design for circularity, the benefits and risks need to be clearly identified. In current timber engineering research, the main facilitators or strategies for circularity are:

1. Disassembly potential connections [1], [7], [16], [18]–[20], [23]–[25]
2. Avoiding glues, non-compostable coatings or elements [16], [18]
3. Keeping timber inside the thermal and waterproofing system and eliminating risks from internal water damages [16], [23]–[25]
4. Standardising components or modularity [1], [20], [23], [25]
5. Certification of circularity and reuse [16], [19]
6. An independent building envelope [1], [18], [23], [25]–[27]
7. Durability and possibility to repair or replace the damaged parts [19], [20], [26]
8. Facilitating the adaption to increased loads [19], [26]

The abovementioned strategies for wood as a circular structural material can be seen as design for disassembly (1, 2, 4, 5, 6), design for robustness (8), design for durability (3, 5, 7), or design for repairability (3, 7). Although design experts rate design for deconstruction/disassembly as one of the least effective enablers for adaptability [2, p. 426] [24, p. 25], it is mentioned most in timber literature. These strategies primarily focus on the material and components level of circularity. Very few studies focus on the scale of a building for circularity and on design for adaptability although this leaves the most of the embodied carbon in place. [28]

As Campbell argues [16, p. 150], there is a need for mass timber construction research concentrating on durability and adaptability for buildings as a whole. Also, Ahn argues that there is a lack of expertise and knowledge on circular mass timber construction and stresses the lack of research attention in the timber construction sector directed towards public and stakeholder awareness for the circular economy. [20, p. 12]

In summary, it can be stated that the technical conceptualisation for adaptability is limited to the element and material level and that the elements are discussed here largely independently of their local and functional use in the building.

4 ADAPTABILITY IN ARCHITECTURE

The disposable building culture has been called upon by multiple authors in the twentieth century. Nowadays, many features of the built environment are purpose-built. Before adaptability became a research subject, many vernacular buildings were already genuinely adaptable to functional problems and responded to changes. [29] The foundations of adaptable architecture are is found in the early Modernist movement and applied in Europe in the housing crises following the first and second world war. [9], [30], [31, p. 158] In the early sixties, the Dutch architect Habraken proposed a participative concept for public housing and thereby introduced the terms 'base building' and an adaptable 'infill'. [32] The Open Building design movement was based on this first work. [33]

The definition of adaptability from Schmidt and Austin as given above can be understood both as a characteristic to accommodate the demands without changes to a space - also known as polyvalence [31, p. 26]- or by altering the physical form of a space. Therefore, they introduce six types of change: adjustable as a change of task, versatile as a change of space, refitable as a change of performance, convertible as a change of use, scalable as a change of size, movable as a change of location. According to Schmidt and Austin, the structure of a building interacts with versatility, convertibility, and movability, but scalability could be added. Circularity is not mentioned in the book, however the concept of adaptability clearly is linked to the circular economy.[11]

Even though all types of adaptability are to a certain extent realisable for any building, universal adaptability is not realistic nor advantageous. [11, p. 274] Many design practices are wasteful and over specify for instance electrical services or one-system connections which could be outdated or unavailable promptly. [11, p. 7] Modelling

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building adaptation is in a nascent stage. [34, p. 284] Data-driven models are rare, but Ross (2016) cites four enablers for adaptability based upon expert reviews: separation of building systems, whether interiors are free of structural elements, reserve capacity and as-built documents. [2] These four enablers are discussed in following points in detail.

4.1 Distinct Layers

One could go back to Laugier's primitive hut [35] and discern a structure and a protective layer as two separate building systems. Also, Semper's [36] four elements - hearth, earthwork, roofwork and enclosure – can be understood as the origins of the layer's theory. In a modern context, Duffy (1992) recognizes distinct elements of (office) buildings in a modern context: shell, services, and scenery. The literature on circularity mostly cites Brand (1995), who proposes buildings consisting of shearing layers. [31, p. 31] Schmidt and Austin later defined building layers as nominal categorisations that describe a building at a given scale that allow for the stratification (decomposition) of a building as a way of gaining further insight into how it will change over time. [11] The separation of building systems facilitates change, as adjusting one layer does not imply other layers have to be adjusted. The differentiated rate of change of the structure versus - for example - the scenery creates a hierarchy between the layers. To the layer model, ARUP (2016) adds a system level to cover more of the built environment than just buildings. The report crosschecks the ReSOLVE framework with the layers of Brand.[37] Leupen, in 2006, spatially related the layers in axonometric schemes and theorized the frame and the generic space as a less hierarchical model. [31] His layers: 'structure', 'skin' (building envelope), 'access' (circulation), 'service', 'scenery' (interior) are accepted in this paper. The distinction of these layers is seen as the first enabler for adaptability.

4.2 Spatial overcapacity

The literature is unanimous about adaptability due to spatial overcapacity. 'Loose fit' promotes a larger floor area than is strictly necessary for the first use.[38], [39] An open plan free of permanent objects in space allows for easy conversion, stated as the second enabler. Loadbearing walls should be minimized. [11, p. 21] [24, p. 25] Likewise, heigh ceilings allow for maximum daylight, other uses and intermediate floors. Structural typologies such as a short or a wide span, skeletal or massive structures are likely to persist, since they are the backbone of a building. [11, p. 73] Overcapacity could also mean extra storage space, a bigger window size or a predesigned fire safety division. [11, p. 4] For example, constructions built before 1970 often have this extra load-bearing capacity or large dimensions and are therefore favoured by developers for reconversion. [40, p. 4]
To conclude, spatial overcapacity is incorporating the third enabler 'reserve capacity' for facilitating changes. [13, p. 213] A wall-based or column-based structural system and its floor height are seen as key parts in adaptability. Therefore, the choice of a structural system has a significant impact on its adaptability. The equilibrium between over-dimensioning and reducing material use generates a potential conflict which has to be assessed case by case. [17]

4.3 Readability

Readability is about conveying a message to be adaptable. Hence, as-built documents – the fourth enabler - are vital deconstruction information in order to disassemble parts but also to assess load capacity, demolition or repair diagnostics. [20, p. 7] [24, p. 23] Sometimes, however, readability is understood as simplicity. Schmidt and Austin expanded the concept of legibility as a straightforwardness and implicitly clean and exposed joints. [11, p. 96] Others go further and focus on easily understood load paths and repeating thus predictable layouts and grids. [2, p. 422] [13, p. 215] However, when Hertzberger accepts the rigidity of a structure on which an identity can be based, he accepts a structure which suggest spatial possibilities. [32, p. 24]
Simplicity could bring in functional neutrality. For example, 'Solids' are designed as urban buildings with different functions in mind. [40, p. 7] This neutrality is seen as a means of adaptability. Nevertheless, Leupen mentions 'articulating the frame' as a way to give it cultural significance. By adding architectural expression instead of neutrality, the permanent gains meaning and therefore endurance, it becomes an intelligent ruin. [31, p. 33] Or as architect Mies Van de Rohe states: 'Only a clear expression of the structure could give us an architectural solution which would last.' [31, p. 63]

Even though many strategies like these four enablers can be applied at little or no raise of the construction cost – with standard construction methods and decrease in construction time [13, p. 216] - universal adaptability of an entire building is not reasonable nor useful. [11, p. 274] Adaptability has mostly been researched at a building level. [41, p. 118] Aside of these most effective enablers, we propose to add zones of changeability where adaptability in a building is most expected depending on changing demands.

4.4 Degrees of permanence

The theory of shearing layers can provide the framework for applicable design principles, but they mostly refer to a building as a whole. Therefore, the hierarchy of the circularity layers and their durability should be adjusted to their degrees of permanence diversified in a building. While the structure could be designed to last one hundred years, the services and scenery will most likely be adapted in about 15 years. [42] As argued by Rinke and Pacquée in [15], access routes in buildings are less likely to be adapted because of their essentiality. A differentiated look at the structure has to be adopted. The function of a space

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as an access route demands a more permanent structure than the division between two programs. The shearing layers that were previously conceived for the entire building would therefore have to be related to the specific functional zones of the building.

Rinke and Pacquée define the porosity of structural surfaces, related to the higher-level porosity of the building, as the capacity to open walls or slabs. They suggest specific zones of a building which could be designed for disassembly, as a hierarchy of substructures and demountable components. Therefore, they refer to the first half of the twentieth century, where material economy and post-war reconstruction demanded faster and cheaper modes of construction. Their critique on the layer model challenges the unitary view of an entire building without differences in zones of permanence. The load-bearing structure, the functional areas, the access routes and the horizontal and vertical circulation of supply and people are seen as more permanent. [15, p. 4]

As the circulation system and access are critically necessary, they rarely are subject to changes. Other authors also consider vertical circulation as necessarily permanent. For example, Habraken mentions the staircase as a lasting feature. [32, p. 184] To improve the flow of people and things, the location and the number of cores (service risers) are critical adaptability parameters because of their difficulty to change. [11, p. 73] [13, p. 215] According to Leupen, access has significance and permanence if it takes up an extra function, for example a gallery being more than a corridor. [31, p. 114] Access could thus be a permanent layer.

In contrast, Remøy and Van der Voordt see the plinth of a building as more subjected to change. Consequently the ground floor could be the ultimate place for adaptability investments such as ceiling height and open plan. [43, p. 4] Also, in the centre of a building, Leupen intends an adaptable structure with an open zone which could be filled in with a wooden floor or accommodate service risers. [31, p. 166] These two examples demonstrate strategies for more volatile zones of permanence.

A structure's adaptability characteristics should be adjusted to the degrees of permanence of the structural members in the building.

4.5 Non-physical aspects

Other aspects of adaptability which are rarely included in timber literature, but which are very influential, are location (such as social image, amenities, public transport) and non-physical values such as acquisition and operation costs. [11, p. 152] A building always has a social function and has the ability for social change. [11, p. 20] Many of the experts involved in multi-storey timber projects are motivated by social, economic, and environmental aspects of working with the built environment and its stakeholders. Process adaptability should not be minimised but falls out of the scope of this paper. [34, p. 275]

4.6 Adaptability in timber literature

The abovementioned enablers and the nuanced zones of permanence can be compared with the strategies for circularity in timber engineering literature identified in section three.

Firstly, in the list of facilitators for circularity the concept of layering is presented as the building envelope 'skin' independent of the 'structure.' However, the detachment of other functional building parts, such as Leupen's other layers: 'access,' 'service,' 'scenery,' regarding timber architecture are not discussed. Nevertheless, Kaufmann mentions layers of timber structures for maintenance, disassembly and recycling. [18, p. 27]

Secondly, overcapacity is revealed as a technical option to facilitate higher loads, but spatially only Jockwer points out the possibility to adapt according to the comfort demands regarding room size and structure, acoustic and interior performance. [19, p. 9], [26, p. 2] The open plan, in this paper identified as part of spatial overcapacity, is not to be found as a strategy in the timber literature on circularity.

Thirdly, readability of a structure or the exposure of structural members is not detected in studied literature. The cited certification of circularity fixates on labelling components, while a full as-built dossier or a straightforward structure which could make the whole timber building readable.

Lastly, the focus on components and design for disassembly in timber literature demonstrates the conceptual design mode, where the building exists as a whole and can be disassembled. It overlooks the possibility for gradual changes through zoning and corresponding degrees of permanence. The closest to this strategy is repairability, which seeks the replaceability of damaged parts in an intermediate scale between component and building.

As Brand mentions, the buildings which proved to be the most adaptable (like Amsterdam canal houses) are built upon knowledge acquired by centuries of trial and error. [11, p. 14] Therefore, the abovementioned existing research on adaptability could be a basis for analysing and frame the current trends of multi-storey timber construction.

5 CASE ANALYSIS

5.1 Adaptability in practice

The current trends in multi-storey timber buildings are studied in [1], [17], [44], [45]. Recent developments in practice like prefabrication, system construction and rigid structural grids are critically discussed against the background of the presented adaptability research. In the following, these trends are assessed against the enablers for adaptability and the degrees of permanence.

For risk mitigation and time saving, onsite works are increasingly minimized and prefabrication is introduced. Since most prefabricated projects are focussed on simple assembly on site, disassembly can be designed in a similar fashion. In contrast, old-school timber framed buildings are not designed for disassembly because of the extensive fixing of materials to the frame. However, the adaptability of contemporary timber structures might depend on the size and development of the prefabricated units. The deconstruction effort and cost depend on the size and weight of elements, the number and type of connections, and their location in the building. Disassembly might require heavy construction equipment like cranes and temporary scaffolding, just like during the construction phase. [20, p. 2] The larger (façade) units can complicate disassembly since they often arrive fully equipped and watertight on the construction site. [1, p. 134] This might also complicate the readability of a timber structure. Furthermore, when services are hidden behind a structural lining, the adaptability or refitability will be restricted. Above all prefabrication targets, services as well as all layers should remain separable.

System construction is an important trend in timber construction. As Kolb described the size of the prefabricated units as room modules, wall or plan units, or small modules, one can discern volumetric, planar or linear (post and beam or frame) systems. [46, p. 44] The earlier multi-storey timber buildings are mostly constructed in a cross-laminated structural system. Volumetric and planar elements were the two most common structural systems. [17, p. 3], [44], [45, p. 22]
The first structural system, volumetric modules, is programmatically very specific, as it is limited to room spaces. Hotels, (affordable) collective housing projects, retirement homes and schools are the most frequent programs in volumetric modules. These specific programs do not imply a high possibility of convertibility. [45] The entire volumetric modules can be removed but these blocks are often too large for changes in individual demands. [19, p. 8] In a repetitive and enclosed structure made of volumetric modules, there is no possible diversification based upon degrees of permanence. At the moment, volumetric modules incorporate few architectural versatility and there is no market push towards the functional versatility of volumetric modules. [24, p. 21]
The second structural system of the early multi-storey timber buildings comprises planar structures. Mostly up to 10 stories, the CLT structures allow only limited spans and require many wood resources. [47, p. 27] The massive use of CLT between functional spaces or room modules with two load-bearing walls contradicts the spatial overcapacity, open plan and the degrees of permanence of architectural adaptability. Out of 350 studied projects in [45], 79% of the buildings with planar systems have residential programs. This suggests a limited convertibility.
From 2011 onwards, hybrid and frame structures are rising, especially in the tallest timber towers. [17, p. 3], [44], [45, p. 22] The open plan makes space for spatial overcapacity. Unsurprisingly, linear systems have more evenly distributed programs with a focus on commercial, which implies high convertibility. [45, p. 22] There is a shift from residential planar structures to commercial linear structures. This suggests that timber buildings are evolving towards more open plans and thus provide more adaptable structures.

However, the linear systems are very dependent on the spans for their plan layout. In multi-storey residential buildings, smaller spans are usually used in timber construction compared to conventional solid construction with reinforced concrete ceilings, resulting in rigid structural grids. [1, p. 25] Based upon the principle of spatial overcapacity, a large span is desirable for adaptability. One can argue that this would use more timber resources than a smaller grid. However, the total cost of a timber frame structure with a larger grid is lower, as there are fewer joints, and those are the most cost-intensive factor. [46, p. 90] Also, the optimal column spacing is material specific. Still, many grid layouts are based the historically used materials like concrete and steel and are therefore not efficient. [48, p. 1]
Nowadays, the grid layout of rectilinear volumes with regular flat extrusion is dominant in multi-storey timber structures. Probably because of the industrial (pre)fabrication processes and the resulting linear or rectangular geometries, any deviation turns out more costly. [47, p. 30] Often, when greater design freedom is needed, other structural materials are used. Svatoš-Ražnjević challenges how these rigid timber structures will adjust to complex urban contexts. [45, p. 29] The repetition of the grid might suggest a readability and an open plan. Indeed, the rigidity of the element geometry could accommodate adaptability and the high degree of modularity required. However, more combination systems and hybrid structures can multiply the possibilities for a structure based upon the degrees of permanence. The specification of the structural grid is crucial for adaptability and a weighted effort of the expectations of the owner, architect, engineer and contractor. [48, p. 8]

To conclude, in multi-storey timber structures, the practice focuses on efficiency and technological developments. Yet, currently in conventional high-end taller building typologies spatial design is part of the development and engineering focus. [49, p. 8] Moreover, the architectural expression is purely the exposure of timber as a material. [45, p. 4] The discussion of the current trends shows that developments in modern timber construction are very dynamic. Their limited reflection together with increasing longevity demands suggest that more complex design strategies need to be discussed and applied.

In the following section, three cases are analysed against the adaptability types of Schmidt and Austin and the identified adaptability enablers.

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5.2 Adaptability Case Vodafone Headquarters

The Vodafone Headquarters in Newbury, United Kingdom, is an example given by Schmidt and Austin (2016) for all adaptability types except movability. It is a part of the campus designed by Fletcher Priest Architects. Since 2003 the headquarters have been made up of seven non-timber buildings linked by demountable footbridges. The building's layers are distinct, as the separation walls are movable, the cladding part of the skin is replaceable while it contains loadbearing elements, and there are several free-standing cores for circulation and services (fig. 1).

It offers great convertibility due to the generous provision of good daylight through a central atrium in a doughnut plan. This is part of the spatial overcapacity with an open plan, polyvalent spaces, and a column-based structure. The typical floor plan reads easily and consists of two connected rectangles. The campus buildings are standardised, although of different lengths. The scalability is demonstrated by its possibility to split a building up into two bays or per floor thanks to multiple access points. However, there is no compliance with the degrees of permanence as the structure is uniform throughout a building. The architectural expression of the structure has not been discussed in the literature. This case is featured as an exemplary project for the current understanding of adaptability in the architecture literature. [11, pp. 215–217]

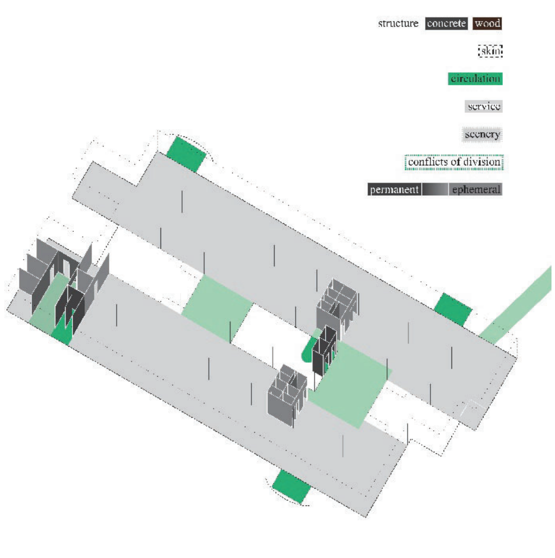

Figure 1: Leupen 's layers and degrees of permanence on a typical floor of Vodafone Headquarters Newbury

5.3 Timber Case Kajstaden, Västerås

In Västerås, Sweden C.F. Møller Architects and Bjerking designed a 2,400 m² tall building with a cross-laminated timber (CLT) structure. The CLT core provides structural stability to this nine-storey high housing block which opened in 2019. Thanks to the mechanical joints, the building is designed for disassembly. However, this building has little adaptability characteristics. The basic ceiling height of 2.5 m is generally limited with only an elevated ground floor and higher ceilings on the top floors featuring a spatial overcapacity. The façade 'skin' is loadbearing, and the structure is also the 'scenery' (fig. 2), which means that most conceptualised wall parts are directly translated into CLT panels. The division of the typical floor plan by load-bearing walls, however, might conflict with its versatility, as the load-bearing flat partition walls do not allow the floor plan to be rearranged at a later stage to accommodate larger units of use. Thus, there is no zoning according to the degrees of permanence, as the whole typical floorplan has a regular, non-hierarchical structural logic. The current size of the units, together with the given floor height, practically limits their use to residential. In the interior, there are no visible wooden surfaces, but the structure certainly has architectural expression in the façade.

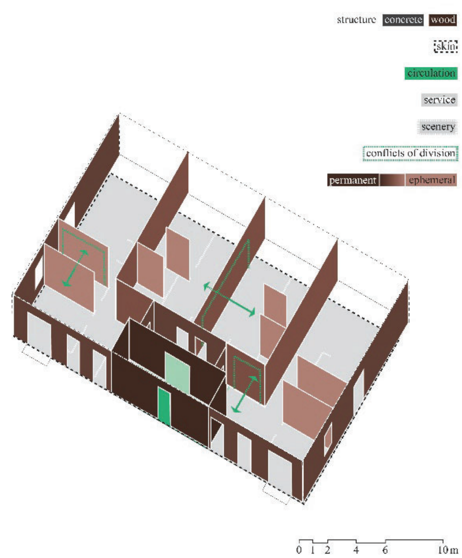

Figure 2: Leupen 's layers, adaptability conflicts and degrees of permanence on a typical floor of Kajstaden, Västerås

5.4 Timber Case Haut, Amsterdam

Team V and ARUP designed Haut as a housing timber-concrete structure in the Netherlands in 2022. The 21-storey building has a central concrete core and CLT load-bearing walls (fig. 3). The ceiling is left bare for appreciation of the hybrid wood-concrete slabs. The non-loadbearing façade is a detachable skin. The CLT walls divide the gross floor area of about 550 m² into eight spaces between 38 and 100 m². As Svatoš-Ražnjević writes, this post-and-beam construction at the perimeter with inner load-bearing walls might suggest "a link between heterogeneous structures and architectural variety, or a compromise to achieve more flexible open spaces." [45, p. 16] Indifferent of the circulation, the same structural logic is applied to the whole semi-orthogonal floor. The combination of load-bearing walls and an undiversified structural logic with dispersed technical shafts might hinder its adaptability in the future. Even though the internal walls provide necessary stiffness against wind loads and torsion on the tower on serviceability limits, they are not necessarily always needed where rooms are divided. To detach the structure from the scenery and possible later circulation, some of the walls can be identified as conflicting with adaptability layers which should be reconsidered in an early design stage. This means that such walls, which delimit the corridor next to the lift or whole organisational segments of the building, are likely more permanent and thus well made of load-bearing panels. Other space-dividing walls between single room units, on the other hand, which could be removed to couple rooms later, should rather consist of frames that are then optionally filled.

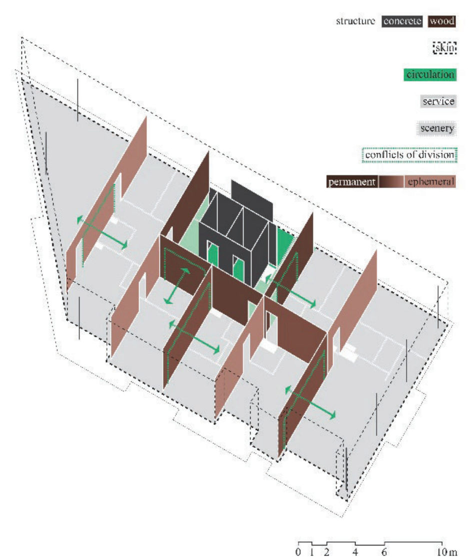

Figure 3: *Leupen 's layers, adaptability conflicts and degrees of permanence on a typical floor of Haut Amsterdam*

6 CONCLUSION

The premise of the paper has been that the design of multi-storey timber buildings has been discussed solely technologically. Even though timber is part of the biological cycle, experts need to work with the market forces, the regulations, and the physical conditions of wood to design for circularity. Circularity, as demonstrated in this paper, is considered very differently in engineering and architecture as both often refer to distinct levels of change. In timber engineering literature, circularity is focussing on design for disassembly and looking at components or materials regardless of their position in the building. In architecture, design for adaptability is based on several concepts, such as the separation of functional layers, providing spatial overcapacity and a readable plan layout. These strategies are not to be found in the timber literature. Also, mostly buildings are looked at here as a whole but omit the desirable diversification of adaptability according to the degrees of permanence.

The trends in timber buildings towards more prefabrication and volumetric modules are challenging the very concept of adaptability. However, there is a shift from planar residential structures to commercial linear structures, which suggests timber buildings are evolving towards more open plans and adaptable structures. The rectangular grid plan layout provides readability but might overlook architectural expression through its structure. The three cases exemplify the potential of adaptability concepts and demonstrate that more complex design strategies could be beneficially applied to timber architecture.

It is important to emphasize that the accessibility of the literature and availability of structural information on the case studies limit our findings.

The focus on material and components in the literature on circularity of timber architecture can be related to the massive influence and the relative newness of engineered wood products. Framing their potential for sustainable timber buildings within the conceptual architectural framework of adaptability, precise demands for zones of changeability and permanence within the building can be predicted and timber components can be applied accordingly in a targeted manner.

It would be insightful to apply the demonstrated methodology to contemporary multi-storey timber buildings which have been converted, but so far none are known. A post-completion analysis of timber buildings could significantly enhance circularity strategies in the field. Also, the stakeholders of these cases could be involved in further research on adaptability in timber buildings to better understand design conflicts.

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