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Review

The Potential Contribution of Modular Volumetric Timber Buildings to Circular Construction: A State-of-the-Art Review Based on Literature and 60 Case Studies

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Abstract: When facing the increasing demands of the housing market and balancing the requirements of sustainable development in the construction sector, building design methods should practise material conservation and adopt carbon reduction measures to alleviate the current environmental burden through the implementation of a circular economy approach. Volumetric modular timber design is recognised as a practical application to test the feasibility of a waste-reduced approach. Driven by the aim of further improving volumetric modular timber construction and increasing its use in a circular economy framework, this paper presents a case study review of 60 modular timber building projects constructed using volumetric modules. The dimensions, the architectural and structural design, and the manufacturing and assembly processes of the three-dimensional modular units were assessed to explore their potential for contributing to a circular built environment. The results show that the similarly sized modular volumetric timber units have the potential to serve different functions, and to be reused in subsequent projects. The stacking design allows modular volumetric units to be reused in a way that supports function conversion and satisfies project coordination criteria. The case studies illustrate that modular timber buildings are increasingly used for flexible design solutions, and to meet carbon emission reduction targets. The analysis results can address prevalent misconceptions regarding modular wood construction, provide interested parties with a better understanding, and promote the use of modular volumetric timber units in general.

Keywords: circular economy; modular construction; volumetric modules; reuse; design for disassembly; taxonomy; case study review; timber buildings

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1. Introduction

Urbanisation is a global phenomenon caused by rural–urban migration, and the consequent population growth rates vary depending on the economic circumstances of each region [1,2]. Housing remains one of the most pressing issues that needs to be addressed in the context of urban demographic changes, including a shortage of urban housing supply, and an upsurge in suburban housing demand [3,4]. For instance, the Copenhagen housing market report reveals that young individuals and small-scale families have the greatest demand for small flats of up to 60 m^2 [5]. However, it is anticipated that by 2050, more than 85 percent of constructed buildings may still be in service [6]. To successfully address the issue of housing resource restrictions, creative approaches can be employed to modify existing buildings and guide new building proposals.

The building and construction industry is the biggest source of greenhouse gas (GHG) emissions. The Global Status Report for Building and Construction, published by the United Nations Environment Programme (UNEP), states that the total amount of carbon dioxide (CO_2) emitted from the production of building materials will account for approximately 37 percent of global CO_2 emissions in 2021 [7]. Therefore, building projects should be designed to practise carbon reduction as much as possible in order to address anthropogenic climate change and natural resource shortages. The concept of circular construction has been proposed to reduce environmental impacts during the building process and subsequent use and maintenance phases in order to simultaneously address the requirements of sustainable development and the demand for housing.

The objective of circular construction is to optimise materials and their embedded carbon in a closed loop of application. According to this method, buildings that are approaching the end of their functional lifespan should be dismantled so that non-obsolete components can be reused for subsequent projects [8]. More than one-third of all waste generated globally is comprised of construction and demolition waste (CDW), and this proportion has been growing [9]. In Denmark, 40% of the country's total refuse comes from construction sites [10]. In practical terms, a project entitled "Ressource Blokken" has been launched in Denmark. It focuses on the reuse and recycling possibilities of buildings that need to be demolished. Researchers examined the characteristics of the materials used in 15 different concrete residential buildings. The designers accordingly proposed several solutions for reusing concrete components in new buildings [11]. It can be concluded that the modular design of the source buildings facilitates their reusability. With increasing studies on how to maximise reuse in the building process, implementing circular economy concepts in the construction sector is essential. Outside the building site, modular components are manufactured prior to being transported to the construction site for assembly. As a result, this type of construction provides significant advantages in terms of waste reduction and construction time reduction [12]. Additionally, the excellent quality of modular building units contributes towards the circular economy's primary goal of material reuse, which can further emphasise the benefits of the modular construction approach [13].

Considering the material characteristics, timber presents significant advantages over conventional concrete and steel modular construction. According to Tavares et al., an evaluation study was conducted on identifiable modular designs constructed using three distinct materials: concrete, steel, and wood. The conclusion reached was that timber construction has the lowest embodied energy (EE) and greenhouse gas (GHG) emissions per unit of living area [14]. The carbon emissions related to manufacturing and transporting can be decreased by up to 25% when using wood as a substitute for steel and concrete. The most promising buildings for the circular economy are modular timber structures [15].

A circular economy can be achieved by developing modular designs to reduce resource consumption and save costs, as well as employing pre-assembly techniques to conserve energy. In the end, there is a dearth of qualitative data in the context of applications for modular wood construction. In order to address technological and public awareness gaps, regulatory and legislative hurdles, and to serve as a reference for future optimisation efforts, it is necessary to summarise the dimensional design of volumetric timber modules, the number of floors that can be built in a modular timber building, the transport of volumetric modules, and construction methods. This work also poses the intriguing question of why cyclic construction has been made possible by volumetric modular systems that can be rented, as opposed to traditional projects that appear to be fixed in place and cannot be reused. Therefore, the purpose of this article is to summarise the numerous design parameters and relevant construction data for modular timber products with the goal of promoting their use within a circular economy framework.

1.1. Literature Review

Modular design is an off-site construction method that has been widely utilised in concrete, steel, and timber buildings in relevant organisations around the world, such as the Modular Building Institute (US), The European Commission (EU), Modular and Portable Building Association (UK), Japan Prefabricated Construction Suppliers and Manufacturers Association (JP), China Association for Engineering Construction Standardization (CN), and the Building and Construction Authority (SGP) [16–21]. Modular buildings are defined similarly, with an emphasis on off-site construction, prefabrication in a closed factory environment, transport to a site, adherence to local building codes and standards, and customization to meet distinctive project requirements. Modular units are designed differently depending on whether they are employed for temporary or permanent buildings. As a result of the development of assembled structures, the percentage of permanent modules in the modular building sector has risen to more than 50% in recent years [22].

Hundreds of multi-storey modern wooden buildings have been constructed around the world in the last two decades [23]. High-rise timber projects such as Mjøstårnet in Brumunddal, Norway, and HoHo Tower in Vienna, Austria, have set new standards for what can be achieved with timber. The new tall timber buildings have an average height of more than 50 m. Technical constraints no longer restrict timber projects to low-rise structures [24,25]. Engineered wood products (EWPs) have improved the structural efficiency of timber buildings, driving the growing popularity of wood projects [26]. Due to the evident advantages of modular construction, such as expedited construction schedules [27], wooden structures increasingly represent a substantial component of overall projects [28]. Nevertheless, the case study conducted by Ahmed et al. demonstrated that the cost of mass timber projects, when considering the new type of EWPs and the expertise of technicians, was still 6.43 percent greater than that of concrete solutions [29]. Modular timber solutions decrease overall project costs by duplicating items in contrast to custom timber designs, resulting in savings on production and scheduling expenditures [30].

The categorization of modular timber elements is generally based on their shape and can be classified into three types: linear, panel, and volumetric products [31]. Linear structural elements include beams and columns, and two-dimensional panelised structural elements refer to walls and slabs. Volumetric three-dimensional modules encompass turnkey load-bearing modules and non-load-bearing pods [32]. Bhandari et al. discovered that more than a third of the cases analysed were erected in high seismic hazard zones. This observation implies that modular timber buildings can be improved for greater seismic targets [30]. Ormarsson et al. have conducted numerical and experimental analyses to study the structural performance of 3D wooden modules. The findings indicate that the stiffness of these modules exceeds the anticipated values established by prior research [33]. However, the geographical separation between manufacturing facilities and building locations can hinder the widespread implementation of modular construction, regardless of its noteworthy sustainability benefits [34,35]. According to a survey by Koppelhuber et al. to gather professional viewpoints, it is anticipated that the use of 3D wood modules will rise in the future, notwithstanding the numerous technical obstacles associated with its implementation [36]. Hudert and Mangliár have explored the possibilities of upcycling wood by creating a design space for a multi-hypar structure. The project utilises modular hypar-shaped components, and the final product serve as a reference for applying modular wood products to intricate designs [37].

A systematic review on Life Cycle Sustainability Assessment (LCSA) concluded that modular buildings are the most effective design for circular construction [38,39]. Modular structures provide the fifth highest annual savings to the construction industry, supported by a 20 to 50% reduction in construction duration [27]. Thirunavukkarasu et al. studied the expenses of the conventional versus modular method. They discovered that the amount of materials utilised in modular construction as a percentage of overall cost was reduced from 30% to 15% [32]. Wood stands out among numerous modular building materials because of its light weight and ability to store carbon. According to studies, reusing building modules can significantly mitigate material wastage [40]. The disassembly and reuse of materials resulted in an 88% reduction in GHGs emissions [41]. Therefore, the dismantling of modules needs to be further investigated for its feasibility. Mangliár and Hudert studied volumetric modules and assessed the contribution of interlocking connection to achieving circular construction goals. The experimental results show that interlocking outperforms plate-to-plate nodal connections in maintaining overall stability, and this study provides a reference for the disassembly of volumetric modules [42]. In order to broaden the application scope, 3D timber modules are also favoured for the rehabilitation and expansion of existing structures. Flex Modul A/S completed an extension project to an office building. A third floor was added to the existing building using timber modules to provide 296 m^2 of office space, with the dimensions and materials of the addition remaining the same as the original building [43]. Dind et al.'s pilot project on a 1970s office building's vertical enlargement proved wood modules' retrofit potential. The use of wood in the additional two-storey module provides almost 100% renewable energy at a cost 20% lower than budgeted [44]. Consider the minimal carbon footprint of wood as a building material. Both academia and industry are looking forward to implementing more practises to evaluate the overall performance of timber buildings. More research is required to explain and demonstrate whether timber buildings can reduce the massive carbon footprint of construction-related emissions, reduce waste, and shorten construction cycles.

1.2. Review Aims and Scope

In order to promote modular wood buildings to foster the circular economy, it is imperative to consolidate knowledge pertaining to modular construction. The study focuses on a comprehensive analysis of 60 volumetric timber projects built throughout Europe. The primary objective is to provide an overview of volumetric timber modules and demonstrate how these modules can be utilized in design, structural, construction, and sustainability considerations. The aim is to reduce the cognitive differences in modular timber building applications between designers, builders, and the general public. The second purpose of this study is to elucidate the potential of timber modules for the realization of a circular construction economy through a range of approaches.

The paper begins with Section 1, introducing the current state of research on modular timber buildings and its efficacy within the context of the circular economy. Next, Section 2 comprehensively elucidates the employed literature review and case study approach. The underlying concept of modular wood products is also introduced based on the results of the literature review. The findings of the investigation outlined in Sections 3 and 4 encompass an analysis of information obtained from a subset of 60 volumetric modular timber projects. Section 3 centres on the design data specifically related to the volumetric timber modular products. In Section 4, an in-depth analysis is conducted, focusing on the design and construction parameters of structures utilising 3D timber modules. These characteristics will be utilised to evaluate the extent to which this building form contributes to circular economy objectives. Finally, the conclusions of this case study are presented in Section 5.

This study focuses on the analysis of data obtained from constructed projects, with the aim of deriving insights into the design of volumetric timber modules. Therefore, this paper is intended to serve as a valuable resource for researchers and professionals to enhance their comprehension and investigation of volumetric timber modules.

2. Theory and Methodology

This section begins with a description of the literature review, case summaries, and interviews with industry experts that were conducted for this paper. To better introduce the modular timber system, this section provides a taxonomy of modular timber products from components to systems, based on the concept of literature accumulation, to help the reader comprehend the results of the subsequent case study analyses.

2.1. Review and Case Selction Methodologies

The PRISMA tool is generally acknowledged and embraced throughout the academic community as a valuable resource for the execution and documentation of systematic reviews. The technique is to secure the integrity of the reviews and enable readers to evaluate the merits and shortcomings of these reviews. The official institute regularly updates its resources to give researchers a checklist and workflow diagram. These tools help researchers follow a logical process to effectively organise the material used in their research. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [45] checklist was used to identify pertinent research articles for a systematic study on modular timber constructions. Using the PRISMA approach, Oluleye et al. performed a comprehensive examination of circular economy strategies for managing building and demolition waste [46]. The utilization of PRISMA screening criteria enables a straightforward display of the quantitative results, thus, mitigating potential bias and enhancing the overall trustworthiness of this review. This subsection describes the modular timber project criteria and the literature assessment product selection approach. Nevertheless, the case studies aim to offer a complete analysis. However, the limited accessibility of non-confidential data from open sources inhibited project data collection.

2.1.1. Literature Review Process

This study includes two distinct review procedures to evaluate modular timber projects and products: a primary direct search in academic databases, and a secondary relevant search on the Internet. The selection criteria and methodology are presented in Table 1 and Figure 1 in accordance with the PRISMA protocol. The systematic literature review encompassed an analysis of online databases, including scientific publications updated up to 2 April 2023. A comprehensive search was conducted in the Web of Science Core Repository and the Scopus database. The search terms "modular timber frame building case study" were utilised. Initially, a total of 443 papers were identified. Duplicate and incomplete articles were eliminated, and results in other fields were excluded. Upon reviewing the title and abstract, the exclusion criterion was determined based on the lack of relevance of the study to 'modular' timber constructions. This is a result of utilising the logical operators AND/OR while inputting search parameters to generate search results that meet several criteria. In the end, 20 pertinent papers were chosen as references for examining building timber modules.

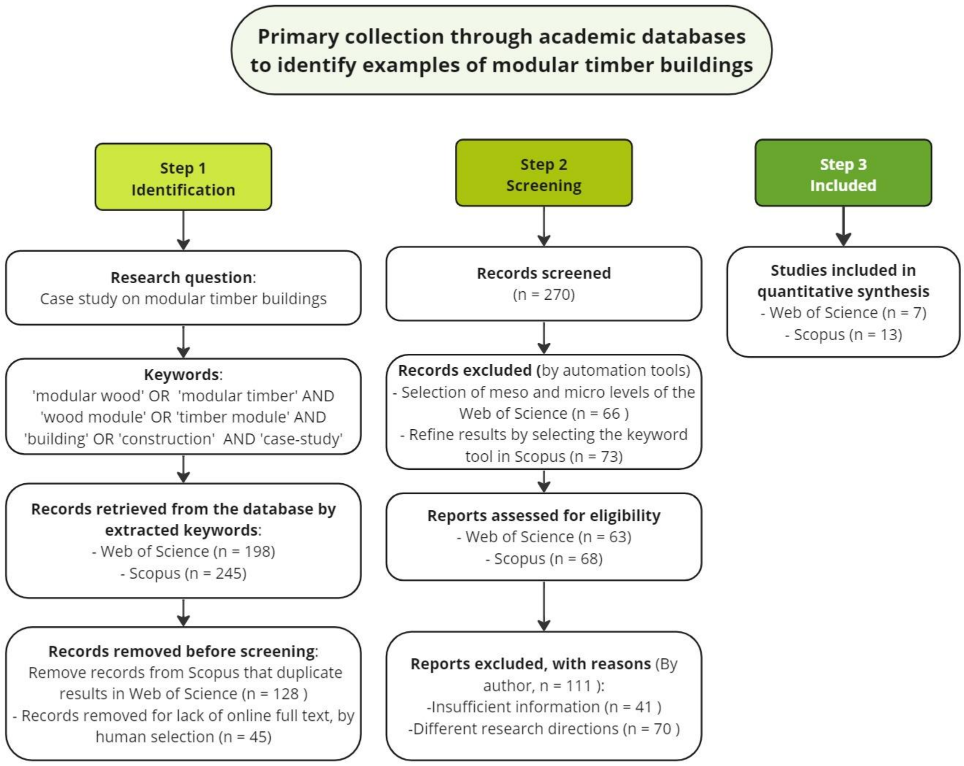

Figure 1. Collection of references through academic databases to identify studies on modular timber buildings.

Table 1. Four-steps for the 'Cases study on modular timber building' PRISMA.

Steps	Objectives	Implementation
I. Identification	Research question	Cases study on modular timber building
II. Screening	Extraction of keywords	'modular' OR 'module' AND 'wood' OR 'timber' AND 'case study' AND 'building' OR 'construction'
III. Eligibility	Language Research areas	English 'Civil Engineering', 'Architecture'
Exclusion criteria	Duplicate results Resources	Duplicate results between two databases Full-text available online
IV. Inclusion	For further study	20 results in total

2.1.2. Case Selection Process

Due to the difficulty of gathering all the research cases, the seven-case selection procedures outlined by Seawright and Gerring were employed as the basis for selection: typical, diverse, extreme, deviant, influential, most similar, and most different [47]. However, it is essential to note that the development history of 'volumetric modular wood building' is brief. Consequently, adherence to the seven criteria for removal was not rigorously assessed in projects with a relatively small number of investigations.

Furthermore, alongside examining the relevant literature, data relating to the Modular Timber Project was gathered from four primary public sources: architectural periodicals, publications and institutional studies, product specifications provided by wood manufacturers, and project introductions authored by architects. The initial inquiry begins by examining the case studies in the publication *Building in Timber-Room Modules* [28]. Following that, the initiative supplied information on wood designers and manufacturers, allowing for more insight into relevant situations and organisations. Furthermore, the authors sent interview requests via email to all the experts in charge of the design and production of wooden modules at each identified company. This was performed to collect comprehensive information and inquire about the present stage of development of this building type from the industry's perspective.

After the case search, the authors decided to utilize the availability of volumetric timber module dimensions to determine study eligibility. This is because the case documentary's most prevalent characteristics are the module dimensions. The authors will assess the data by examining publicly accessible construction and structural drawings where dimensional information is unavailable. Companies and designers in related fields were invited to interviews in order to obtain non-confidential design information. Although these sources have not been academically reviewed, they are the only feasible means to analyse constructed projects. Through expert interviews and a literature review, quantitative and qualitative data on the evaluated projects were found and documented. Throughout the case search, product information was systematically verified across many platforms to mitigate potential biases and enhance the reliability of Internet-based data.

After identifying the instances, the authors summarised the design and construction data for each case. Five topics were developed by the authors to group the pertinent information: (1) project details, such as project site, construction year, floor count, and building classification; (2) dimensions of the module, encompassing the overall dimensions (length, width, internal height, and total height), weight, and floor area of the volumetric timber module; (3) modular design, including the number of 3D wood modules used in each building, the overall dimensions of the building, the design of the floor plan layout; (4) non-structural units, such as balconies, façades, and corridors; (5) construction considerations, including the production speed of 3D modules, time required for assembly, distances for transportation, and evaluation of product sustainability. The documentation of the selection process for in-depth research of the 60 volumetric modular timber projects is provided in Appendix A. The workflow depicted in Figure 2 presents the procedure for determining cases.

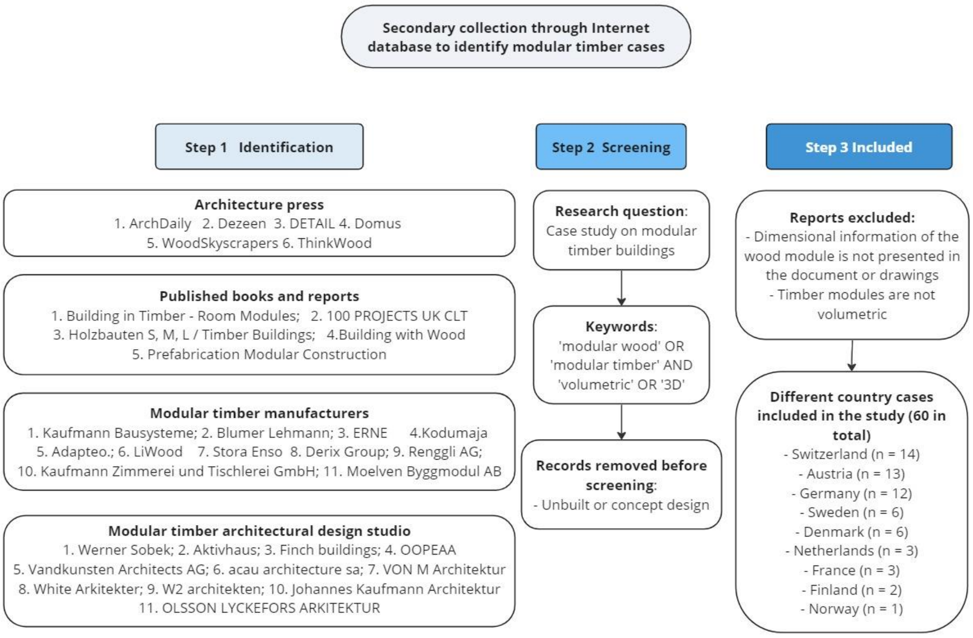

Figure 2. Collection through Internet database to identify volumetric modular timber cases.

2.2. *Principles of Modularity in Timber Buildings*

The utilisation of modular units exhibits variability across diverse building materials. Prior to analysing the case data, a comprehensive explanation of the fundamental principles of wood construction is presented. This overview aims to enhance comprehension of the modular system and subsequently facilitate the examination of the feasibility of reusing.

2.2.1. The Concept of Modularity and the Kit-of-Parts Approach

The off-site production of building modules can be classified into four phases according to the scale of the product being manufactured. These levels comprise segmented assembly components, non-volumetric units, volumetric units, and fully functioning volumetric modules. The functional modules are made up of modular parts to increase the degree of modularity [38]. In order to fulfil design objectives with the least amount of variation in building components, the modularization technique was developed to reduce the number of discrete building components in a project. Modular components should be generalizable across a variety of building projects in addition to serving a single project.

In conjunction with modular construction, the kit-of-parts methodology is an additional approach to sustainable design. Contrary to the modular approach, it refers to "a pre-designed collection of discrete building components that can be assembled in a variety of ways into a finished building" [48]. Kit components are created in a combinatorial approach to allow for a wide range of designs. Nevertheless, the lack of universally applicable toolkits and libraries of configuration tools is a challenge to expanding the application. Consequently, manufacturers are required to intensify their endeavours in developing solutions that integrate the supply chain from design to production [49]. To facilitate onsite assembly, kits are delivered in flat packs. In contrast, 3D modular transportation involves stacking and delivering large items to a site. In a case study, the volumetric modular technique completed construction 16% faster than the kit approach. Despite the apparent transportation difficulties of modular construction over the kit method, the volumetric construction method saves more time without sacrificing quality [50].

2.2.2. Taxonomy of Modular Timber Products

To gain a comprehensive understanding of the practical uses, benefits, and drawbacks of modular timber products, we have undertaken a systematic categorization of timber modules into four distinct classifications based on their geometric properties. The taxonomy of wood modules comprises the following categories: three-dimensional volumetric modules, two-dimensional panelised components, one-dimensional linear elements, and modular connectors.

The definition of a three-dimensional volumetric module in prefabricated prefinished volumetric construction (PPVC), modular integrated construction (MiC), and the permanent modular construction (PMC) all refer to individual 3D modules complete with interior decoration and fixtures and fittings, manufactured off-site. Figure 3(a,a′) shows a closed three-dimensional rectangular module. Some combinatorial designs require module grouping to create more space, as shown in Figure 3(b,b′,c,c′). The four-sided 3D timber module was created by Barreca et al., and it has a length and height of 3.14 m. Each panelised element is the same width as the modular unit, measuring 0.9 m. A room can be made up of three units, and the wet module can be made up of two units. According to the findings, the biochar storage value of this module is approximately six times that of a temporary housing container [51].

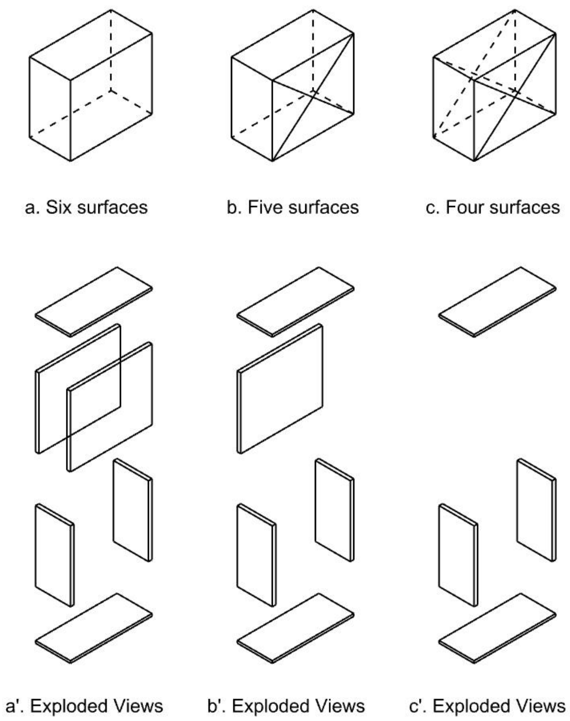

Figure 3. Three different compositions of volumetric timber modules.

Horizontal floors and ceilings, vertical walls are examples of two-dimensional panel elements, as seen in Figure 4a–c. To expedite construction of non-volumetric mass timber projects, the floors and walls will also be modular [52]. EON's panel modules are designed independently of the various projects, and the component is designed with one thickness (30 cm) and two widths (30 cm and 60 cm). Ten products are available in 30 cm increments, with sheet lengths ranging from 30 to 300 cm [53]. The modular product's distinctiveness is the flexible design. For instance, the components can be combined to accommodate windows and doors in various locations and sizes. This item has received certification as a passive housing solution appropriate for sustainable design.

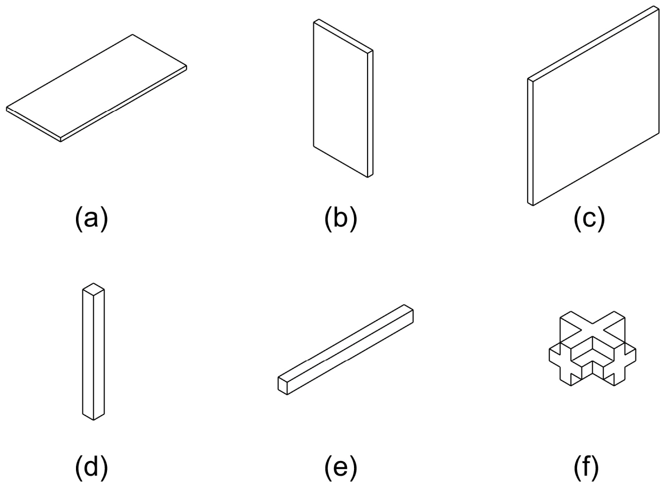

Figure 4. A taxonomy of modular timber components ((**a**) 2D floor, (**b**,**c**) 2D wall, (**d**) 1D column, (**e**) 1D beam, and (**f**) example of a nodalised connector).

The one-dimensional components depicted in Figure 4d,e consist of linear items, specifically timber columns and beams. The dimensions of the linear members exhibit variability across different projects. For volumetric timber modules nowadays, the column and beam structural form is overqualified and infrequently employed. Conversely, this method of building better satisfies the structural design criteria in mass timber projects.

The term "modular connectors" refers to zero-dimensional connections based on the shape of the nodes, which may include portions of structural components, as well as one-dimensional (linear) connectors used to connect between panels and beams of a wood frame system. Those connectors have been created to be disassembled easily in the future. In terms of the modular connector in volumetric modular timber units, the modular elements centred at the vertices of the volumes bounded by the horizontal and vertical divisions of a building. The classification of vertex modular connections is based on the placement of modules. There are three types of connections: intra-connections, inter-connections, and connections between the module and the foundation [54].

In the context of structural calculations, the nodes are frequently the most challenging work. However, the study of modular nodes can also contribute to the realisation of a disassembly design. For example, the X-RAD connector developed by Rothoblaas is a prefabricated mounting box designed for CLT elements. The utilisation of this metallic link enhances the ductility of wooden structures and facilitates expedited assembly processes [55]. BetaPort creates an on-demand building system that connects vertical columns with its crossover modular connecting products, as shown in Figure 4f. The documentation claims that this connection product makes dismantling work easier [56]. Nevertheless, it is necessary to conduct tests to assess the robustness of the node and confirm its suitability in light of the more rigorous requirements.

2.2.3. The Circular Economy Benefits from Volumetric Modules

Flexible design and logistical efficiency are advantages of 2D panel solutions. The 3D product option is frequently used for designs with high repeatability. According to McKinsey's report, transporting materials for 250 km costs \$8 per m^2 of floor space for 2D panels and \$45 for 3D solutions. When compared to volumetric timber modules, flat-pack panels can move larger floor areas of material in a single trip. However, the report estimates that 3D, 2D, and hybrid 3D/2D solutions could save 24%, 17%, and 20%, respectively, of the cost associated with traditional affordable housing solutions. Cost savings increase proportionally to the percentage of modules that contain 3D solutions [27]. The second utilisation of 3D timber modules plays a significant role in fostering a circular economy by saving materials. In addition to new projects, the volume module has other uses: leasing the module, reusing the module by changing its function, and adding vertical extensions to a building.

A wooden module rental service is being marketed by some sales companies, e.g., Adapteo. The wooden modules are returned to a designated factory at the end of the service period so they can be repaired in time for the following rental period. According to expert interviews, renting wooden modules is an alternative for projects where steel containers are unsuitable due to extremely high indoor temperatures. It is imperative to ensure that rentable modules are designed with compatibility. Figure 5 illustrates three reuse strategies for volumetric modules. Rotary placement module for new designs. The stacked structure facilitated the repositioning of the modules on the floor slab. The combined module creates a large space that can be split and used separately at the next service by replacing the sliding panels or filling the framed area's internal walls. The practise of reusing is not solely confined to room modules—evacuation modules can also be entirely reused. Variations are not limited to volume modules; the total number of floors can also be adjusted to suit different designs.

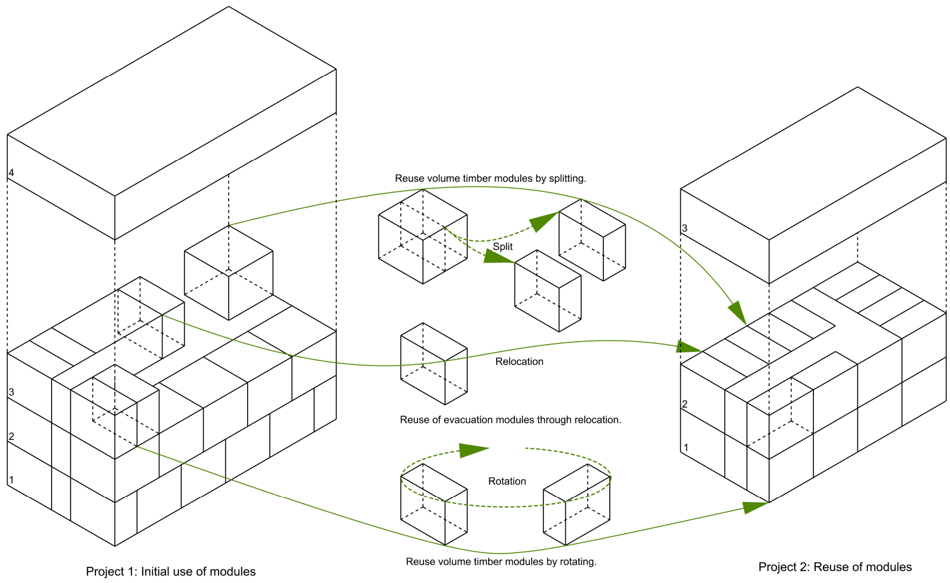

Figure 5. Methods of reusing volumetric timber modules (The numbers in the building model represent the number of floors).

The building profile and façade are important considerations when determining the viability of reuse. There are two methods of installing modular building façades: on-site or off-site. The first method involves stacking volumetric modular products and mounting the façade onto the modules after the main structure is completed. The façade of the second type installed in the factory with modular products. For projects where the façade is designed to be dismantled or to present a modular appearance, it is possible to change the profile of the building by adjusting the layout of the modules for the second use. Therefore, the initial project design is not a restriction on the reuse and extension of the wooden modules. Consequently, projects can then be customised and effectively managed.

3. Analysis of the Volumetric Timber Module in Study Cases

3.1. Projects and Products

The results presented below were acquired using the search methodology outlined in Section 2.1.2, which focuses on identifying projects and product sources. Figure 6 depicts the quantity and utilisation types of the 60 modular wood projects and 8 volumetric timber products from modular manufacturing. As listed in Appendix A, the first 39 of the total 60 cases employed identical module sizes, while the other 21 projects used various modular units to offer a broader range of flat types. Commercial, residential, public institutional, and mixed-use projects are the first to be separated into four major categories based on the service purposes of buildings. The buildings are then separated into nine sub-categories in accordance with the design aims of the building, as depicted in Figure 6. "Commercial" includes offices and hotels. "Residential" contains care housing, apartments, social housing, and student housing. "Public Institutions" comprises schools and hospitals. Projects classified as "Mixed-use" have an integrated public space for commercial, cultural, and social amenities on the ground storey and a modular space that makes up the remaining floors above ground storey.

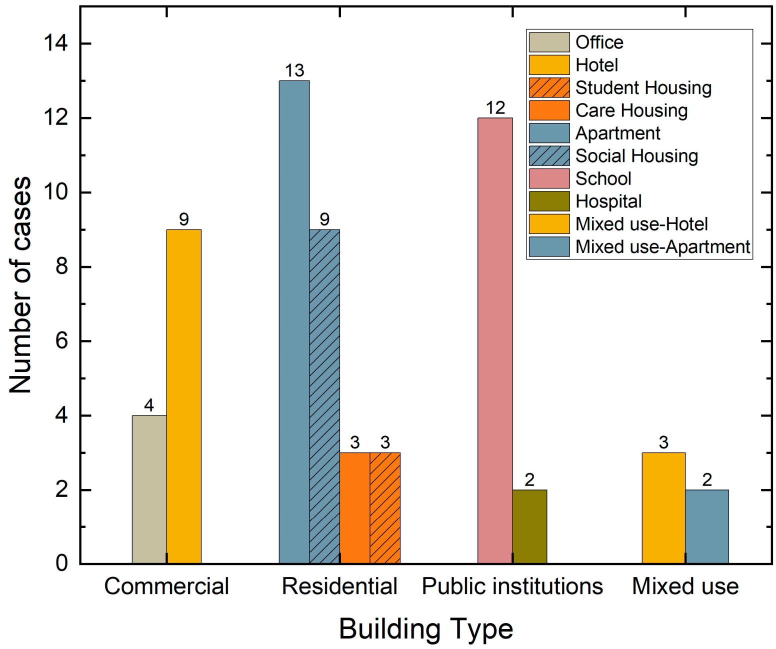

Figure 6. Building usage type of the selected projects.

In Figure 7, the numerical values displayed above the bars correspond to the quantity of non-timber floors. A quarter of the research instances (15 cases) featured non-wood structural components. The ground or first two storeys are constructed using concrete flooring to fulfil structural requirements. This phenomenon is especially prevalent in projects that have intricate foundation conditions and higher structural design requirements. The illustrations depict the high-rise building being constructed entirely with wood on every floor. It is worth noting that these types of buildings are typically used for several purposes. However, it is important to mention that the analysis did not include the ground floor section.

Figure 8 shows the functionality and storey count results for the study cases. The five instances of mixed-use purposes entail the incorporation of non-modular spaces that serve as a kindergarten, restaurant, sports facility, theatre, and exhibition hall. The classification of buildings is based on the utilisation of modular areas in the upper section. The numbers within the internal pie chart correspond to the cases within each group. The number of pies that are not displayed indicates that there is only one case in that category. The data graphic indicates that the majority of modular volumetric timber structures are between two and five storeys tall. The bulk of cases involve three-storey residential and public buildings. Out of the total sample size of modular timber cases examined, precisely half were specifically designated for residential purposes.

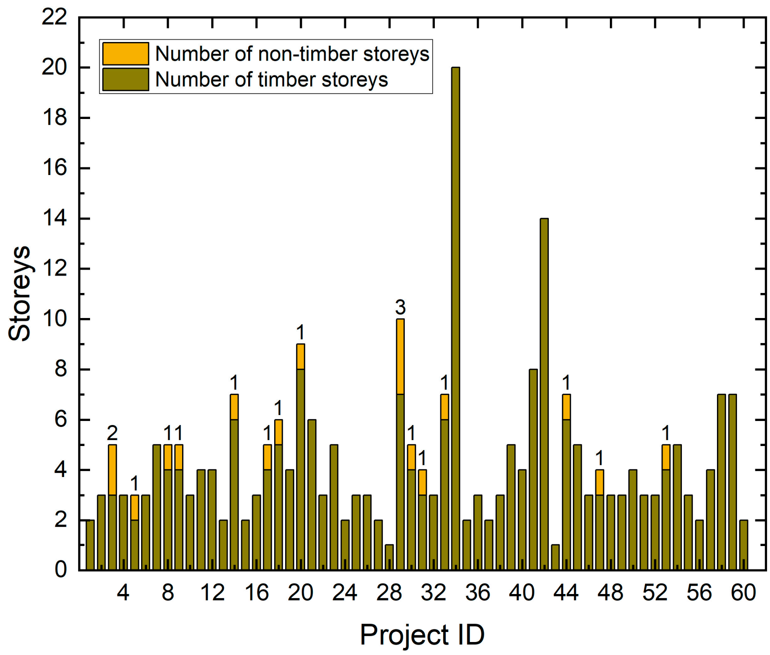

Figure 7. Number of storeys.

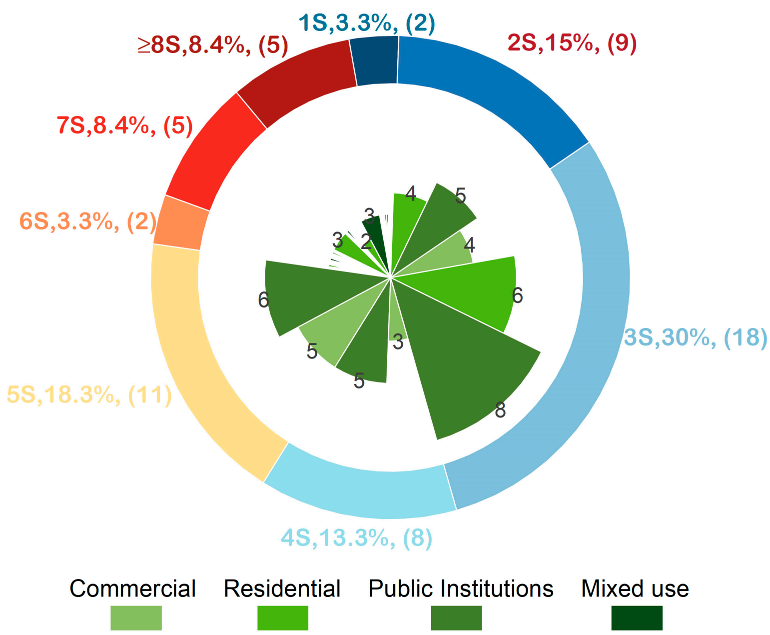

Figure 8. Number of storeys of study cases.

3.2. Dimensions of Volumetric Timber Modules

This subsection reveals design details for the dimensions, weight and floor area of volumetric timber items. The assessments included modular products made by eight suppliers as well as modular products used in 60 modular timber projects.

Figure 9 displays a box plot illustrating the dimensions of the studied volumetric modules. The average, minimum, and maximum values of volumetric modules' dimensions are shown. The considerable variation in lengths can be attributed to the flexible design. The shorter lengths are taken from functional modules, including bathrooms apart from the residential units. The transportation conditions are primarily responsible for the concentration of the width values between 2 and 5 m. Typically, modular rooms that have a width exceeding 5 m are constructed by integrating multiple 3D modules. Most of these situations take place in offices and educational facilities that require more space. The height depicted in Figure 9 is the overall height of 3D modules. It has the least variability of the three dimensions. The mechanical, electrical, and plumbing (MEP) system area is either located above the ceiling or below the floor of the room module, depending on the construction technique.

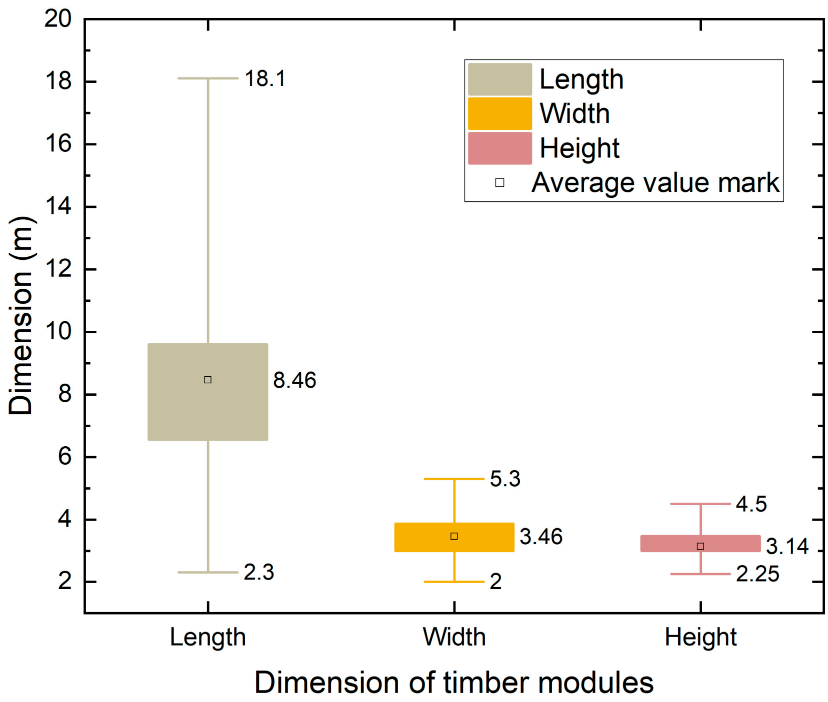

Figure 9. Dimension of volumetric timber modules.

The purple dots in Figure 10 present the dimensions of studied volume timber modules in the (width, length, height)-coordinate system. The projections on the three planes demonstrate the relationships between each pair of the three dimensions, e.g., between the width and the length. This projection chart provides a more comprehensive visual representation of the design of floor, wall, and window side façade regions in existing volumetric timber products.

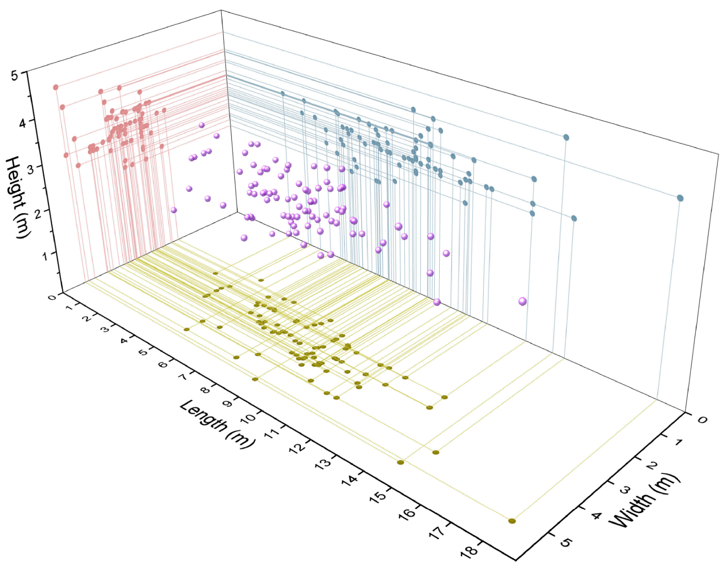

Figure 10. Three projections (length, width, height) of wooden module dimensions.

3.2.1. The Length of Timber Modules

In Figure 11, the terms L_T and n_T stand for the length of the timber module and the number of wood products with lengths within each bar interval. Each interval is in 1 m increments. For example, [7, 8) represents study modules with module lengths greater than or equal to 7 m but less than 8 m. The majority of the modules are between 5 and 10 m in length. Modules that are less than 5 m long are functional or flexibly designed modules. Modules longer than 10 m are typically made for apartments. The most variable building types in terms of module length are apartments and social housing structures, followed by hotels. This is primarily attributable to the module combinations that were used to meet the demand for various types of living space. Shorter lengths are typically merged to create larger areas. For student housing, nursing homes, and hospitals, the modules in these buildings do not typically use a combination design method. However, the module's dimensions may still change based on the application; for example, some modules should be designed with no barriers and slightly greater lengths to accommodate wheelchair access.

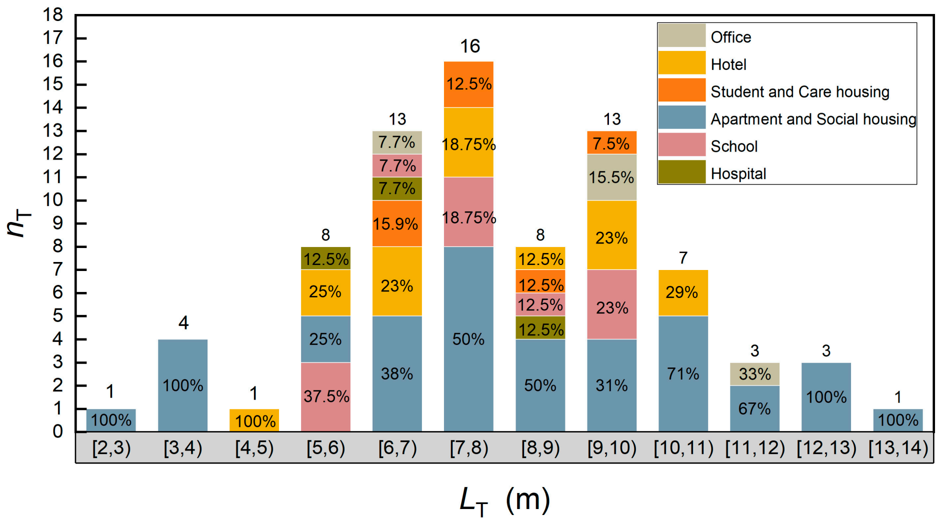

Figure 11. Lengths of wooden modules in different subtypes of buildings.

3.2.2. The Width of Timber Modules

In Figure 12, W_T denotes the timber module's width, and n_T denotes the number of wood products with widths within each bar interval. Each interval is in 0.5 m increments. For example, [4, 4.5) represents study modules with module widths greater than or equal to 4 m but less than 4.5 m. The majority of wooden volumetric modules are between 2.5 and 4 m wide. The width is not considerably affected by the module's use function. However, the modules utilised in apartment and social housing encompass an extensive range. The hotel modules had the greatest degree of variability in width.

In Figure 13, N_T denotes the cumulative number of cases determined by n_T from the results in Figure 12. The greatest number of modules are found at 3.1 m in width. There is a greater understanding of the precise size distribution of the various sorts of projects from the cumulative findings of the width of the research instances. There is a concentration of modules utilized for hotel developments between 3.4 and 4.1 m. Although many of the examples fell under the student and care housing categories, the modules were mostly 3 or 4 m width values.

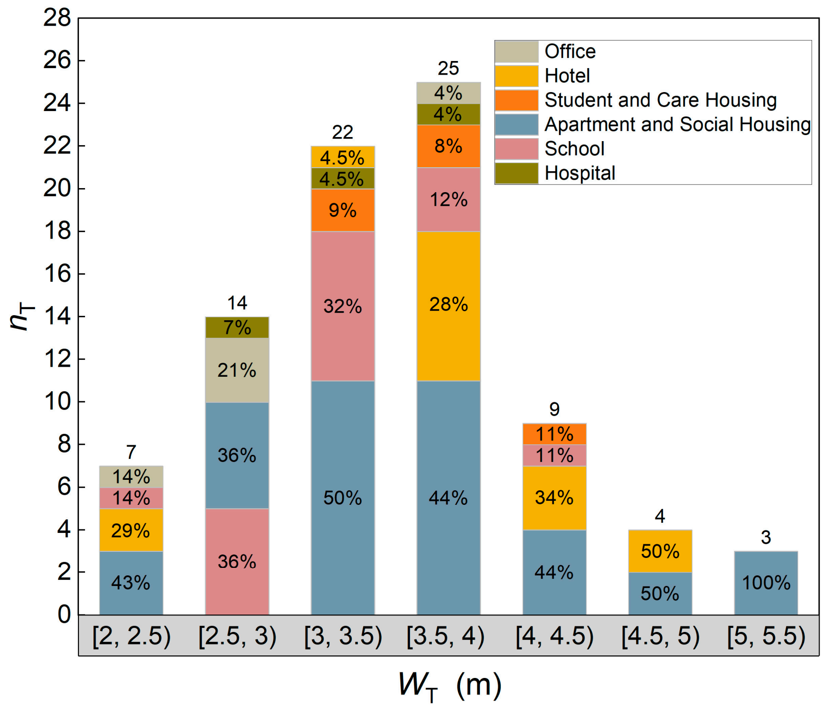

Figure 12. Width of wooden modules in different subtypes of buildings.

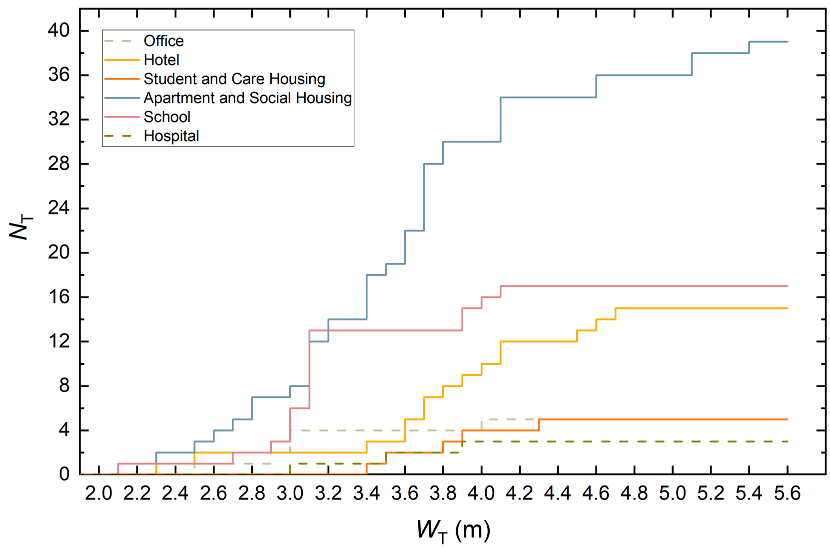

Figure 13. Cumulative number of cases based on the width of wooden modules in different subtypes of buildings.

Transportation constraints play a significant role in defining the width of the modules. The overwhelming majority of volumetric modules are produced in off-site factories. As a result, the chose mode of transportation greatly affects the maximum width of a 3D wood module. The primary modes of transportation for volumetric modules are road and maritime. A detailed discussion about logistics is presented in Section 4.2.2. Contrary to maritime transport, the dimensions are constrained by the road transport legislation implemented in each country. In order to demonstrate the variations in module widths according to the location of usage, the statistics acquired are displayed in Figure 14. The predominant width of products is under 4 m, with Germany having the most notable diversity in modular product widths, closely followed by Austria and Switzerland. This is because the majority of cases were constructed in the aforementioned nations, which provided a larger study sample.

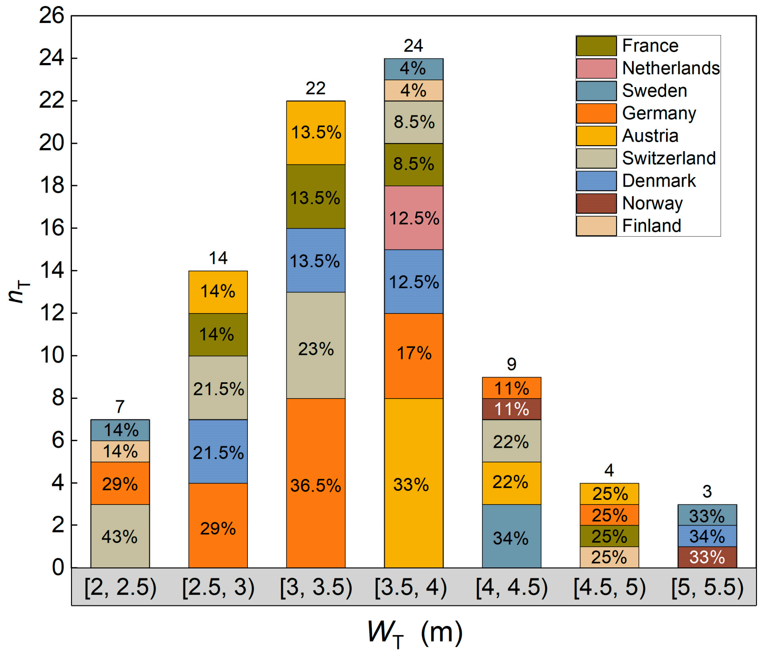

Figure 14. Module widths of wooden modules in different countries.

3.2.3. The Height of Timber Modules

In Figure 15, H_T denotes the overall height of the wood module, and n_T denotes number of wood products with heights within each bar interval. Each interval is in 0.5 m increments. For example, [3, 3.5) represents study modules with module heights greater than or equal to 3 m but less than 3.5 m. The volumetric products were concentrated on a 2–4 m height range. More than half of the modules that were investigated had heights in the interval [3, 3.5) m. The lowest module among the examined items has a height of 2.3 m for residential application. The maximum height is 4.1 m, designed for a hotel project.

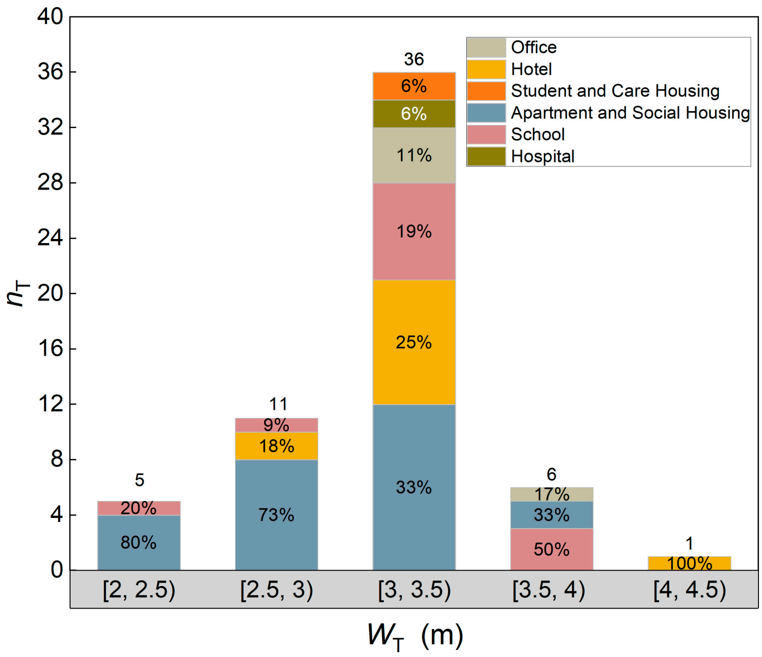

Figure 15. Height of volumetric wooden modules for different subtypes of buildings.

Figure 16 illustrates the height difference between the interior and exterior of the wood module in 11 projects (the number of cases is restricted by the data acquisition). The areas for the MEP systems were either above the ceiling or below the floor. Different interior heights have been designed for corridors and rooms in various instances. The average difference in height is 0.77 m.

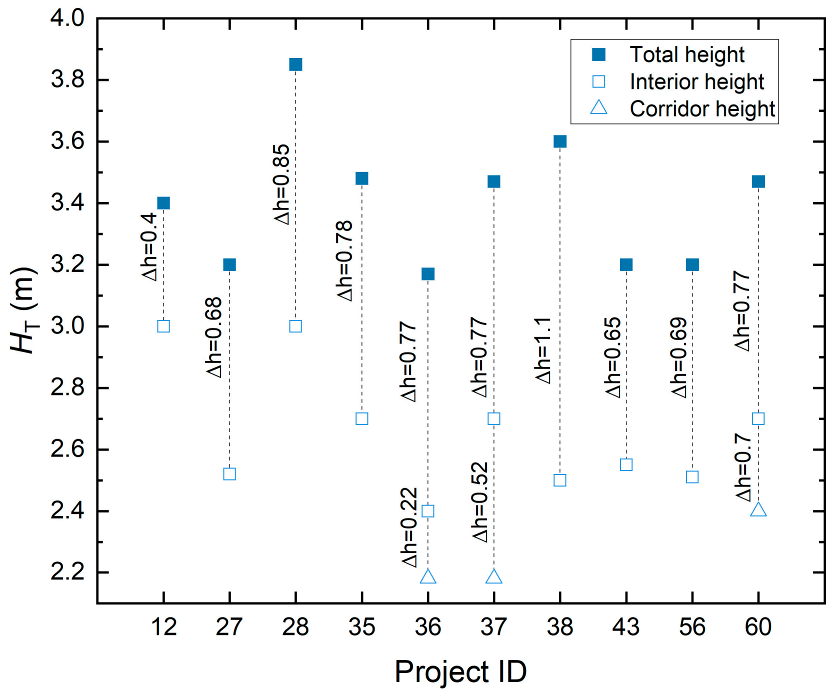

Figure 16. Difference in height between the interior and exterior of the wooden module.

3.2.4. Mass of Timber Modules

In addition to the impact of the modules' dimensions, the mass significantly varies based on the function of the module. Wooden modules can be divided into functional and room modules based on the difference in mass. Functional modules encompass various facilities, such as lavatories (including saunas), as well as equipment rooms. Mass data for 18 products are gathered in Figure 17. In modular systems, the mass of steel volumetric modular products ranges from 15 to 20 t, while the mass of concrete products ranges from 20 to 35 t [57]. None of the aforementioned values include the mass of equipment. The mass of wooden room modules falls into the range of 5 to 15 t, and the mass of equipment timber modules is less than 25 t. Therefore, compared to concrete and steel products, the mass of timber modules is substantially smaller.

3.2.5. Exterior Surface Areas of Timber Modules

The study of aspect ratios can assist in the rational designing of module sizes. Modular timber buildings are typically built using a stacking manner. Each volumetric product can support itself. The findings can serve as a data source for assessing structural stability, as seen in Figure 18. Offices and schools have higher aspect ratios because most rooms must be designed along the modules' longitudinal sides for combinations. The data for student and care housing types fluctuate more consistently, with aspect ratios of about 2. The interquartile range for apartments and affordable housing is centred around 2.3 and exists in a variety of ratios to fit different design combinations.

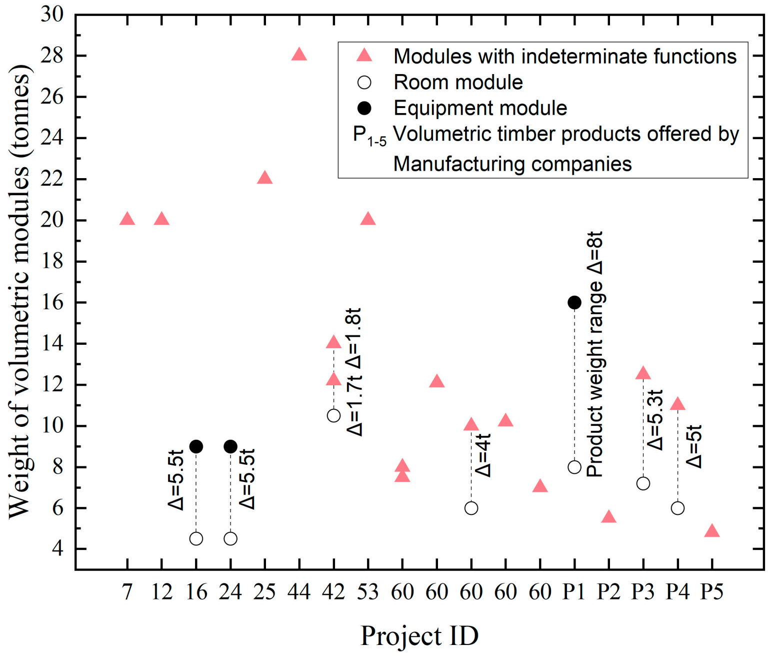

Figure 17. Weight of volumetric timber modules.

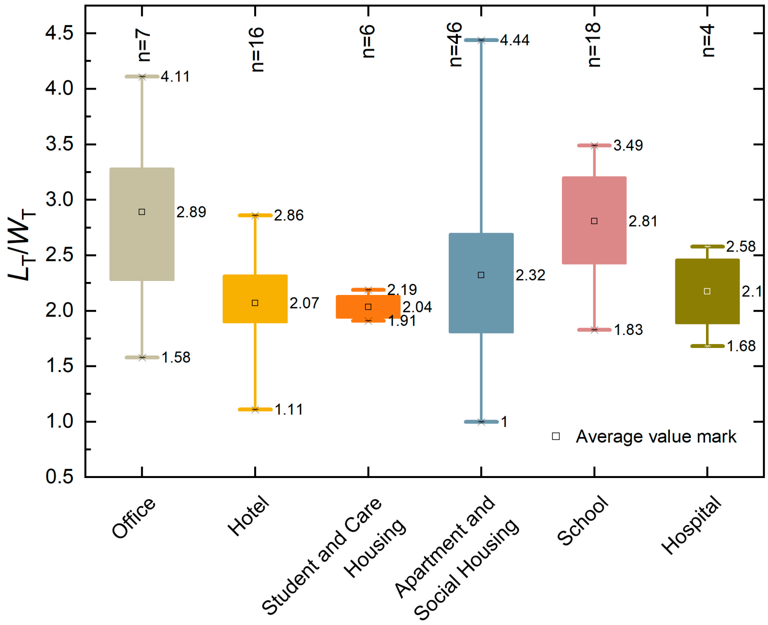

Figure 18. The aspect ratio of timber modules.

According to the data comparing the area of volumetric modules, the largest floor area of 50 m^2 is used for hotels and residential buildings. For volumetric modules, the standard floor space ranges from 15 to 25 m^2. Longitudinal wall surface areas are found by multiplying length by height and range in size from 10 to 35 m^2. The transverse wall surface area is defined as width times height. The region is densely populated within a range of 8 to 12 m^2.

4. Analysis of Buildings Made of Volume Timber Modules

4.1. Architectural and Structural Design

Designers and builders are becoming more aware of the design techniques for modular timber frame buildings as they are gradually becoming more popular. During an online interview, a representative of Kodumaja stated that one of the biggest obstacles is convincing people that modular wood buildings can be variable rather than merely modular. To provide a holistic research viewpoint on modular timber project design techniques, this part summarises the modular layout, combination methods, balcony design, corridor and façade design, and structural design from 60 built cases.

4.1.1. Layout Design

The layout of a building is determined by its use, structural design, seismic effects, topographical restrictions, and requirements of various design options. Figure 19 uses references to open-source designs to reconceptualize the building shapes. Three categories are identified: (I) rectilinear, (II) rotated and non-orthogonal, and (III) extruded and recessed layouts. Category I outlines are rectangular or rectangle-based shapes, accounting for 64% of all cases investigated. Floor openings, decreased floor areas by reducing modules' quantity, and rectangular combinations are all placed in this group. The remaining 36% of the cases analysed involved meandering and non-rectangular buildings that fell under Categories II and III. Rotating the module placement results in the angular design of the exterior building outline for Category II. All the architectural outlines in Category III originated as rectangular shapes. Folded contours have been created from linear edges via extrusions and indents. For example, in (III,c), (III,d), (III,e), (III,k), and (III,l), folded edge lines are created by balconies. In the remaining instances, changes in product positioning result in edge line discontinuities. The number follows each icon character denoted as the project ID in Appendix A. The remaining cases not mentioned are designed as rectangles, as shown in (I,a).

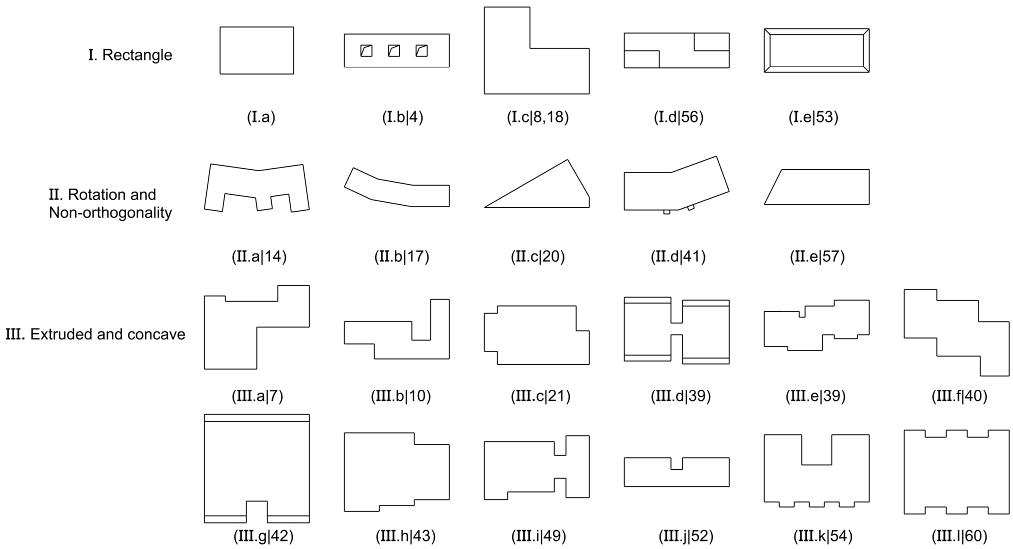

Figure 19. Modular timber projects in a variety of building shapes.

4.1.2. Design Combinations

In 60 volumetric timber projects, the ratio of structures employing a single 3D product to numerous products is close to 2:1 (39:21), indicating that the use of identical modules in modular timber buildings has become increasingly prevalent. All the studied examples in this work are grouped into three groups, namely vertical arrays, hybrid arrays, and unique situations, depending on the positioning of timber modules.

In the scenarios depicted in Figure 20, every module is installed next to another along the long side. External entrances are designed for all cases in Category i. Corridors and staircases in cases (i.b) and (i.d) offer access to all rooms. The entrance to the cases within Category ii is situated inside of the structure. Vertical connection spaces can be placed in the central space surrounded by modules or can replace modules in the array. The orientation of the modules is varied in Category iii, with the most typical rotation angle being 90 degrees. This integrated approach establishes areas for evacuation or public use. Rotating modules increase the lateral stiffness related to the overall bending about the global weak axis of the building and resist wind forces and stabilise the system in structural calculations. The number follows each character denoted as the project ID in Appendix A.

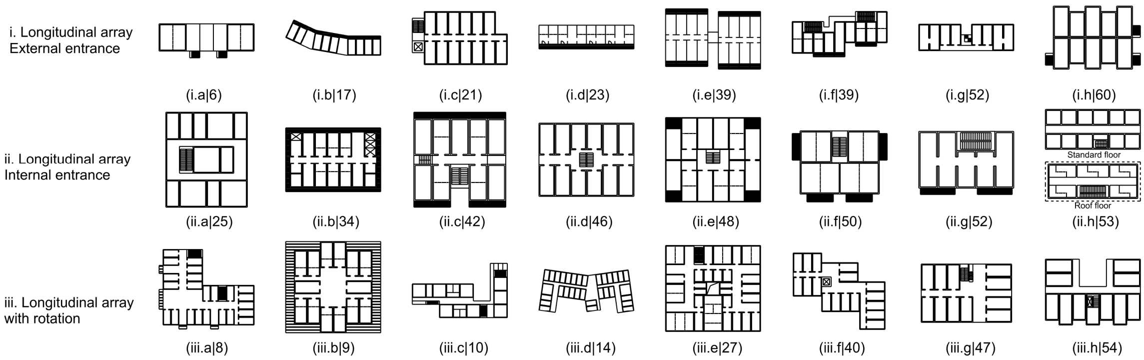

Figure 20. Longitudinal and hybrid array.

Furthermore, some designs are placed along the width of wooden modules, as seen in the cases in Category i of Figure 21. Nevertheless, the space efficiency of cases connected to shorter sides is lower compared to the vertical alignment method. In 21 modular timber projects of various 3D products, combination methodologies were applied to offer multi-room alternatives. The combination is shown in diagram ii. In this case, (ii.a) is the most common strategy. The edge modules feature a longitudinal side wood wall and a spanning beam. For residential buildings, sidewalls of middle modules can be created to slide or remove infill material between frames to give residents greater options. Intermediate modules often contain only two longitudinal spanning beams for business buildings and schools that need more open space. In this configuration, a classroom or office consists of two to five modules, ranging in size from 59 to 90 m^2. For the combination method utilised in residential buildings, as seen in Category ii (ii.b), Different placements can result in various housing types. In the analysed examples, two-bedroom apartments range from 42 to 65 m^2, with an average of 54 m^2. The size of a three-bedroom flat ranges from 62 to 127 m^2, with an average of 81.89 m^2. In Category ii (ii.c), there exist distinctive villa projects that are constructed from volumetric modules. The modules allow six or possibly more schemes within the design. In order to enhance diversity, the number of top-level volume modules was decreased.

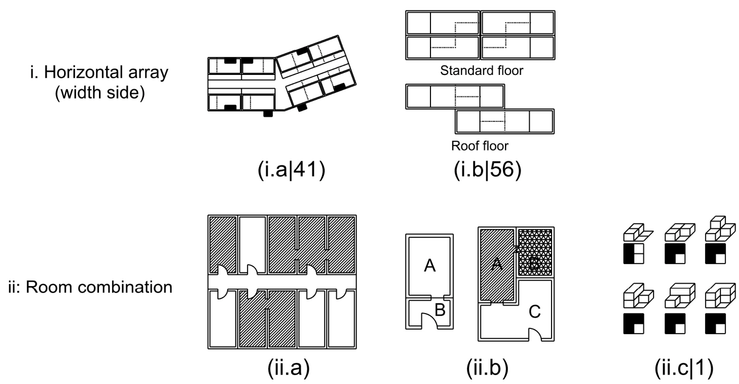

Figure 21. Horizontal array and room combination.

4.1.3. Design of Ancillary Facilities

Balcony and façade design are other important design elements worth considering in a project. Both components can be built on-site or assembled with modules in an off-site factory. The material selection is not restricted to wood and can be accomplished aesthetically to hide the appearance of modular construction.

Built-in balconies and external balconies are the two alternative placements of balconies. For built-in balconies, like (i) and (j) in Figure 22, windows are put inside the module rather than along the outer wall, allowing the setback space to function as a balcony. The floor slab may extend to an exterior balcony. As seen in (c) and (d), the extension is not only restricted to the individual module, and the balcony area entirely surrounds the structure. Another choice is to link to the building using the conventional method, which is stabilised by external columns. This methodology is employed in projects (f) and (h). As in projects (a) and (b), balconies are sometimes combined with hallways in low-rise buildings. As in the project in (e), the balcony might serve as the lower module's ceiling. These examples show that modular building techniques donot necessarily restrict balcony design.

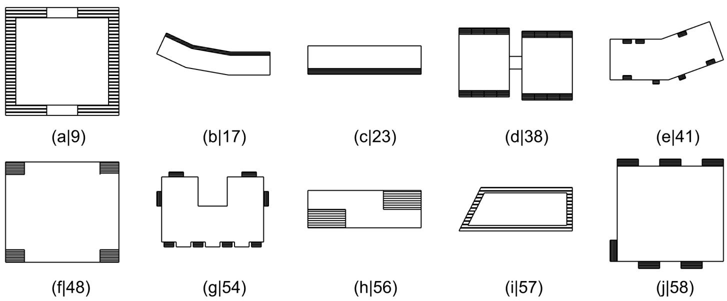

Figure 22. Balcony positions.

The materials used for façade cladding encompass a range of options, such as timber battens, stainless steel, fibre cement board, glass panels, copper, photovoltaic panels (BIPV), and aluminium. The majority of timber façades are made of spruce formwork and Douglas fir plywood. A greater diversity of façade forms can be provided using coated and corrugated aluminium panels. All of the aforementioned designs of façade are well-suited for on-site installation. In addition, the building's façade can be chosen from the wood modules; outside surfaces. The case studies demonstrate how the façade design can give modularly constructed buildings a non-modular appearance. The elevation drawings of these cases are shown in Figure 23. The term "non-modular façade" in this paper refers to a situation in which the material completely hides the modular connection details. Based on these criteria, the ratio of modular façades using the original production face of the modular product to non-modular façades with a different design covering the original modular façade is close to 1:1 (29:31).

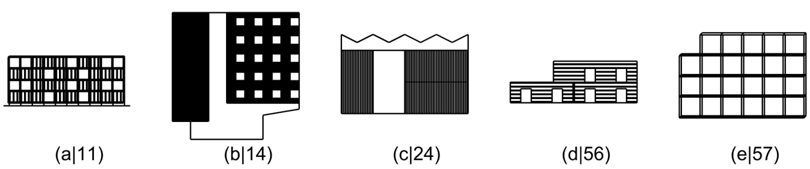

Figure 23. Different approaches towards façade design.

4.1.4. Overall Dimensions of the Building

The total length, width, and height of a building are crucial to architectural and structural design. Buildings are rigorously limited in length and in the ratio of their height to their depth from the perspective of stability. The aspect ratio is important in layout design because it helps maximise space utilisation and enhance energy efficiency. There is no prescribed design code that regulates the aspect ratio of modular timber buildings. Hence, the authors propose that the aspect ratio criteria for modular wood structures should be adjusted based on the construction approach employed, such as the manner in which the modules are stacked or if the core tube is utilised to ensure structural stability. To enhance comprehension of the present design, the subsequent illustrations present the correlation between the overall size of the building for reference.

Most of the cases in Figures 24 and 25 have lengths between 15 and 35 m, and the longest structure is 82 m long. Concrete buildings must be divided into sections upward from the foundations using deformation joints to prevent damage caused by temperature changes, uneven foundation settlement, and seismic factors. However, wood has a far lower coefficient of thermal expansion than concrete. Wood's shrinkage from moisture loss balances out the thermal expansion caused by rising temperatures. Wood deforms mostly perpendicular to the grain, so humidity variations have little effect on longitudinal dimensions [58]. Therefore, the length of the floor components stays relatively consistent. Additionally, a specific space should be kept between each wooden module because of the stacking building approach. Therefore, in timber buildings, expansion joints are not required. However, in order to maintain stability, the overall dimensions of the building should provide adequate stiffness to resist lateral displacement and torsion.

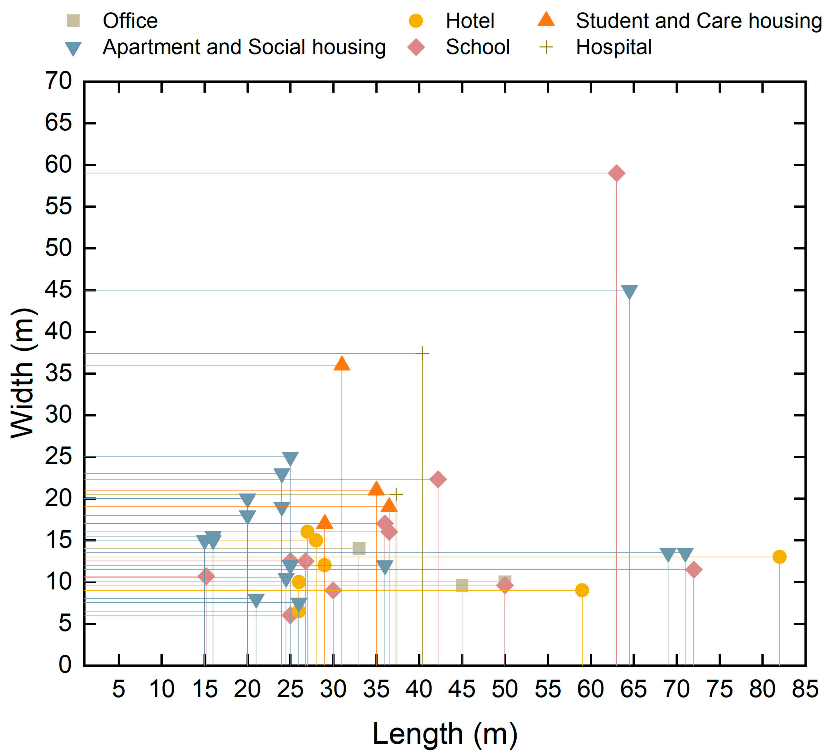

Figure 24. Length and width of the studied buildings.

Aspect ratios have a crucial role in enhancing energy efficiency. The identification of the optimal aspect ratio can enable the structure to effectively harness renewable energy sources and minimise the demand for heating and cooling [59]. According to the case study, there are currently 21.77 modules on average per floor, which serves as a benchmark for the research of module utilization.

The width of a building is a critical factor in assessing structural stability. It was utilised in structural calculations to resist wind loads and control building overturning. According to the data in Figure 26, the height-to-width ratio commonly observed is close to 1. There are a few outliers, such as a mixed-use project with a total height of 75 m and the upper modular part with a 7.5 aspect ratio that is used for hotels. A rectangular school project has an aspect ratio of 0.15 because there is a courtyard in the centre.

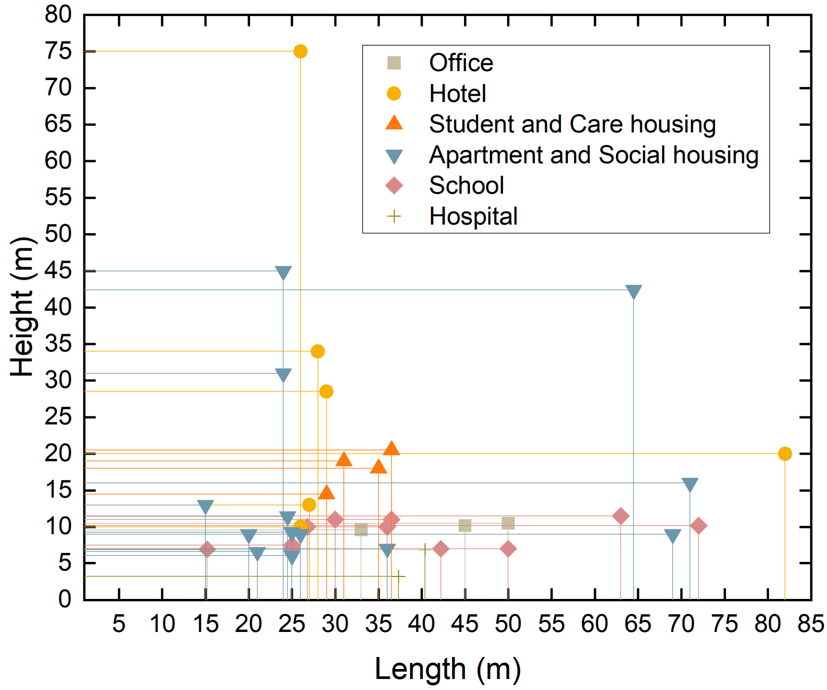

Figure 25. Length and height of buildings.

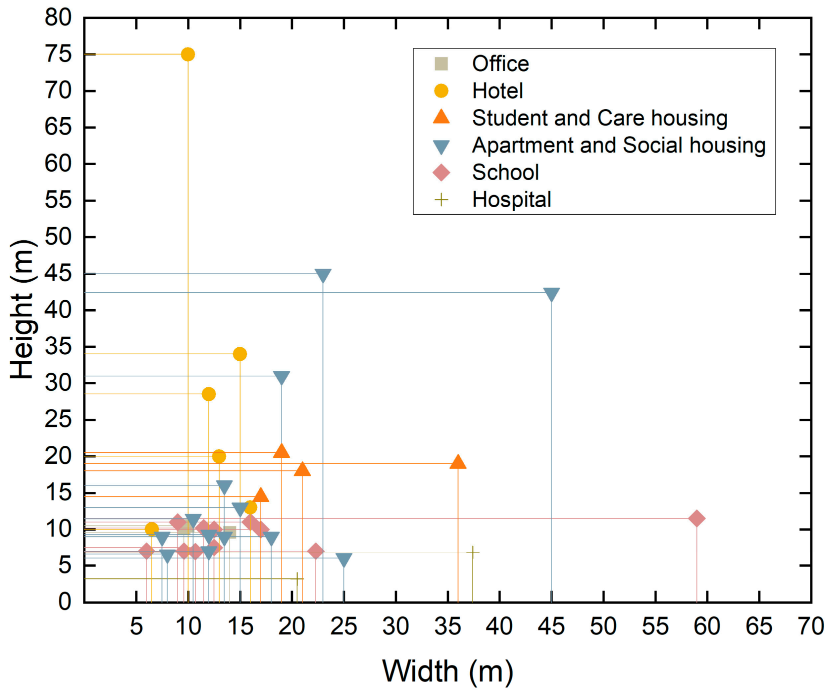

Figure 26. Width and height of buildings.

4.1.5. Stacked Construction and Structure of Timber Modules

The construction techniques employed in wooden buildings encompass timber framing for low-rise timber structures, as well as post-beam and paneling systems for high-rise mass timber projects. A box-shaped component made of panels and engineered timber ribs was built to install the pipes and place the integrated cable routes for ventilation, heating, and cooling. The box component is mounted to the volumetric module's ceiling or floor. The thickness of the box element, as discussed in Section 3.2.3, reflects the height difference between the internal and the total height of the wooden module. The wooden modules can be made beamless using this building technique. Glass mineral wool is typically used as insulation in the cavities between the timber frames and the box elements [60]. In the majority of situations, modules are built using a self-supporting approach to stack modules. Restricted space for foundation treatment and significant wind loads are two project limitations that cannot always be overcome with stacked buildings. In order to increase the overall stability of the stacked modules, additional measures must be designed to meet complex requirements. In some circumstances, the edge timber modules on both of the building's longitudinal sides are built using a combination of steel and wood to prevent lateral movement. In order to prevent exterior observers from noticing the difference, the steel frames were completely inserted inside the timber cavities. In some circumstances, concrete design methods are necessary to tackle complex foundation conditions, such as constricted foundation areas and sloping conditions.

4.2. Fabrication and Assembly of Timber Modules

An essential benefit of modular timber projects is their speedy construction. Building volumetric modules off-site in a closed manufacturing environment ensures accuracy of assembly. This subsection contains the findings on the production and assembly speed of 60 constructed modular timber structures. The transport status of volumetric modules, as well as their benefits and drawbacks, are also explored.

4.2.1. Production and Assembly

The production process for wooden modules begins with the factory production of floor slabs, timber beams, and walls, followed by volumetric unit assembly, interior decoration, pipework installation, and transportation. Installing external walls and roof waterproofing follow modular product assembly on site. Production and assembly information collected from 19 projects was collated by average speed to compare results.

The number of separate production lines owned by the fabrication facility and the production steps affect production speed. Certain procedures require additional waiting periods for material maintenance or coating drying, which prevents them from moving right away to the next stage. The studied data indicates an average production rate of 4 volumetric modules per day and a mean erection rate of 9.8 on-site modules per day across 19 projects. Consequently, the installation rate offers almost 2.5 times productivity. The data presented in Figure 27 illustrate the rates of production and assembly observed in the cases studied.

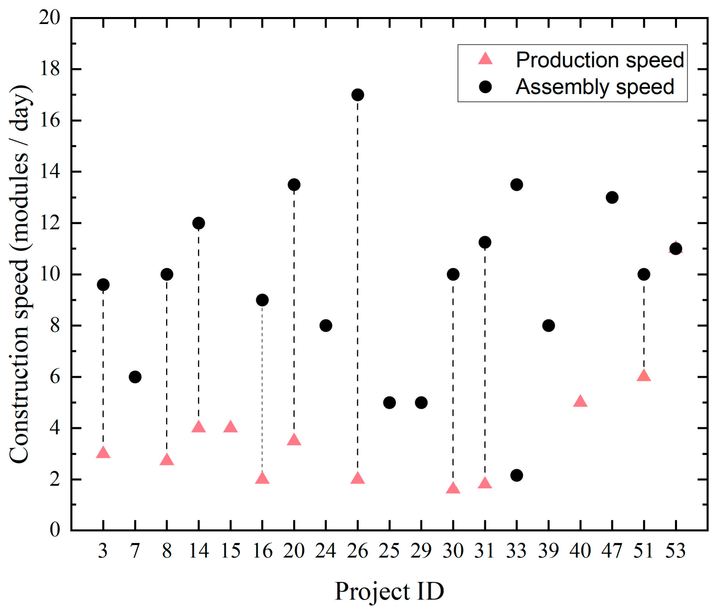

Figure 27. Speed of production and assembly of timber modules.

Another distinguishing advantages of timber structures is that off-site assembly eliminates the conventional buildings' inescapable construction lag time (the production of the superstructure can be synchronised with foundation construction) [61]. According to case studies of mass timber buildings, construction times can be slashed by 20% to 50% when compared to conventional construction [62]. In light of the differences in installation between mass wood components and volumetric timber modules, 3D modular timber projects speed up off-site fabrication and MEP fit-out, which saves labour and reduces installation time. Figure 28 displays the production, assembly, and overall construction duration schedules. The length of the blue line represents the duration in weeks. Only 13 examples were displayed, since they were the cases that included data from at least two of the three previously indicated time periods. The total number of wooden modules (shown on the right vertical axis) will determine how long it takes to build.

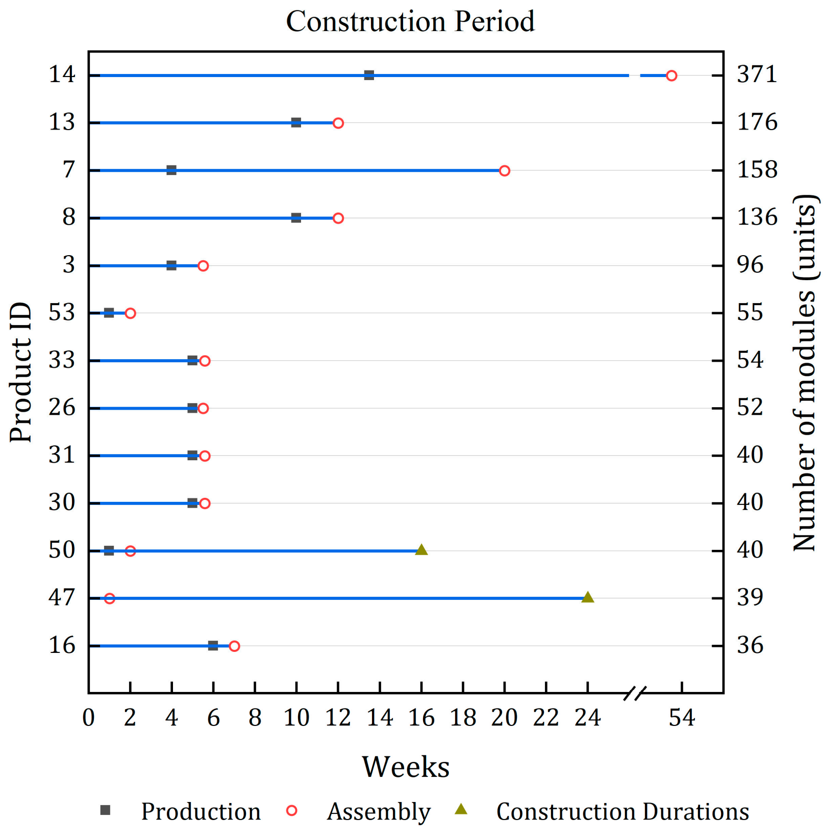

Figure 28. Production, assembly, and construction duration.

4.2.2. Logistics

The transportation required for prefabricated modular timber projects has a considerable impact on the total budget and environmental evaluation. It has consequences for the design of timber modules, distinguishing it from traditional building approaches.

The case files with transport data indicate that the distance between the stationary factory and the building site ranged from 64 to 1450 km. The cases investigated in this research were all built in Europe, and the wood module factories were typically in the same country as the construction site. Producers of wood modules, like those in Austria and Estonia, are now attempting to break into nearby and even further-off markets, including those in Norway and the Netherlands. For cities with harbours, maritime transport is feasible. Otherwise, land transport, i.e., lorries or freight trains, remains the only option. Transporting large modules requires longer, heavier trucks. A typical vehicle can transport one volumetric wood unit. However, a single truck can transport several smaller 3D modules at the same time.

For vehicles weighing more than 3.5 t, the restricted dimensions in Europe are 12 m for trucks and trailers, 16.5 m for articulated vehicles, and 18.75 m for road trains. The maximum width and height for all vehicles are 2.55 m and 4 m, respectively [63]. EMS (European Modular System) manoeuvre on the approved road network allows transport vehicles up to 25.25 m long and 60 t heavy. However, the module's width is the most impacted dimension. Countries have additionally tailored EU vehicle size and weight restrictions to their needs [64]. In Sweden, vehicles with a width of less than 3.2 m do not need an additional permit. The maximum width of residential modules has been expanded by the authorities to 4.15 m [65]. Norway's exemption width for irregular traffic, according to Statens Vegvesen, is 3.25 m, but 4.2 m widths have also been utilised in some circumstances [66].

The study conducted by Bhandari et al. showed that three-dimensional modules are carried across an average distance of one-third that of a two-dimensional modular timber buildings' distance [30].

According to an interview with a representative of the company Kodumaja, the transport cost for a volumetric modular timber project can be 10–20% of the total project expenditure. In order to prevent potential transportation issues from impeding the development of modular buildings, the modules' ability to be reused can help make up for poor transport performance. It was expressly advised that disassembling designs be taken into account for potential future reuse in eight of the examples analyzed.

4.3. The Embodied Carbon of Timber Modules

Based on a comparison study of prefabricated projects with various material scenarios, the embodied impacts are most noticeable in the material production phase, which makes up 80% of the entire production. Tavares et al. concluded that timber has a much lower energy cost compared to steel, concrete, and lightweight steel structures [14]. There are six projects among all study cases that mentioned embodied factor indicators. The carbon dioxide stored in wood, the carbon dioxide averted by using wood, and the wood consumption for each module are analysed.

Each wooden module consumes different amounts of wood depending on its size and construction method. The volume data mentioned in the project profile shows that the volume of engineered wood products used in each module varies from 30.3 and 99.5 m^3. Since volumetric consumption data are rarely included in publicly accessible information, it is challenging to draw more exact conclusions about the amount of carbon released/stored by each volume of wood module. Nevertheless, there are still a small number of producers and designers who distribute this data to the public as a point of reference. For example, Finch Buildings reveals that an average of three trees are used to produce one module [67]. By absorbing and storing carbon dioxide, wood helps cut construction emissions. Some projects specify the volume of CO_2 that each volumetric module's wood can store, while others indicate the building's total CO_2 storage. The quantities for stored or averted CO_2 emissions are presented in carbon from each wood module to guarantee consistency.

According to Figure 29, the average amount of carbon dioxide captured by each wood module was 13.42 t. The variability in module sizes and total wood consumption among projects introduces some margin for error into this calculation. Carbon emissions from cement and steel manufacture can be mitigated by substituting wood. Meanwhile, the lightweight construction of the area above the foundation reduces the use of concrete slabs in the basement, which cuts the CO_2 emissions of this part of the concrete. In addition, studies have indicated that the timber solutions can reduce carbon emissions by up to 25% per m^2 of floor area compared to traditional steel or concrete buildings [68]. Apart from that, the studies presented here have the potential of improving the early-stage evaluation of embodied carbon in future modular timber buildings [69].

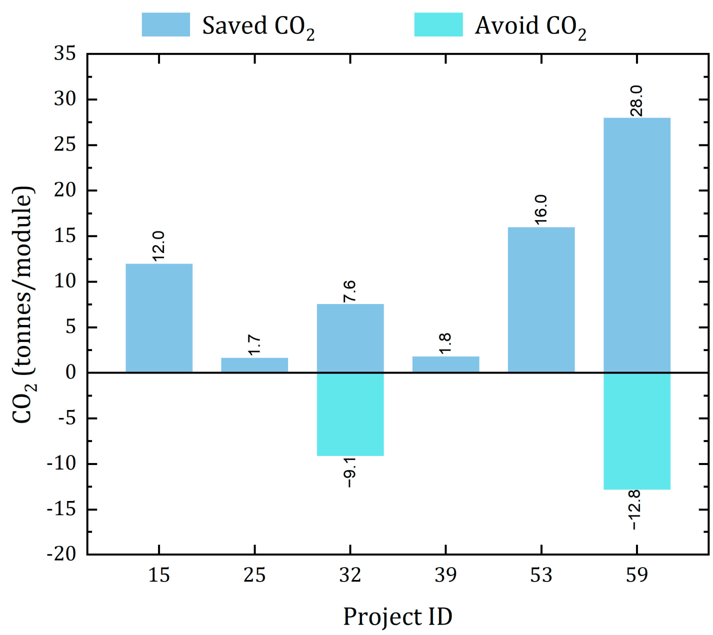

Figure 29. Greenhouse gas emission per timber module.

5. Conclusions

The following information is derived from the comprehensive analysis of 60 projects that employed volumetric timber modules as a construction method. The design of the volumetric timber module provided to optimise circular construction is described as follows:

1. The current height status of modular timber buildings is designed as two to five storey structures (76% of all cases). A total of 15% of the designs used partial concrete floors. Volumetric timber buildings are mostly residential, followed by office and commercial structures. Approximately 65% of projects have a uniform design across all modules;
2. The average dimensions for all volumetric modules are 8.46 m $\times$ 3.46 m $\times$ 3.14 m (length $\times$ width $\times$ height). The majority of the module lengths fall between 5 and 10 m. In almost 50% of instances, the modules were constructed with a total height ranging from 3 to 3.5 m. Product evaluation in this study indicated that all but one of the 3D modules were less than 14 m in length and less than 4 m in height. The length and height dimensions were within the limits of EU conveyance regulations. The width of the timber modules is most affected by transportation, and it typically ranges from 2.5 to 4 m. Relevant authorities in many countries are amending transport laws or providing transport privileges for 3D home modules to facilitate their adoption;
3. The mass of the wooden room modules studied ranged from 5 to 15 t. A discernible disparity exists in the weight between timber room and functional timber modules. Regular and functional modules differed by 5.3 t on average across the seven projects;
4. The building profile is an orthogonal rectangle in 64% of the instances. The remaining profiles consist of extruded and contracted patterns that are derived from orthogonal shapes. Modules are usually arranged in $L \times H$ sections, with adjacent faces side-by-side. Design flexibility is achieved by placing project modules at different angles. Façade design is not limited to the construction method of 3D timber modules. The study found that non-modular façade designs were nearly twice as common as modular designs. A greater range of applications for modular buildings is made possible by the use of façade design to conceal the structure's modular information;
5. The overall length of the modular timber structures under investigation varied between 15 and 35 m. Expansion joints are not required to mitigate thermal expansion because of the moisture characteristics of wood. Controlling building dimensions is crucial for structural stability and energy efficiency. The majority of contemporary modular timber buildings have a rectangular shape and an aspect ratio of less than

2. The study case comprised an average of 21.77 modules per storey by studying space utilization;
6. Modular timber buildings offer notable benefits in terms of production and assembly efficiency. Data from 19 projects show that producers can create 4 volumetric products, and that 9.8 modules are erected on site each day;
7. The use of engineered wood products per 3D room module ranged from 30.3 m^3 to 99.5 m^3, based on a review of data from the public project documents. The embedded CO_2 is an essential part of modular wood construction's considerable contribution to sustainable design. A total of 9.34 tonnes of CO_2 on average were stored in every project, according to an analysis of relevant data. The avoided CO_2 content as a result of using wood rather than concrete is also significant.

The conclusions of this paper may not provide a fully accurate representation of the current practises in volumetric modular timber buildings due to the limited number of cases analysed. The case selection process adheres closely to the PRISMA methodology. The investigation has the potential to offer valuable insights into the design methodologies that are now utilised in modular timber buildings. Through a review of the dimensions and layout design of volumetric timber modules, it has been revealed that modular volumetric timber modules display the capacity for reuse in subsequent projects. When considering the energetic impact of its structure, as well as the time advantages associated with its manufacture and assembly procedure, it becomes evident that the structure in question merits attention. The findings of this study, which analyses constructed cases, can contribute to addressing the information gap regarding modular timber projects. A comprehensive evaluation of utilised timber modules can yield dependable evidence for examining the feasibility of circular construction. Nevertheless, this study is constrained by the insufficient availability of data sources, which hinders the conclusion of more extensive results that accurately represent current applications. In anticipation of future endeavours, it is expected that a greater abundance of concise overviews pertaining to structural design and construction specifics would be accessible for study.

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Appendix A

Project ID	Project Name	Location	Year	Storeys (Wooden)	Building Type
1	BBB Kvistgård	Denmark	2008	2	Apartment
2	Office building	Switzerland	2009	3	Office
3	Hotel Ammerwald	Austria	2009	5 (3)	Hotel

Project ID	Project Name	Location	Year	Storeys (Wooden)	Building Type
4	Residential and Care Home in Fieberbrunn	Austria	2011	3	Care housing
5	Social Center Pillerseetal	Austria	2011	3 (2)	Care housing
6	Züri Modular Pavilion	Switzerland	2012	3	School
7	Student hostel	Germany	2013	5	Student housing
8	Hallein	Austria	2013	5 (4)	Care housing
9	Hotel Saentispark	Switzerland	2014	5 (4)	Hotel
10	European school	Germany	2015	3	School
11	Egger headquarters	Austria	2015	4	Office
12	SOLHÖJDEN VISÄTTRA	Sweden	2015	4	Apartment
13	Refugee accommodation	Germany	2016	2	Affordable housing
14	Woodie	Germany	2017	7 (6)	Student housing
15	Leiden	Netherlands	2017	2	Affordable housing
16	Schulraumerweiterung Champagne Biel-Bienne	Switzerland	2017	3	School
17	Hotel Revier	Switzerland	2017	5 (4)	Hotel
18	Östra Sala Backe	Sweden	2017	6 (5)	Apartment (mixed use)
19	2nd Home Business Hotel	Germany	2018	4	Hotel
20	Hotel Jakarta	Netherlands	2018	9 (8)	Hotel (mixed use)
21	Gibraltar Guest House	Sweden	2018	6	Student housing
22	Mobile housing Vulkanplatz	Switzerland	2018	3	Apartment
23	Rigot collective dwelling centre	Switzerland	2019	5	Affordable housing
24	School building in Pieterlen	Switzerland	2019	2	School
25	Gymnasium Frankfurt Nord	Switzerland	2019	3	School
26	Hotel Löwen Teamhaus	Austria	2019	3	Hotel
27	Provisional Lake Hospital	Switzerland	2019	2	Hospital
28	K33 Micro-Living	Austria	2019	1	Apartment
29	Sports Center Kerenzerberg	Switzerland	2020	10 (7)	Hotel (mixed use)
30	Hotel Alpenstern, Damüls	Austria	2020	5 (4)	Hotel
31	Employee house	Austria	2020	4 (3)	Apartment
32	Hausburg School Berlin	Germany	2021	3	School
33	Hotel Alpstadt	Austria	2021	7 (6)	Hotel
34	Sara Cultural Centre	Sweden	2021	20	Hotel (mixed use)
35	The town's Steiner school	Denmark	2021	2	School
36	Novo 3 plan Kalundborg	Denmark	2021	3	Office
37	Aarhus int. Skole	Denmark	2022	2	School
38	Sundholm special school	Denmark	2023	3	School
39	P18	Germany	2023	5	Apartment
40	Residential Complex in Toulouse	France	2015	4	Affordable housing
41	Puukuokka Housing Block	Finland	2015	8	Affordable housing

Project ID	Project Name	Location	Year	Storeys (Wooden)	Building Type
42	Treet Tower	Norway	2015	14	Apartment
43	Langenthal Hospital	Switzerland	2015	1	Hospital
44	Eskolantie	Finland	2015	7 (6)	Apartment
45	Wohnsiedlung in Rive de Gier	France	2016	5	Apartment
46	Wohnen 500	Austria	2016	3	Affordable housing
47	Hotel Katharinenhof	Austria	2017	4 (3)	Hotel
48	2nd Wohnen 500	Austria	2017	3	Affordable housing
49	Idorsia	Switzerland	2017	3	School
50	Hasenbergl	Germany	2018	4	Apartment
51	Westend School Campus	Germany	2019	3	School
52	Subsidized housing	Germany	2019	3	Apartment
53	HOTEL BAUHOFSTRASSE	Germany	2019	5 (4)	Hotel
54	Cederhusen	Sweden	2019	5	Apartment
55	Lattich creative district in St. Gallen	Switzerland	2019	3	Office
56	Subsidized housing in Kernen	Germany	2020	2	Affordable housing
57	73 Saint Mande Housing	France	2020	4	Apartment
58	O2 Orminge	Sweden	2021	7	Apartment
59	Buiksloterham	Netherlands	2022	7	Apartment (mixed use)
60	KU	Denmark	2023	2	School

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