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Advanced Timber Construction Industry: A Review of 350 Multi-Storey Timber Projects from 2000–2021

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Abstract: Throughout the last two decades the timber building sector has experienced a steady growth in multi-storey construction. Although there has been a growing number of research focused on trends, benefits, and disadvantages in timber construction from various technical perspectives, so far there is no extensive literature on the trajectory of emerging architectural typologies. This paper presents an examination of architectural variety and spatial possibilities in current serial and modular multi-storey timber construction. It aims to draw a parallel between architectural characteristics and their relation to structural systems in timber. The research draws from a collection of 350 contemporary multi-storey timber building projects between 2000 and 2021. It consists of 300 built projects, 12 projects currently in construction, and 38 design proposals. The survey consists of quantitative and qualitative project data, as well as classification of the structural system, material, program, massing, and spatial organization of the projects. It then compares the different structural and design aspects to achieve a comprehensive overview of possibilities in timber construction. The outcome is an identification of the range of morphologies and a better understanding of the design space in current serial and modular multi-storey mass timber construction.

Keywords: multi-storey timber construction; timber buildings; mass timber construction; survey; typologies; trends and perspectives; timber morphologies

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1. Introduction

The use of timber in construction has seen a resurgence since 1995 [1], and particularly in the last decade [2,3], owing in part to environmental and urbanization challenges [4]. Its credentials as a renewable material [5] that can store CO_2 [6] with comparable structural performance to steel and concrete, have made it unignorable. As these are still the main materials used in construction today, and the construction sector is one of the largest contributors to the global carbon footprint [7], being responsible for nearly 40% of annual GHG (greenhouse gasses) emissions [8], 40% of global resource consumption, 40% of energy use, and 50% of global waste [9], wood is a valuable alternative material [10]. Usage of wood (in conditions of responsible forestry), as it is a natural carbon sink, could allow the construction sector to avoid the substantial GHG emissions associated with unsustainable material usage. Furthermore, timber elements could continue to store CO_2 during the building lifetime.

As cities become larger [11] and denser [12], projections of population growth and future space needs in North America and Europe alone account for an almost 50% increase in building floor area [13]. However, productivity within the construction sector has been stagnating since the 1990s [14] and is related to a low degree of digitization in the construction industry [15]. Along with challenges of skilled labor and slow construction time, this poses a challenge for the reduction of GHG emissions. At the same time, timber is remarkably suitable to high levels of prefabrication, which has been suggested in studies as one of the best ways to increase productivity [16]. Timber is light and easy to work with, making timber building lightweight and hence more sites viable for timber construction, including vertical extensions of existing building stock [17].

Recent technical advancements in engineered timber products [18] (EWP) and systems, as well as regulatory adjustments in fire code, building code, and many government initiatives, have enabled multi-storey timber construction to reach new heights. It is precisely the developments in heights and technical problems of mass timber construction that have been in focus in industry and academia, rather than an overall analysis and survey of multi-storey timber building (referred to as MSTB from here forward) development. This paper builds upon several previous studies and surveys in order to better understand and identify perspectives in MSTB from an architectural design and manufacturing perspective.

1.1. Literature Review

In recent years, there has been a growing number of design-related studies on the topic of multi-storey timber construction and its international adoption since the changes in building code in the early 2000s [19]. Pioneering 'Nordic Wood Program' with light frame timer residential projects in Sweden, as well as cross laminated timber (CLT)-based projects in Austria and Bavaria, starting in the 1990s set the foundation of the technologies these studies have built upon [19]. Most existing scientific literature on multi-storey timber buildings discusses technical, acoustic [20–22], structural [23–27], or energy [28] and sustainability scopes [29,30]. However, although there have been numerous publications, up until recently, very few comprehensive, comparative design studies have been made, as can be seen in Table 1.

Table 1. List of relevant literature and main comparative surveys.

Study	Year	Type	Projects	Status	Min. Height	Analysis Aspect
Lattke and Lehmann	2007	paper	6	built	none	technical aspects
Lehmann	2012	paper	8	built	four-stories	viability of MTBs
Perkins and Will	2014	global study	10	built	five-stories	stakeholder experience
Smith et al.	2015	report	18	built	none	cost and schedule savings
CTBUH Audit	2017	survey	49	built and planned	seven-stories	no comparison or analysis
Salvadori	2017	master's thesis	40	built and planned	22 m	structural, facade, fire strategies
Kuzmanovska et al.	2018	paper	46	built and planned	25 m	structural, envelope, architectural massing
Wiegand	2019 2021	master's thesis paper	49 47	built and planned	seven-stories	policy
Žegarac Leskovar et al.	2021	paper	3 (31)	built (and in construction)	seven-stories	architectural, environmental, energy, structural (overview)
Salvadori	2021	paper	197	built	five-stories	structural
Salvadori	2021	PhD dissertation	197	built	five-stories	structural, material, program, cladding, building volume, stakeholders

The Lattke and Lehmann paper from 2007 [31] focuses on technical aspects of timber usage for multi-storey residential buildings in Europe. Lehmann's later 2012 paper [32] examines the viability of MTSBs in Australia through eight case studies from a technical and regulatory framework perspective. In 2014, the Perkins and Will office published a report by Hold and Wardle on timber buildings [33]. It was commissioned by Forestry Investment

Innovations and BSLC, contained 10 early built case studies, and summarized experiences of main stakeholders involved in the design, construction, and jurisdiction of the projects. The focus was mainly on the processes and challenges of design and delivery of timber construction, which was then in its early stages. The 2015 Solid Timber Construction Report by Smith et al. [34] summarized findings from 18 case studies regarding the cost, schedule savings, and safety data offered by the mass timber construction methodologies. A list of 49 built and unbuilt tall wood buildings was published in the CTBUH Journal in 2017 [35], however, without any analysis or comparison and only with rudimentary information on location, height, and type of structure. From the same year, Salvadori's master's thesis examines 40 mass timber building projects, both built and proposals, and examines (i) structural, (ii) facade material, and (iii) fire safety strategies [36]. In 2018, Kuzmanovska et al.'s comparative study [2] is the first to describe architectural trends in tall timber construction. It focuses on three analysis lenses: (i) structural limitation, (ii) envelope systems, and (iii) architectural massing. Wiegand's master's thesis in 2019 [37] examines the effects of policies on 49 case studies linked with CTBUH structural systems, and graphically displays the division, his later 2021 paper deals with the same topic on a set of 47 tall timber buildings [38]. The 2021 study by Žegarac Leskovar et al. [39] contains only a list of 31 MSTB projects, and creates four lenses of examination: architectural, environmental, energy, and structural, based on previous literature [2]. However, it focuses on an in-depth analysis s of only three selected projects with pure timber structural systems. Within the analysis of the three projects, it looks at (i) location of the projects relating to climate, seismic zone, (ii) various structural aspects such as elements, bracing systems and their materials, height, and wind loads, (iii) building façade thermal values and energy classes, and (iv) from architectural design aspects, program, rough plan and vertical geometry, and façade design for the purpose of examining the suitability of MSTB construction in different climate regions, and existing construction techniques' usability and adaptability to local specifics. In 2021, two other publications from Salvadori, a paper [40] and a doctoral dissertation [19], provided a comparative survey of 197 multi-storey timber-based buildings, determining geographical differences in characteristics of MSTBs. The paper is an excerpt from the dissertation presented exclusively on (i) structural categorization, while the dissertation presents a more comprehensive overview of MSTBs with the addition of analysis and comparison of certain building elements materials, as well as other design aspects such as (ii) program, (iii) exterior cladding, (iv) interior timber exposure, and (v) description of building volumes. In addition, it also provides a comparative analysis of factors influencing the realization of MSTBs, the regulatory framework, the professionals and stakeholders involved, such as universities and city council, as well as the industry which manufactured and supplied the timber elements.

As can be seen in Table 1, the height-threshold varies across the studies. The literature does not clearly define what minimum height threshold is required to be considered an MSTB. The comparative study by Lattke and Lehmann [23] as well as some MSTB books [41] and databases [42] considers three-storey buildings as they were at some point in time some of the tallest examples. More recent literature [19,39] defines the division of MSTB as: (i) low-rise buildings with one-to-three stories, (ii) mid-rise buildings with four-to-ten stories, and (iii) high-rise buildings with more than ten stories. Prior to Salvadori's 2021 study [40] there were no surveys which included mid-rise buildings (from five to seven stories). In addition, the number of case studies has mostly been limited to around 50 projects.

Although the last survey expanded the height threshold, there is a lack of analysis of more low-rise buildings in current literature, which is necessary to be able to fully understand the possibilities and limitations in multi-storey timber construction and the range of possible programs. Therefore, this study includes all MSTBs found in data sources starting with three stories (in timber) and has the highest number of projects compared to previous studies.

Although the largest part of the literature is dedicated to technical and structural aspects and rarely on other design aspects, the few design aspects examined so far have had a limited scope of geometric description and have not fully described the variety of forms and spatial organizations in timber construction.

The studies executed so far [2,19] show that the focus in MSTB construction is on technological developments in structural engineering and the buildings' energy efficiency qualities, rather than innovation in spatial design. They reveal that "unlike current trends in high-end concrete or steel tall building typologies, the results show a dominance of rectilinear plans and regular extrusions, where simply the use of timber, rather than its expression as the main material, is an architectural and marketing feature in itself" and that the plans do not show a huge degree of innovation in terms of how these buildings are actually lived in and used [2]. In addition, exceptions are rare and projects with more complexity usually have hybrid structures or small footprints.

Although Žegarac Leskovar et al. [39] roughly touch upon the geometry of buildings, there is no architectural or typological analysis present in the paper. On the other hand, both Kuzmanovska et al. [2] and Salvadori [19] examined the building volumes and forms. However, neither of the studies defined the range of regularities or irregularities in building forms or the ordering principles and its effect on internal spatial organization.

1.2. Aim of the Study

This study aims to examine the architectural variety and spatial possibilities in current serial and modular multi-storey timber construction. This study will showcase that so far the increase in timber construction is limited to specific typologies, massings, and structural systems, and it will provide a finer grain of resolution on the range of timber morphologies. The results of the study will provide a clearer view of the possibilities of various structural systems in terms of design, as well as applicability of mass timber construction to different design conditions and requirements. Along trends in construction, this research sets up the first steps to identify the current directions, trends, gaps, and the extents of possible designs of multi-storey timber buildings worldwide.

2. Materials and Methods

This research was conducted as a comparative global survey of 350 projects (as Figure 1 shows), including 300 built, 12 projects in construction, and 38 proposed multi-storey timber buildings from 2000 onwards with a minimum height threshold of three stories of mass timber construction. Quantitative and qualitative data was collected on the buildings. Table A1 in the Appendix A lists the selected projects. It contains information on (i) year of construction (or proposal), (ii) number of stories and timber stories, (iii) location, and (iv) project status. The complete data set on buildings analysis will be deposited in a publicly available data repository of University of Stuttgart, DaRUS and can be accessed at: https://doi.org/10.18419/darus-2733 (accessed on 8 January 2022).

2.1. Data Sources

The project selection was based primarily on listings in existing surveys and publicly available data. As Figure 2 shows, the data sources comprise: academic papers and grey literature sources such as government and institutional reports, master and doctoral theses, published timber construction books, magazines, websites, and online project databases. Out of 350 projects, 141 match with the latest Salvadori's 2021 survey [19,40]. In most cases, multiple sources were used to gather necessary quantitative and qualitative information on the projects. In parallel, non-timber focused architectural journals such as Archdaily, Dezeen, and Detail Magazine were used to complement the data collection. Only projects with enough relevant data and information in literature or online were included in the study. Tables A2–A5 in Appendix B group and list the main sources used for project selection and collecting the data necessary for analysis of buildings. The sources were primarily in English or German.

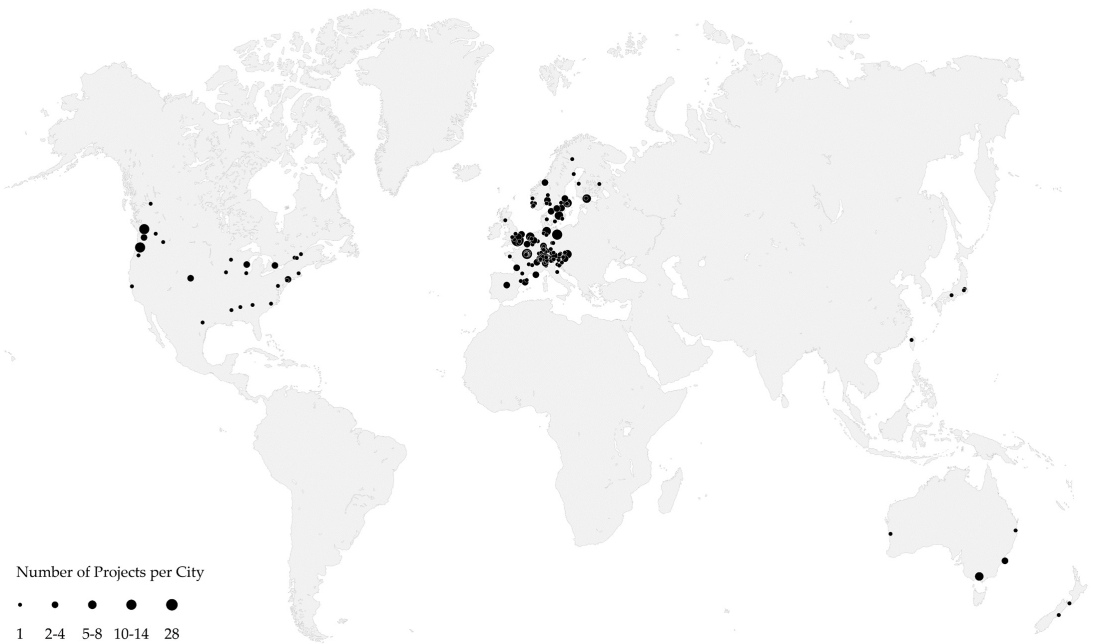


Figure 1. Project location map.

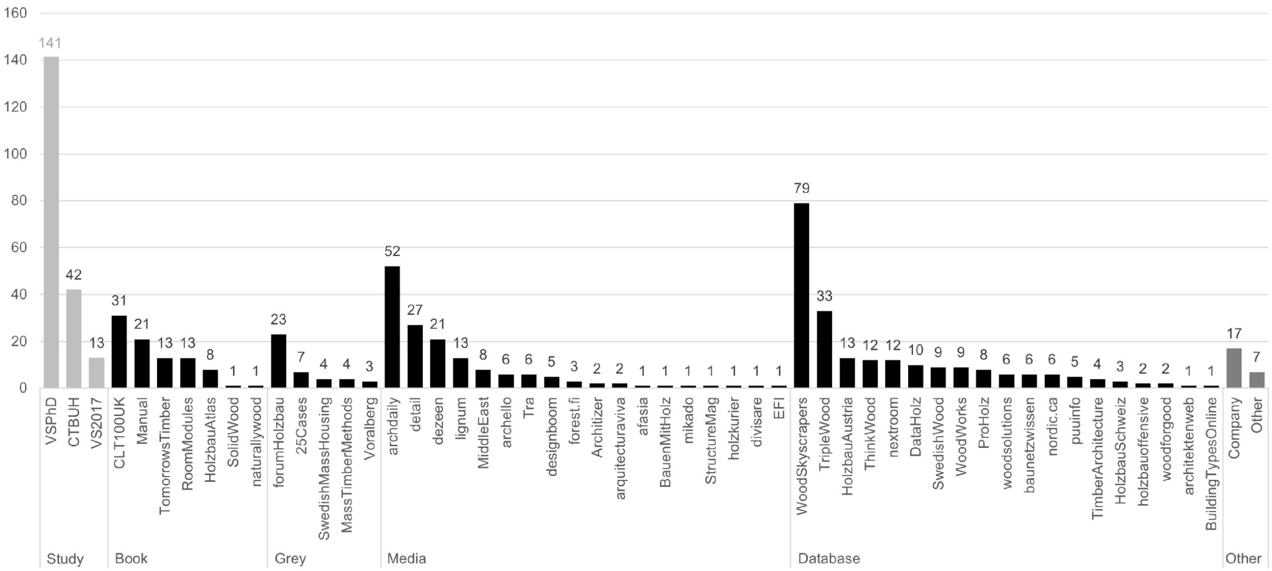


Figure 2. Data sources organized by type of literature.

2.2. Methodology

In order to investigate the architectural variety in multi-storey timber buildings, the survey analysis is structured into five parts: (1) structural, (2) program, (3) massing, (4) ordering system, and (5) material classification. As spatial configuration and general massing are inevitably tied to the structural strategy, results of parts 2–5 were cross-compared to the structural system in order to understand the link between structure, presence of different materials, and architectural factors. Therefore, the selected projects were grouped primarily based on structural classification and results for each criterion were structured into two categories: (1) across all categories, and (2) results based on structural system categorization.

The classifications per criteria were refined and established during data collection once there was a high enough number of projects, therefore the categorization of criteria is a result of the study itself (as it is adjusted after all projects are described, it is impossible to set categories first due to unknown variations of projects). Qualitative and quantitative data were sourced from existing literature listed in Section 2.1. Data Sources. The data were specifically collected from project descriptions and available project documentation in the form of architectural and structural drawings (plans, sections, elevations, diagrams, and renders), as well as photographs and construction videos.

2.2.1. Categorization: Classification by Structural System

The structural categorization of mass timber buildings is not consistently agreed upon in the literature. However, there are three main paths of thought in the literature where structure is classified into: (i) platform, post-and-beam, and modular, [43–45] (ii) panel systems, frame systems, and hybrid systems, [2,36,46] and (iii) single material, composite, and mixed [35,37,38,47]. As Salvadori explains in his doctoral dissertation, MTBs can be formed by one-dimensional or two-dimensional (vertical and horizontal) structural elements, or by 3D modules, which are composed of walls and floors that have been pre-assembled. Whereas Salvadori established 32 categories [19] that combine and cross-reference main structural and material types of structural systems, this paper establishes four main categories strictly on the basis of usage of 1-D, 2-D, or 3-D timber elements in construction and their respective combinations. The materiality aspect is classified separately in Section 2.2.2.

The categories are as follows:

- 1-D Frame structure;
- 2-D Bearing wall;
- 3-D Volumetric modules;
- Combination or hybrid.

Each structural system includes variations, as can be seen below in the Table 2.

Frame structures form post-and-beam structures, post-and-slab structures, as well as exoskeleton structures where vertical supports (other than the core) are limited to the exterior. The frame is usually anchored to a core and variations differ based on the presence of additional stiffening elements. The structures can consist only of a timber frame, but in order to achieve lateral stability, additional bracing systems such as shear walls, diagonal EWPs or steel beams, and steel cross bracing are added. Floor slabs can be made of different EWP combinations, such as CLT slabs, ribbed slabs, or CLT or glulam-concrete composite floors.

Panel walls usually form honeycomb or party wall structures [48], while some case studies were also formed by only a central core and external load bearing walls, which are connected to the floor slabs. In addition, considerations were also given to the presence of external structural elements, such as circulation corridors or balconies when separate from the main structure. Some of the sub-categories include internal beams or columns, or both. Floor slabs are mostly made of CLT or by box floor and box beam elements.

Volumetric modules, sometimes also referred to as spatial modules or 3-D modules, are made of pre-assembled volumes consisting of ready-made rooms and services pre-installed. The core can be built separately or modularly, as the building can. Although facades and balconies often come with 3D modules, this category also often exhibits the presence of additional external frame structures for balconies or circulation corridors.

Hybrid structural systems consist of different combinations of the categories. This includes projects in one of the following conditions: (a) lower and upper portions of the building volume are constructed in different ways, (b) different areas of the footprint are constructed with different systems, and (c) projects where two systems appear in combination with one another. An additional category is also mass timber combined with light frame construction (mostly in projects in North America), which consists of light-frame walls and CLT floor slabs.

Table 2 provides a full overview of sub-categories of structural systems that appeared during project analysis.

In addition, the structural classification was compared to general information collected for each case study mentioned in Section 2.1 of the paper and listed in Table A1 in the Appendix A The main interest was to map the year of construction, project status, and number of stories against the results to determine the trajectory and trends in MSTB construction.

Table 2. Classification by Structural System.

Dim.	Type of Structural System	Sub-System
1-D	Frame	exoskeleton post-and-beam post-and-beam w linear bracing post-and-slab post-and-slab-band
2-D	Bearing Wall	Crosswall and party wall honeycomb panel + beams [1] panel + box beams [1] panel + truss [1] panel + beam + column [1] panel + columns [1] panel + external frame (balconies)
3-D	Volumetric Modules	space modules space modules + external frame (balconies)
	Combination	frame + panel frame + space modules exoskeleton + space modules light frame + mass timber panel + beams + external frame (balconies)

[1] These subcategories contain a prevalent panel system, with smaller areas with other elements.

2.2.2. Structural Materials

In addition to structural categorization, the survey also noted the presence of concrete and steel material in structural elements for all the projects. The analysis therefore classified projects as (a) all-timber, (b) timber–concrete, (c) timber–steel, and (d) timber–concrete–steel, on the basis of their presence in the following categories: (i) podium or plinth, (ii) core, (iii) floor slab, (iv) lateral bracing and vertical or horizontal structural elements, or (v) 'other', which mostly comprised external structural elements such as columns or staircases and circulation areas.

(I) Cores can be made of timber (CLT or LVL - laminated veneer lumber), concrete, or framed steel. (II) Podium or the lower part of the building was defined as any number of stories before the start of the timber structure. It can consist of only a ground floor, but also several stories. In addition, a timber structure may be erected as an extension of an existing building, or a building may have no podium at all. The podium can be made of concrete, or at times also steel. (III) Floor slabs can be made of many variations of EWPs. [19] However, in this study, the floor slab analysis noted only the presence of concrete, more specifically composite slabs, concrete toppings, or integrated concrete precast beams, as well as steel beams, rather than the range of EWP products used in timber construction. (IV) In addition to the timber structure, steel elements can be present through the structure in various ways. Steel columns or beams can have a primary or secondary role within the structure, steel frames can be present, internal steel bracing or beams, pre-stressed steel rods inside timber frames, and steel rods that can anchor a timber structure. Concrete columns or structural systems can also be present on the exterior or within the podium of the building.

2.2.3. Classification by Program

The architectural program of the projects was analyzed based on three main categories: (1) residential and housing, (2) commercial, (3) public and civic, and (4) mixed-use. Table 3 provides a full overview of program subcategories that were taken into consideration.

Table 3. Classification by Program.

Program	Program Sub-Category
commercial	office retail office + retail office + industrial hospitality (cafe, restaurant, tourism) research facility health and therapy center + offices wellness resort hotel and hostel
residential and housing	retirement home and senior citizens home student housing social and affordable housing co-housing apartments and condominiums multi-family housing apartments + affordable housing
public and civic	sport and leisure culture educational, school, and kindergarten community center health center
mixed-use	office + retail office + residential education + housing residential + commercial office + culture + residential . . .

Although these categories were based on the use of the building, they also highly overlap with the established notion of the amount of necessary spatial enclosure. Residential programs for example require more wall divisions than commercial spaces, except for the cases of hotel and hostel programs. The categorization predominantly covers the main function of the building, rather than listing all of the functions. This is due to the fact that many housing and office buildings, especially projects involving a plinth in massing, most of the time include commercial retail or hospitality programs on the ground floor, or both.

2.2.4. Classification by Massing

Both Kuzmanovska et al. [2] and Salvadori [19] make distinctions regarding architectural massing in their studies. In the study by Kuzmanovska et al., building volumes were organized by overall geometric strategies in plan: (i) rectilinear and (ii) irregular plan, as well as in 'section' as a regular or irregular extrusion. Salvadori also examined the project volumes by distinguishing between four categories: (a) regular, (b) pitched roof, (c) varying heights, and (d) irregular volumes. Although more descriptive, these categories were still based only on the extrusion strategy in height, rather than the plans of the project and the spatial organization themselves.

This study distinguished between a greater range of forms in plan and extrusion types in height and aims to specify the complexities appearing in MSTBs. The main criteria for the analysis were (1) massing in XY (the overall geometric strategy in the floor plan); (2) massing in Z (the extrusion strategies from the floorplan in height). Table 4 provides a full overview of massing characteristics and classification.

Table 4. Massing Classification Matrix.

Analysis Criteria	Categories	Sub-Categories
massing XY (building outline, plan, and footprint)	rectangle rectangle operations rectangle-based linear courtyard polygon curvilinear combination	square, rectangle merged, shifted, overlapped, rotated rectangles quads, trapezoid, parallelogram, rectangles with chipped corner bars and strips, V, L, U, Y, T, meander, curvilinear rectangular, triangular, polygonal, donut, curved triangle, convex and concave polygons (5+) semi-curvilinear or fully curvilinear footprints, 'blobs'
massing Z (building volume)	extrusion: regular incremental extrusion floor plate variation volumetric indents	flat, pitched, sloped, mansard roof terraced, sloped, staggered, different heights, inverted ziggurat shifted floorplates, overhangs massings with volumetric 'cut-outs'
+ smaller scale irregularities (building volume)	balcony core facade	protruding, recessed, indent, scattered, size variation protruding cores dynamic, change of rhythm

The plan analysis of the projects distinguishes between several categories of forms: (**a**) rectangles, (**b**) rectangle operations, (**c**) rectangle-based, (**d**) linear, (**e**) courtyard, (**f**) polygonal, and (**g**) curvilinear forms, as well as their respective combinations. As can be seen in Table 4 rectangle operation forms consist of outlines that are generated with manipulation of simple rectilinear geometries rectangles are combined into more complex forms (Figure 3I), on the other hand rectangle-based form category encompasses mostly quad and quad-like geometries that closely resemble a rectangle such as a square with a chipped corner, or quads with some 90° corners or parallel lines (as shown in Figure 3II). Linear category takes on a more typological approach and lists all strip- and bar-like forms regardless of their orthogonality or complexity (Figure 3III). The courtyard category refers to all projects that showcase a large void area in its center (Figure 3IV). Polygonal category includes triangular, highly angled quads, and all convex and concave polygons with more than four sides (Figure 3V). Curvilinear forms refer to all forms with more organic curves that could not be classified into the other categories (also shown in Figure 3V). Figure 3 provides examples of projects within these groups.

As this initial classification does not provide an insight into the inherent regularity or irregularity of the forms, orthogonality and symmetry of the form outlines was additionally noted for each of the projects. These two aspects together determine whether a form is dominantly regular (orthogonal and symmetrical, or mostly orthogonal with a small degree of non-symmetry) or irregular (complex, non-orthogonal, or non- or semi- symmetrical).

The volumetric analysis distinguishes between the following categories in terms of plan extrusions: (a) regular extrusion—where the building has a simple direct extrusion of the plan regardless of the top floor and roof condition, (b) incremental extrusion—where the building is extruded in different heights but based on a raster, or clear volumes, and it gradually thins as it becomes taller, (c) floor plate variation—an extrusion where the orientation or the overall geometry of individual stories does not match; this can occur through smaller scale overhangs, or larger scale shifts in the floorplates, and (d) volumetric indents—where the building volume appears to have been carved out. Categories (c) and (d) both signify a more complex vertical volume that does not match the ground floor's plan. As additional smaller scale irregularities may impact the overall appearance of the massing as more or less regular, (i) balcony, (ii) core, and (iii) facade strategies were noted when they affected the building volume. This included features that provide geometric recesses or protrusions. Figure 4 provides examples of projects within this classification, while Table 4 wlists the differences in extrusion strategies in MSTBs.

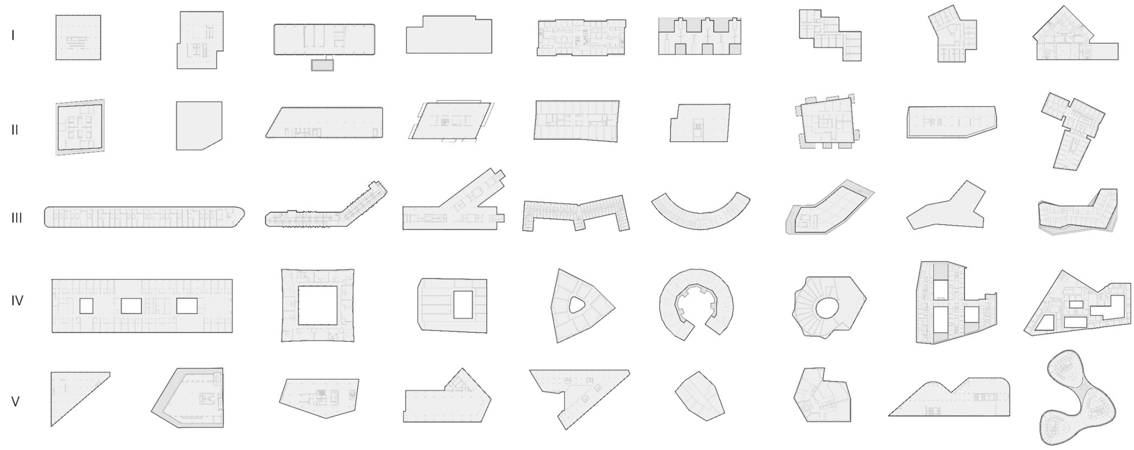


Figure 3. Massing typologies classification overview: (**I**) rectangle and rectangle operation forms; (**II**) rectangle-based footprints; (**III**) linear; (**IV**) courtyard, (**V**) polygonal and curvilinear typologies. Selection of project outlines not to scale. Projects in order left to right; (**I**) BOKU, Suurstoffi22, Modular School in Zurich, 3X Grün, Waldorf, Wohn- und Geschäftshaus Badenerstrasse, Residential Hostel Toulouse, Moholt, William Perkin Church of England School; (**II**) HSB Vasterbroplan, International House, Haut, Lot1 Suurstoffi, 6 Orsman Road, Canopia (**I**), 2150 Keith Drive, Hoho Wien; (**III**) Wohnhaus und Parkplatzüberbauung am Dantebad, UEA Blackdale, MEC Head Office, Woodie, Australia, Canopia, Merhfamilenhaus Gapont, Walderhus; (**IV**) Sozialzentrum Pillerseetal, Cowan Court, La Borda, Max Mell Allee, Valla Berså, Samling, Hotel De Region auvergne, Groupe Scolaire Pasteur; (**V**) de Haro, Bullitt Centre, Valle Wood, Tamedia office, Bjergsted Financial Centre, Schwarzensteinhütte, Mazarin House, Seattle Mass Timber Tower Study, Triodos Bank.

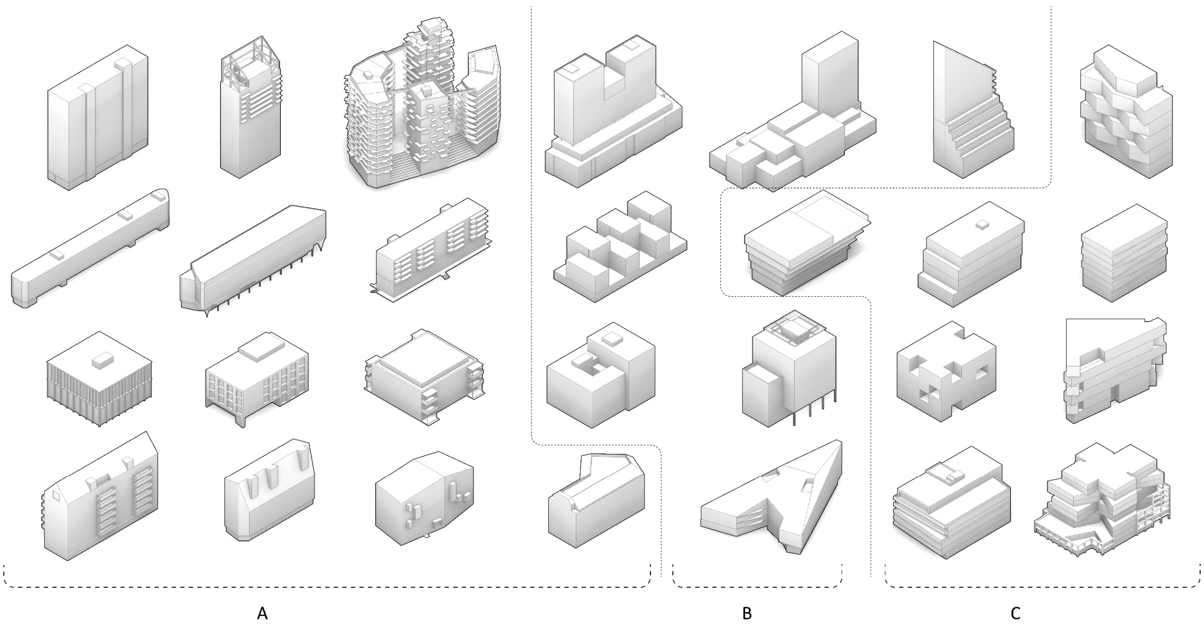
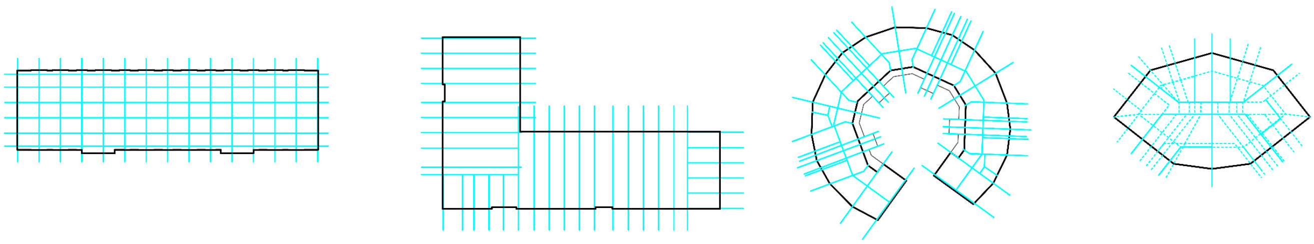


Figure 4. Massing variations classification overview in Z: (**A**) regular extrusions, (**B**) incremental extrusions, (**C**) floorplate variations.Selection of project volumes not to scale. Projects from left to right: (**1st row**) Brock Commons, Mjøstårnet, Canopia, de Karel Bouman, Sara Cultural Centre, Terrace House, Ki-Etude; (**2nd row**) Wohnhaus am Dantebad, Daramu House, Pile Up Giesshübel, Wohn- und Geschäftshaus Badenerstrasse, Nodi, Framework, Patch22; (**3rd row**) BOKU, Hotel Katharinenhof, Wohnen 500, Suurtoffi22, Skaio, IBA Apartment Building, Flatiron Office Building; (**4th row**) Strandparken, Svartamoen Place, Puukuokka, Tamedia Office, Bjergsted Financial Park, 6 Orsman Road, Wenlock Cross.

2.2.5. Categorization: Classification by Ordering System

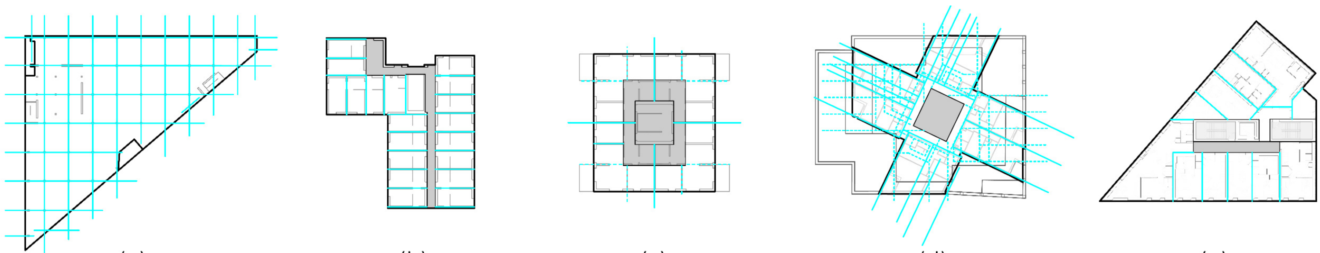
The ordering system refers to a system of rules that shape the structure, layout, and proportions of a design. It establishes the overall guidelines for spatial division and spatial organization of a project. In this study, it was derived from the location of the load-bearing and permanent building elements. Figure 5 shows the basic classification of projects based on the ordering system: (1) grid, (2) linear-array, (3) grid-based, (4) linear, and (5) irregular. Categories 1–4 can be all based on an orthogonal raster depending on the situation, however they can also include semi-orthogonal or non-orthogonal situations such as perpendicularity to outline tangent or a radial array. The irregular category refers to more complex non-raster-based and non-orthogonal strategies.



(a) (b) (c) (d)

Figure 5. Ordering system classification: (**a**) grid; (**b**) grid-based and linear array; (**c**)linear; (**d**) irregular. Project outlines not to scale. Projects: (**a**) Brock Commons; (**b**) Senior Citizens' Home in Hallein; (**c**) Valla Berså; (**d**) Rundeskogen.

In addition, spatial organization of the projects was noted based on the location of vertical and horizontal circulation. Figure 6 shows a selection of projects with the basic categorization: (a) grid, (b) linear, (c) centralized, (d) radial, and (e) combination. Although there are other spatial organizations existing in architecture, these were the only categories occurring among the listed MSTBs projects.



(a) (b) (c) (d) (e)

Figure 6. Project spatial organization: (**a**) grid; (**b**) linear; (**c**) centralized; (**d**) radial; (**e**) combination, centralized + linear. Project outlines not to scale. Projects: (**a**) de Haro; (**b**) Student Hostel Heidelberg; (**c**) Wohnen 500; (**d**) Wenlock Cross; (**e**) Generate Model-C.

There were two main factors that were considered to determine the level of variation within the project's ordering system:

(I) Orientation, which refers to the degree of orthogonality within the ordering system (orthogonal, semi-orthogonal, perpendicular to tangent, non-orthogonal, and combination;
(II) Spacing rhythm, which can be described as regular (constant), regular with variation, irregular, and combination.

In addition, the following irregularities were noted and identified when present: (i) shifts, (ii) spacing variations, (iii) length variations, (iv) angle, (v) orientation, (vi) or grid changes, as well as any (vii) irregular non-orthogonal areas within the floorplan such as interior openings, atriums, or double-height areas. Table 5 summarizes the variations per structural category, while Figure 7 illustrates the noticed variations with project examples.

Table 5. Variations per structural category.

	Shift	Spacing Variation	Length Variation	Angled Walls	Orientation Change	Grid Change	Irregular Areas
1-D frame	grid shift	bay size variation	variation in length and type of vertical support	presence of intersection and angle change areas		deviation distortion rotation combination intersection	atrium central area core open spaces
2-D panel	line shift	wall placement variation	wall length variation	presence of angled walls	module orientation change		atrium central area core open spaces
3-D space modules	module shift	module size and form variation	different modules combination	non-orthogonal space modules	division wall orientation change		core open spaces

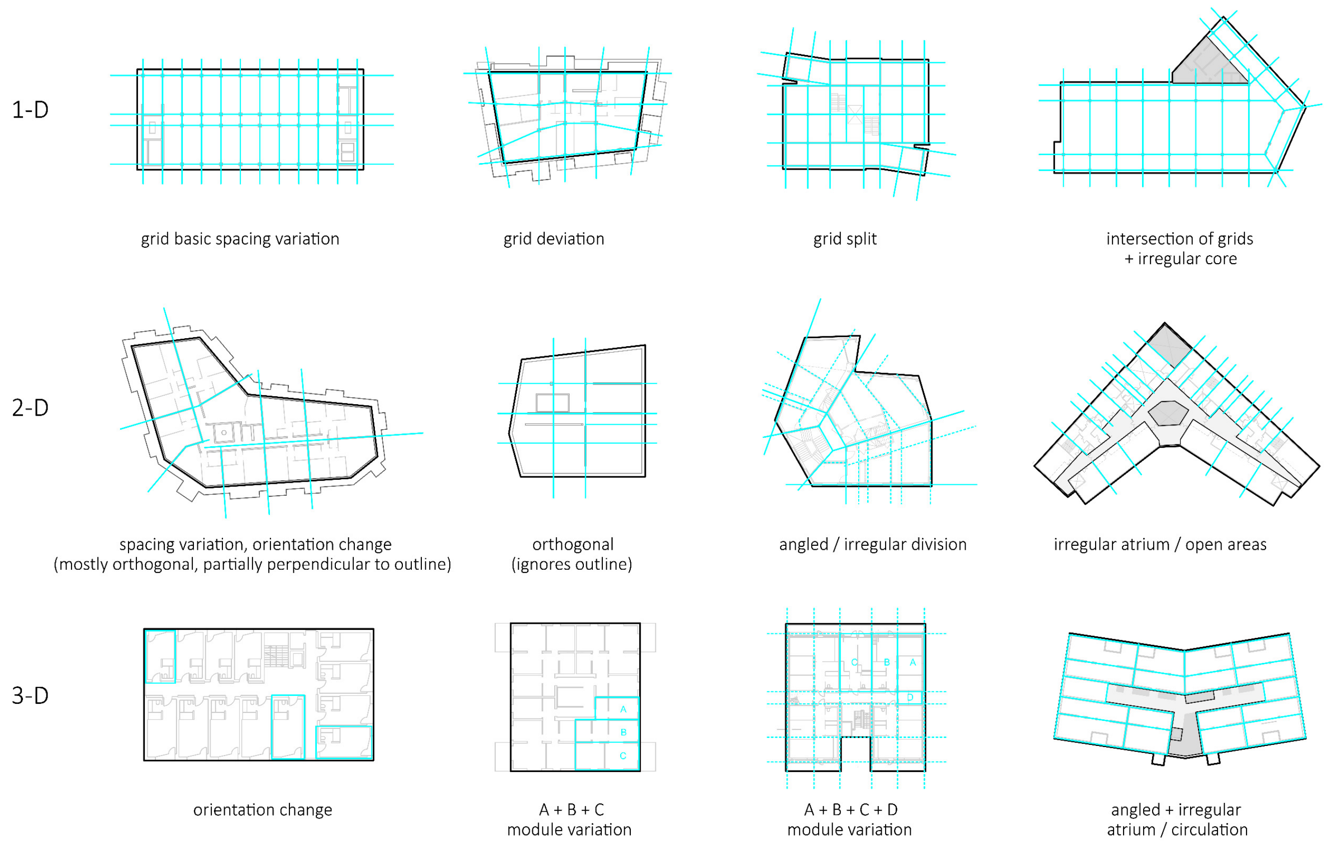


Figure 7. Ordering system classification and variations. Project outlines not to scale. Projects: (**1-D**) Sara Cultural Center, Canopia, Carbon 12, Tamedia; (**2-D**) Canopia, LynarStr., Mazarin House, Ickburgh School; (**3-D**) Hotel Katharinenhof, Wohnen 500, Treet, Puukuokka.

3. Results

The following section summarizes the findings of the analysis. It is structured into two parts: Section 3.1 general project information data results, and Section 3.2 design analysis results. In the design analysis section, the case studies are divided based on structural categorization.

3.1. General Project Information: Height, Year, Location

The list of the case studies consists of projects built between 2000 and 2021. As can be seen in Figure 8, the height of the project is steadily increasing. The first five-storey project from the list appears in 2004, in 2006 the first 6-storey project, in 2008 already both 7- and 8-storey buildings, in 2009 a 9-storey building, in 2012 a 10-storey building, and so on. This culminates in 2021 with a 34-storey building completed in the Netherlands, project *Haut*. The graph shows that 13 more projects are planned to finish construction between 2022–2024, and 33 even taller projects, the vast majority of which are to be between 10 and 80 stories, have no announced date of completion. The graph shows a steady increase in MSTBs over the years. The year 2019 has the most projects (50), while 2020 comes in second with 35, and 2021 with only 15. However, this might be the case as less publication materials were available on newer projects from 2020 and 2021 at the time of this study.

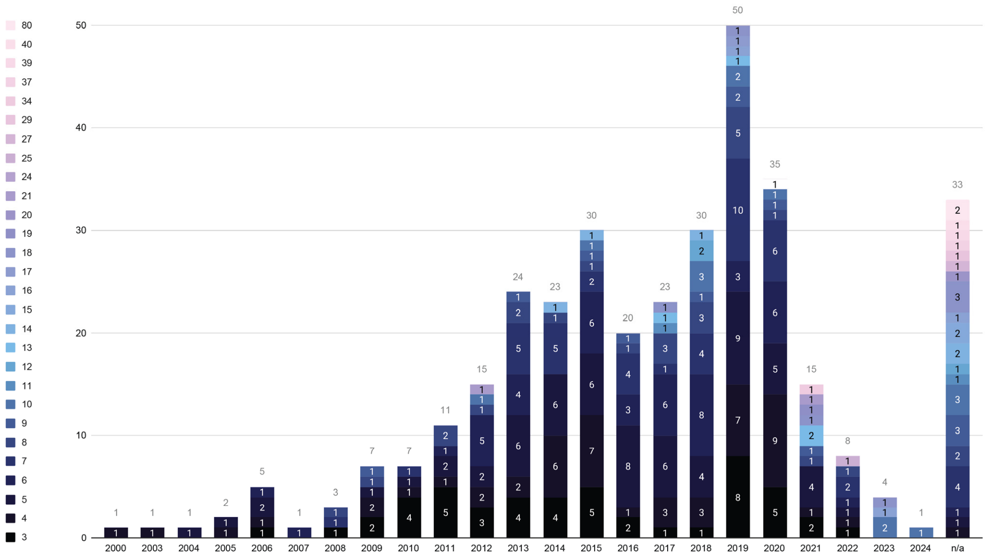
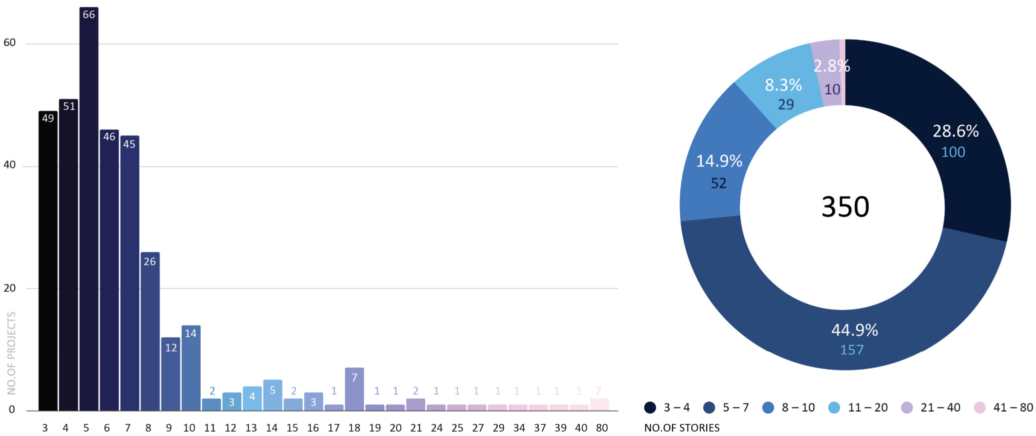


Figure 8. Number of buildings per completion year divided based on height (in meters).

The majority of the case studies are mid-rise projects between 5 and 7 stories tall, accounting for 44.9% of the total buildings. Low-rise buildings from 3–4 stories comprise 28.6%, while taller projects jointly comprise the remaining 26.5% (14.9% being projects 8–10 stories tall). Figure 9 shows the ratio of projects based on height (Figure 9a), as well as grouped into height categories (Figure 9b).



(a) (b)

Figure 9. Ratio of low-, mid-, and high-rise buildings (**a**) Number of projects divided by number of stories. (**b**) Ratio of projects divided into groups of stories.

The distribution of low-, mid-, and high-rise projects varies across the countries. The majority of the case studies, 80.3%, are located in Europe, 14.9% in North America, 3.7% in Australia and Oceania, and only 1.1% in Asia. Most case studies (48) are from Germany, closely followed by 41 projects in Switzerland, 37 in both Austria and UK, 32 in both France and USA, and less than 30 in Sweden, Canada, and Norway. All other countries have less than 11 projects, as shown in Figure 10.

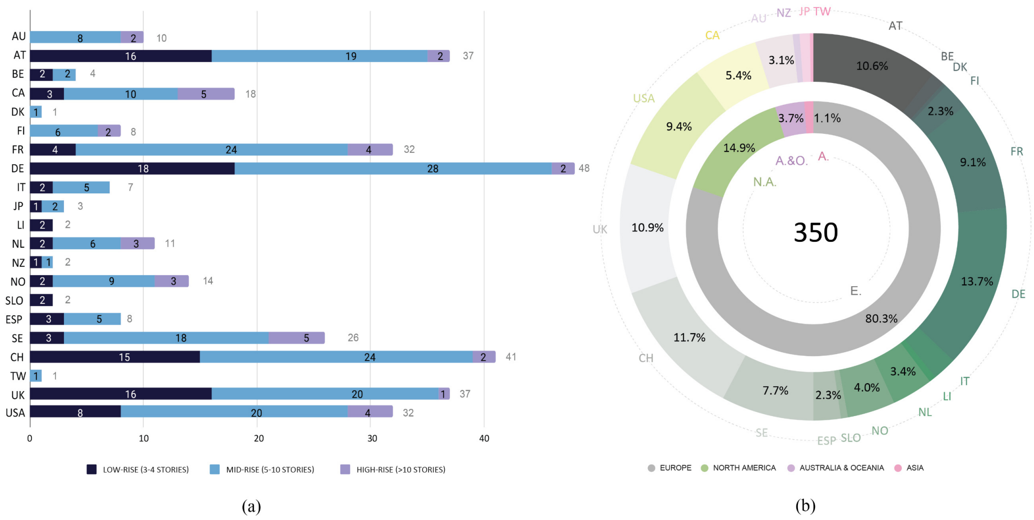


Figure 10. Number of buildings per location. (**a**) Number of buildings per country, divided into low-rise, mid-rise, and high-rise categories. (**b**) Ratio of projects per continent and country. Standard country abbreviations used.

3.2. Analysis Results

3.2.1. Categorization: Classification by Structural System

As seen in Figure 11b, panel and space module systems were the most common systems from 2000–2010, while from 2011 there is a significant increase in frame structures. This might suggest that there is a shift in the dominant structural strategy of MSTBs construction, or also based on Salvadori's results [19] (in his comparison of structural systems and project locations) this can suggest a hype in frame construction for example in the USA where all of the projects had a post-and-beam structural system. Similarly, the results of this study show that USA, Australia, Canada, France, and Switzerland have a dominant post-and-beam construction strategy for MSTBs (as can be seen in Figure 11a).

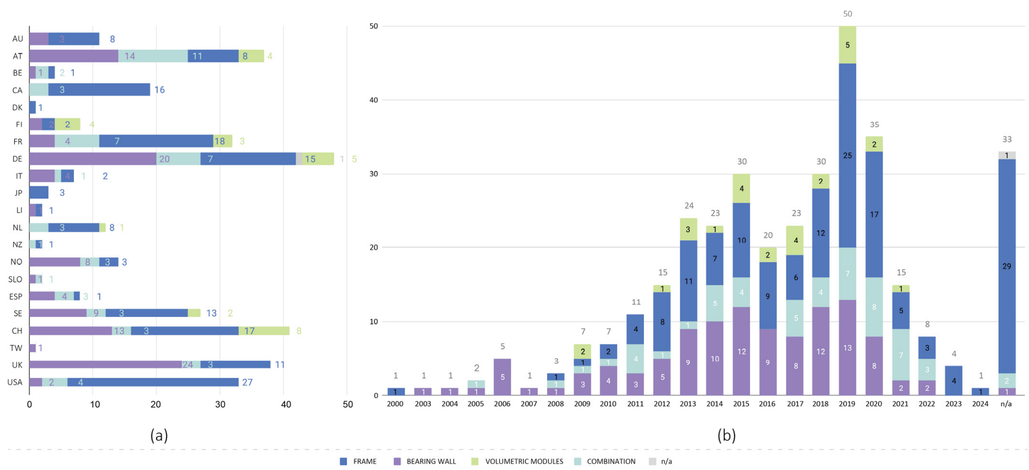


Figure 11. Number of buildings divided by (**a**) structural type per country, and (**b**) structural type per year.

As Figure 12a shows, frame structures consist of 54.8% of projects with 5–8 stories height, 19.1% of projects with 3–4 stories, and a total of 26.11% of projects with over 9 stories, which includes 7% projects taller than 20 stories. In contrast, both panel and volumetric module systems consist of primarily mid-rise projects up to 10 stories. Panel structures consist of 62% mid-rise (5–8st.) projects, 27.03% low-rise (3–4st.) projects, and 10% projects between 9 and 19 stories. Volumetric module projects consist of 40.7% 3–4st. projects, 51.8% 5–8st. projects, and only 6.4% of the projects are between 9 and 15 stories tall. Only combination systems also consist of projects taller than 15 stories; 7.5% of projects are between 29 and 80 stories tall.

This correlates to the fact that 89% of proposed unbuilt projects are frame structures (as shown in Figure 12b), which, correlates to unbuilt projects beingsome of the tallest MSTBs. Figure 12b also shows that the amount of built panel and frame structures is almost the same, 108 and 114 projects, respectively. Specifically, frame MSTBs consist of 72.6% built, 21.6% proposals, and an additional 5.7% are projects in construction. On the other hand, 97.3% of panel projects, 87% of combination systems (47), 27 projects, and 100% of volumetric modules, are built projects.

Overall, the majority of the case studies, almost one half (52%), are composed of frame structures. Panel projects comprise one third (31.7%) of the entire survey, with combination systems comprising 13% of the projects, and finally volumetric modules only 7.3% (Figure 12c). It is possible that this can be attributed to the data sources and less exposure of modular projects in popular literature and timber databases.

Figure 13 shows the variation of structural systems within the main categories of frame, panel, and space modules. It is visible that the categories are quite homogeneous, as each one has a dominant % sub-group.

Frame

Frame structures are composed of 97% post-and-beam projects, with few projects in exoskeleton, post-and-slab, and post-and-slab band systems. A total of three projects are exoskeleton systems, which include post-and-slab construction. These projects are *Oakwood Timber Tower*, *2150 Keith Drive*, and *Cradle*, respectively. Only one project, *77 Wade*, is post-and-slab, and one project post-and-slab band, *Arbour*. Both of these are unbuilt. Another exception is project *Patch 22*, which is classified as post-and-beam, but also contains exoskeletal bracing to support full length balconies. *Atlassian HQ* project proposal also consists of an exoskeleton, however, it was not included in the classification as it is not a timber structure but steel that helps support a separate timber frame structure. Additionally, 18% of frame projects have internal or external bracing elements, as can be seen in Table 6.

Panel

Bearing wall projects are composed of 91% pure panel structures with a few exceptions. A total of 8% of panel projects still have columns or beams integrated in parts of the plan when openings or bigger spans are needed, and additionally, external frame structures are used for balconies. In some projects such as Via *Cenni*, a crosswall panel arrangement is used in the lower areas, while honeycomb strategy is used for the tower segments.

3-D Modules

Similarly, space module structures only have one additional sub-category, in which an additional external frame structure makes the balconies. The *European school* is one example where the ceiling panels of the corridors are positioned between the modules or rest on glued-laminated timber columns.

Combination

Hybrid structural systems are composed of 74.5% frame and panel combinations, followed by two examples of exoskeleton and space module combination, 12.8% light frame and mass timber slabs combinations, 1.8% panel and 3-D modules, and finally 2.6%

combination projects with an additional external frame for balconies. It is worth noting that during the survey several other light frame and mass timber projects were discovered, however, due to lack of information they were not included in the final case-study selection. This does suggest that this type of hybrid structure is becoming increasingly common, especially in the USA.

Projects such as *Canopia* fall under the combination system category as the development consists of four buildings connected by a joint podium with different tower buildings built in either frame or panel construction [49]. *Sara Cultural Centre* is another project where two different construction systems were developed, one for the cultural center and one for the hotel. The hotel segment is built of 3D-modules while the lower part consists of a timber frame structure [50].

Among the panel and frame combination structural systems, some of the projects such as *Samling* combined post-and-beam construction with panels by separating it into different areas of the plan [51]. Larger public spaces were constructed in pure post-and-beam construction, while residential and office areas consisted of a combination of post and panel supports. Cooperative housing *La Borda* uses post-and-beam structure to create common spaces, while a panel system is used for the separation between the apartments. Here, as well as in the *Lucien Cornil Student Residence*, the use of systems is separated more vertically.

Other project examples have a less delineating approach with walls and columns. *LignoAlp office* project consisted of external load-bearing walls, and variations of columns panels or core supports connected with variations of slabs across the stories. Similarly, project *Wohnanlage Kiefernweg Gantschier* consists of mostly panel construction with beams, but with different levels of column supports across the different stories. *Social housing in Saint-Denis* also exhibits this through load-bearing panel construction with half of the footprint incorporating an interior post-and-beam structure. In the *Lynarstraße housing project*, the structure is composed of post-and-beam, shear walls, and external load-bearing walls. Project *Filao* goes a step further; it comprises of larger areas with interior column supports in addition to panels.

Several projects have less common structures. The latest tall rise in Amsterdam, *Haut*, consists of a post-and-beam construction with inner load-bearing walls, and both types of vertical supports occupy roughly the same area of the plan. The project *Stories* consist of a non-typical panel structure, a perforated crosswall sequence minimizes the length of the walls to appear frame-like, while additional use of beams structures the double height spaces. In addition, an external steel frame for balconies is present. Few unique panel-frame structures are present in projects *Qbika* and *Shelves House*.

This trend of combining or borrowing elements from different structural systems to achieve bigger or taller spaces within a project might suggest a link between heterogeneous structures and architectural variety, or a compromise to achieve more flexible open spaces.

Exoskeleton and 3-D spatial modules are combined in different ways. *Treet Tower* consists of glulam trusses along the façade and 3-D modules, which are stacked in groups of four stories on top of 'power stories' or glulam stories with a concrete slab [52]. Therefore, it can be said the 3-D modules are incorporated into a frame structure. In contrast, the *Gibraltar Guesthouse* project combines 3-D modules with a glulam structural frame positioned along the short edges of the building volume in order to create common spaces and six-storey open spaces [53,54]. Therefore, the frame structure here has a programmatic rather than a purely structural function.

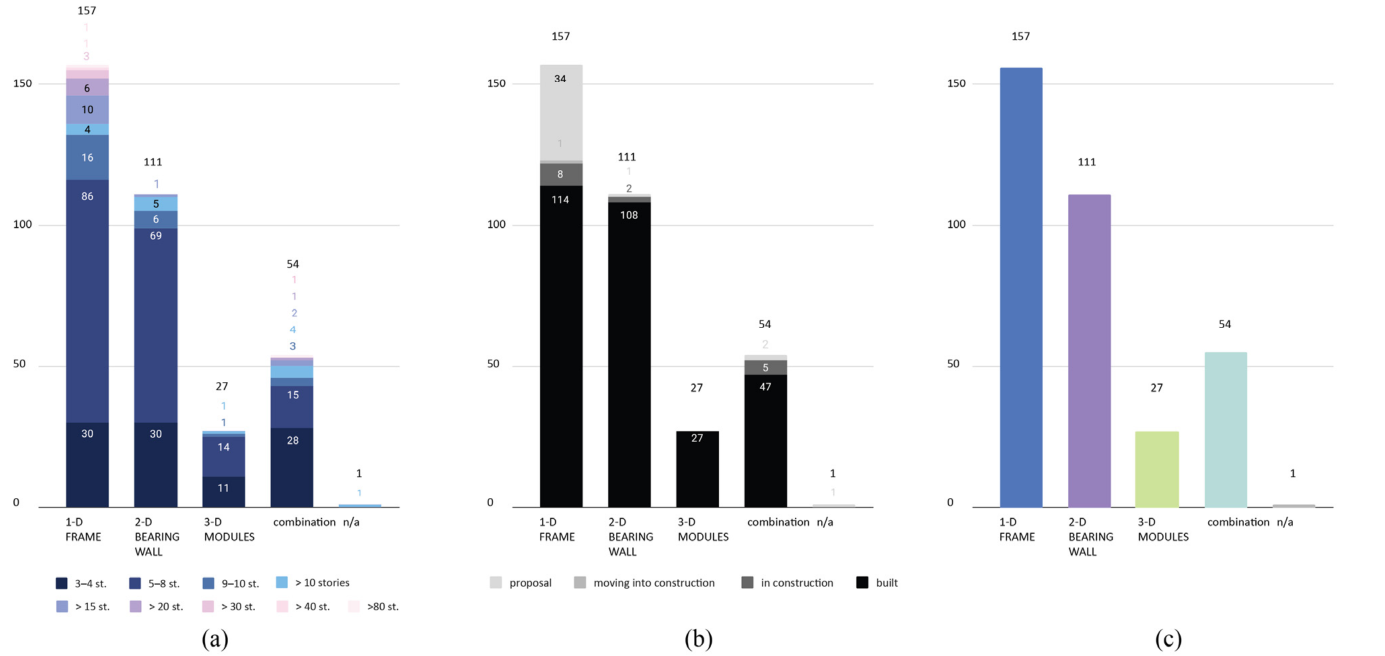


Figure 12. Number of projects by structural categorization: (**a**) Number of projects by building height; (**b**) Number of built and unbuilt projects; (**c**) Number of projects by main structural categories.

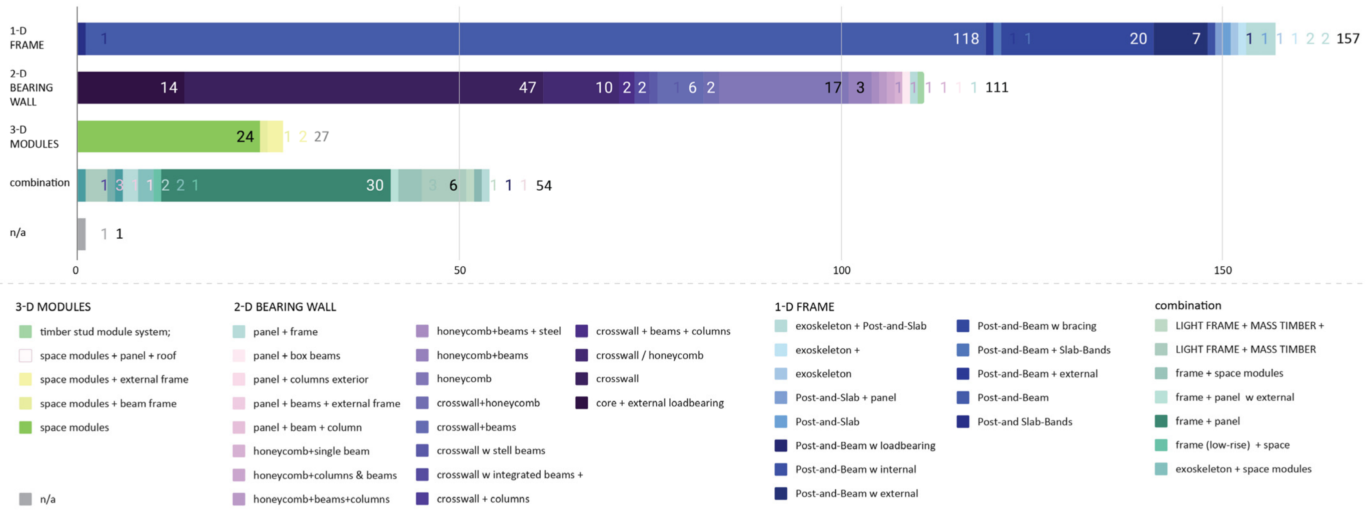


Figure 13. Number of structural system variations per structural system.

Table 6. Structural sub-categories/ratio (%) of different structural system variations per structural system group.

Frame	%	Bearing Wall	%	3-D Modules	%	Combination	%
post and beam	**97%**	**panel**	**91%**	**space modules**	**88.9%**	**frame + panel**	**74.5%**
post and beam with bracing	75%	crosswall	42.3%			frame + panel	58.2%
with external bracing	12.8%	honeycomb	15.3%			w external bracing	1.82%
with internal bracing	4.5%	crosswall variation	10.8%			"shelves" *	1.82%
with external balcony support bracing	0.64%					panel + post and beam (columns/beams/ external balconies)	10.9%
post-and-slab bands	**1.25%**	**panel + additional elements**	**7.2%**	**s.m. + additional elements**	**11.1%**	frame-like panel **	1.82%
post-and-slab	**0.64%**	p. + beams	0.9%	+ external frame (balconies)	7.4%	**frame + 3D**	**10.9%**
exoskeleton variations	**2.56%**	p. + box beams	4.5%	+ external balcony structure + beam frame	3.7%	exoskeleton + 3D	3.64%
		p. + beam + columns	0.9%			regular frame + 3D	5.45%
		p. + frame	0.9%			frame and 3D ***	1.8%
		p. + truss	0.9%				
		p. + vierendeel truss	0.9%			**panel + 3D ********	**1.82%**
		p. + timber stud	0.9%				
		p. + external frame (balconies)	1.8%			**other**	**12.7%**
						light-frame + mass timber	10.9%
						light-frame + m.t. + glulam header beams	1.82%

* Shelves House unique structure, horizontal bands forming an external structural frame. ** Stories structure, perforated crosswall sequence with use of beams in double height spaces with an external steel frame for balconies. *** Frame part and volumetric module parts are separated into low-rise 'plinth' frame structure, and tower 3-D module structure (Sara Cultural Centre project). **** Theatre Tower on the Julier Pass is a project which consists of star-shaped pillars that contain staircases and cores, as well as has panel and bam elements. The tower was prefabricated and parts were brough to site as preassembld 3-D pieces, and therefore can be interpreted as a combination of panel and 3-D volumes. The linear elements were not considered as they accounted only for the atrium roof structure (truss system).

3.2.2. Structural Materials

Overall, most MSTBs are structurally material hybrids and complex timber-based buildings, as can be seen in Figure 14a and as is mentioned in previous literature [19].

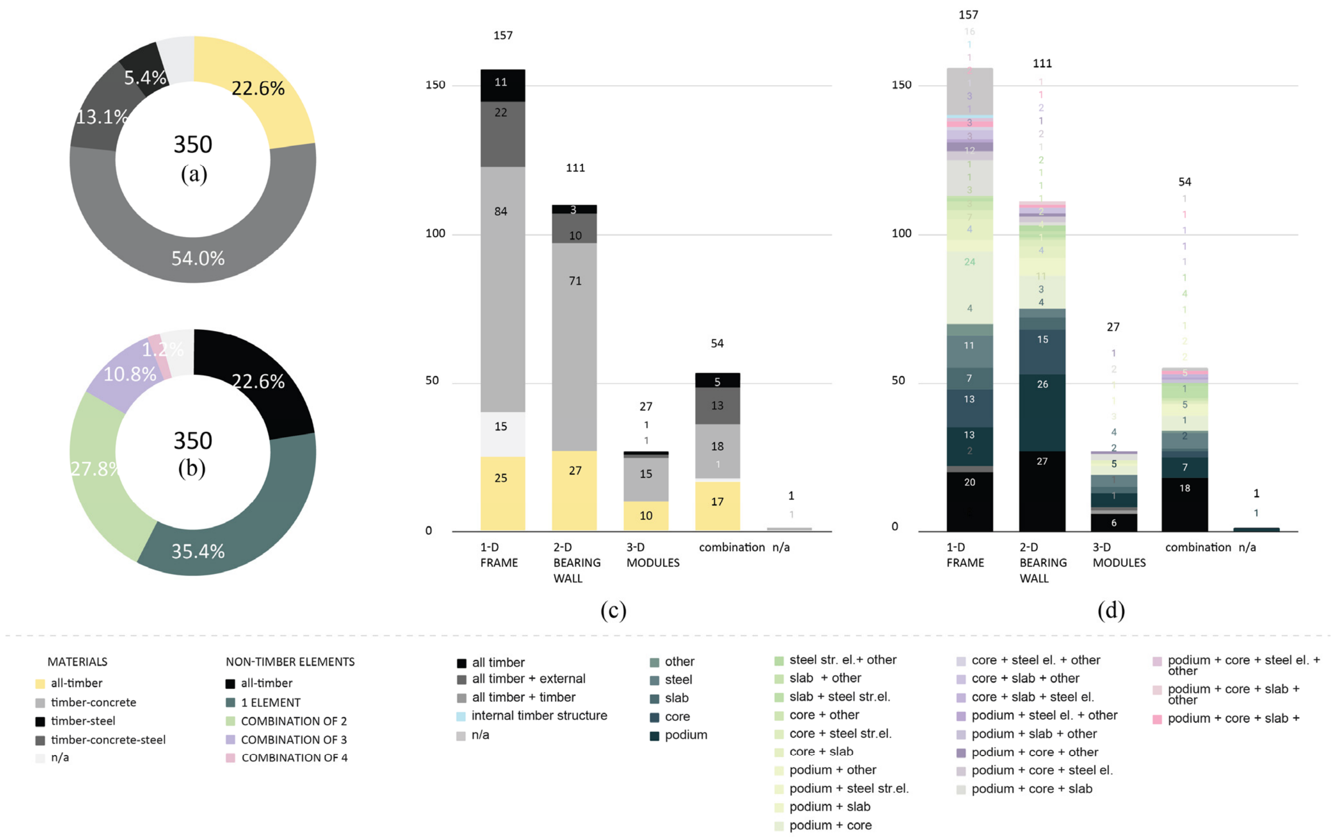


Figure 14. Material classification per structural system: (**a**) ratio of projects based on material 'content', (**b**) ratio of projects based on number of types of non-timber elements, (**c**) number of projectsbased on material per structural systems category, (**d**) number of projects based on type and number of non-timber elements (concrete and steel) per structural systems category.

All-timber projects are rare across all structural categories with a total of 78 projects. They comprise a total of 22.6% of all projects with the rest being hybrid structures. Timber–concrete structures are most common overall, comprising 54% of the total MSTBs. Timber–concrete–steel structures follow with 13.1%, and timber–steel structures with 5.4% of total projects. (While use of steel among primary load-bearing elements is most rare across the projects, this study did not account for connections.)

Table A6 in the Appendix C lists the number of projects and ratio of materials per individual structural element (podium, core, slab, additional structural elements, and other and special category) and per structural system.

Almost half of the projects, 45.4%, have a non-timber podium, 46% of projects have a non-timber core, 10.57% non-all-timber slabs, 18.86% additional non-timber structural elements, and 4.57% have other secondary non-timber elements such as exterior balcony or external circulation supports from ground up. Overall, the main subgroups are concrete podium (38.8%), concrete core (36.6%), and timber–concrete composite slabs (8.29%). All other variations show up in less than circa 2% of all projects, with the exception of steel beams (4.3%). However, when calculated together, all steel structural element variations appear in 15.4% of projects and are therefore more common than composite slabs.

Figure 14b represents the different combinations of non-timber elements in the projects. Non-timber elements appear in the following combinations: 35.43% of projects have only one type of non-timber element; 26.3% of projects have two; 10% of projects have three; and 2% of projects have four types of non-timber elements.

The most prominent combination is podium–core combinations (12.3%), followed by podium–core–slab (4.3%), and core–slab combination (3.4%).

All the MSTBs, except for two case studies, have a reinforced concrete foundation, and a basement when present. Figure 15 shows in detail the ratios of different element usages in the separate material categories and the level of heterogeneity of structural solutions in each group. Within the all-timber group project, '*Asylunterkunft Rigot*' has foundations made of wooden piles and footings, while a temporary school in Biel has screw foundations with steel girders above. Additionally, several other projects classified as all-timber have instances of other materials. Project '*Kampa*' has stairs and landings in reinforced concrete, 'Catalyst' is an all-timber proposal that also has a light concrete topping on the slab, and three projects, '*Wohnsiedlung in Rive de Gier*', '*Zürich Modular Pavillion*', and '*Träloftet*', have external steel structures or steel cable supports for staircases and balconies.

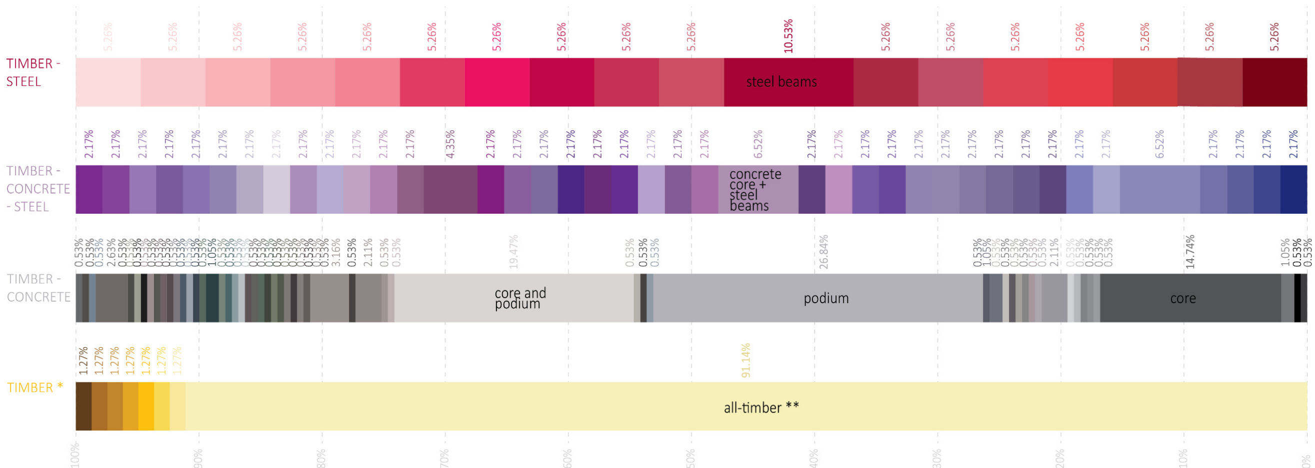


Figure 15. Detailed ratio of elements (podium, core, slabs, combinations, and additional structural elements in concrete or steel) within each material classification group (with highlighted largest ratio groups, smaller ratios present an indication of the range of variation within the groups). * Timber projects include all project that have exclusively timber load-bearing elements. As part of the variation within this group is for example a project with timber foundations, as well as a project with all-timber elements with concrete stairs and landings. ** Largest group of all-timber projects consists of standard all-timber buildings with concrete foundation.

Frame

Frame projects consist of 15% all-timber structures, 53.2% concrete–timber, 23.6% timber–concrete steel, and 7.3% of timber–steel projects (Figure 14a).

Timber–concrete structures consist mainly of combinations of concrete podiums and cores, followed also by either concrete core or podium constellation. The rest of the projects consist of concrete slabs and toppings, minor columns, and beams. An example of use of independent concrete is project *School near Geneva* in Les Vergers, where four timber buildings are encircled by reinforced concrete balconies. The balcony structure is a self-supporting belt into which the timber construction was later set [55].

Table A6 in Appendix C additionally shows that frame structures have the highest percentage of steel elements (22.29%) overall. A total of 2.55% of frame structures also have a steel frame core, and one project only, *Adohi Hall*, has a steel podium. Steel lateral cores are present in four projects, for example in *55 Southbank Boulevard*, which rises on top of an existing building. *Radiator* and *Carbon 12* both have steel cores and internal steel braces that stiffen the timber frame structures. The *Bullitt Center* is composed of a central steel frame, a heavy setup of internal bracing that acts as a core for the structure. Another proposed project, *Terrace House*, has announced a concrete and steel core [56].

More common are concrete cores and podiums with additional steel elements incorporated in the interior or the exterior of the structure. For example, *Green Office® Enjoy* is a glulam frame project, which includes a concrete podium and core with steel columns and bracing beams, which run throughout the facade [57]. Additionally, the top floor of the project is partially made of steel. In both *360 Wythe* and *T3 Atlanta*, steel bracing is used in addition to a concrete core for lateral stability, while in the *MEC Head Office*, bracing as well as steel beams for stair support are used. In *UBC Earth Sciences*, the frame is stiffened by steel chevron braces.

Several projects, *SKAIO*, *Famju*, *C13*, *E3*, Pont de *Flandres*, and *Opalia*, rely on a core for lateral stability connected to a steel beam integrated in the external frame (steel edge beams). *Gymnasium OMG*, and *Woody* also contain steel beams, while *Te Ara Hihiko* is an example of a post-and-beam, timber–concrete–steel building with a concrete podium and steel rods, as well as with a post-tensioned steel system.

Few projects not only incorporate steel as bracing, but also as primary vertical supports. The *Bouwdeel D(emontabel)* project consists of steelwork, into which ribbed wooden slabs are placed [58]. Similarly, *6 Orsman Road* has a steel frame structure with CLT slabs. *De Karel Doorman* extension also consists of a steel frame with wooden floors [59]. On the other hand, *Triodos Bank* project has parts of the building completely built in steel. *Diesel Benelux HQ* contains steel columns, while the *Royal Shakespeare Theatre* includes a hybrid steel and CLR frame [60].

Panel

Panel projects consist of 24.3% all-timber structures, 64% concrete–timber, 9% timber–concrete steel, and 2.7% of timber–steel projects (Figure 14a).

Most projects have a concrete podium, followed by concrete core, and concrete podium and core. Some projects have entire segments made out of concrete, and often their exterior balcony and circulation areas also are. *Max Mell Allee* has a reinforced concrete arcade forming the exterior atrium.

A total of 10 projects are timber–concrete–steel. Among panel projects, use of steel beams and steel rods is most common. There were two projects, *Strandparken* and *Lighthouse Joensuu*, which had a concrete podium and steel rods, while *Limnologen* also had an additional concrete core. *Wenlock Cross* is the only project that is stiffened by an external steel frame that connects to a central concrete core and to CLT shear walls and slabs. *Ki-etude* project has a concrete core and steel beams positioned on the edge of the facade, with few steel beams used inside the building. *Additional Storeys in Wood Construction* use a steel structure to direct new loads into the existing structural members as the new load bearing walls do not correspond to the original buildings grid [61]. This project also includes carbon-fiber-reinforced plastic strips, which are often used in structural retrofitting of concrete structures. Smaller percentages of panel projects consisted of various steel elements used for balcony supports, and steel frames for bigger loads or spans.

Only three projects are timber–steel structures. In the *Woodberry Down* project, an interior steel column was used to create a corner window, while the *Open Academy* and *Housing Block in Merano* have instances of steel supports, columns, and beams, used to achieve long spans.

3-D modules

The 3-D module projects consist of 37% all-timber projects, 55% concrete–timber, and only 3.7% timber–concrete-steel and 3.7% timber–steel projects (Figure 14a). Timber–concrete projects have an almost equal number of projects with a concrete podium as projects with concrete podium and core.

Timber–steel and timber–concrete–steel categories were identified each only in one project in the 3-D module category. However, at a closer look, in *73 Saint Mande Housing*, this is due to steel columns used for external balconies. Therefore, only one 3-D module project, '*WDF 53*', has steel in its configuration with a four-storey steel skeleton, which supports the wooden modules.

Combination

Combination systems consist of 32.7% all-timber, 34.55% timber–concrete, 14.1% timber–concrete–steel, and 7% timber–steel (Figure 14a). The majority of timber–concrete projects have a concrete podium or a combination of concrete core and podium, while the majority of timber–concrete–steel and timber–steel projects contain internal steel beams and columns such as in *Bercahaus* and *Innorenew* where steel forms the central atrium, or steel supports integrated into the exterior walls or can be present in external balcony structures such as in projects *Qbika*, *Eisberg*, and *Agrarbildungszentrum Salzkammergut*. UK project *Curtain Place* consists of external load bearing CLT walls and a light steel frame.

3.2.3. Categorization: Classification by Program

Overall, the most common program in mass timber construction is residential, making up 46.8% of all programs. As can be seen in Figure 16a, all program groups (residential, commercial, mixed-use, public, and civic) are present in every structural system, however in different ratios. The majority of panelized systems have residential buildings. On the other hand, the majority of frame systems have commercial programs. Volumetric module group and combination systems seem to not have a dominant program group.

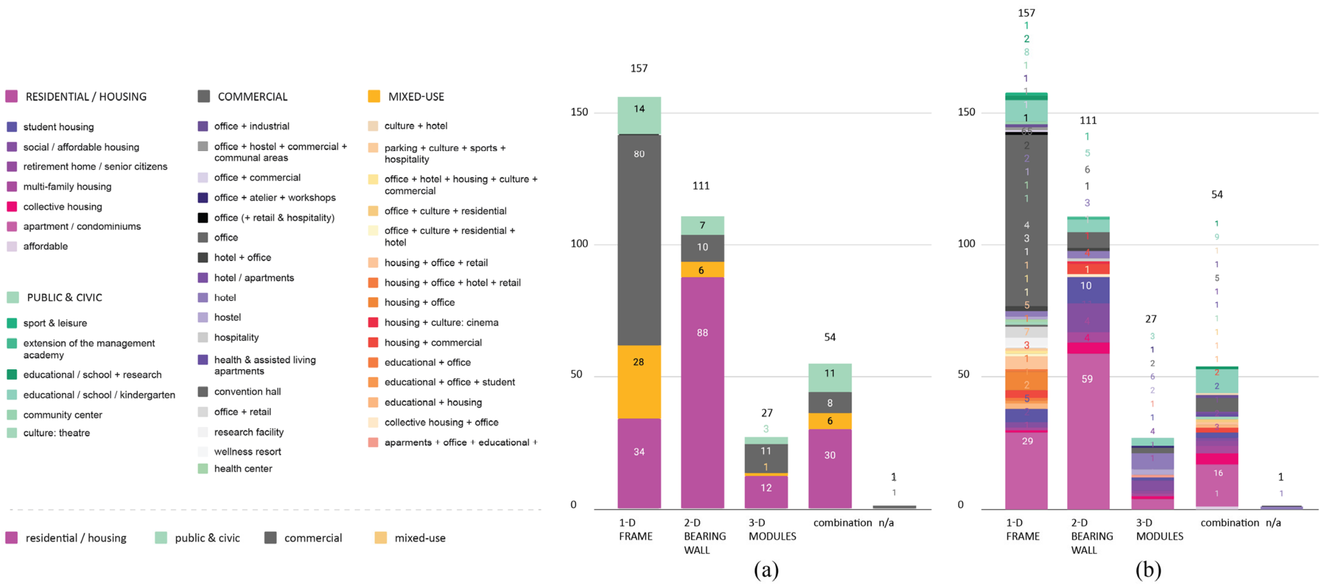


Figure 16. Number of projects by program per structural system: (**a**) overall program distribution; (**b**) detailed program distribution.

Figure 16b shows the specific relationship between the structural systems and program. The majority of frame systems, 41.6%, consist of office buildings with smaller numbers of hotels, hostels, research facilities, and health center programs. Residential programs comprise the next largest group (21.8%) with 16.6% apartments and a small number of other residential program types. Mixed-use comprises 17.9% of frame structures and the majority are variations of office programs with residential or hotels. Most of the civic programs are a few school buildings, as well as some culture and sport and leisure projects.

On the other hand, the majority of the panelized systems have residential buildings (79%) with 53% apartments, 10% social housing, 9% student housing, and a smaller number of collective housing and multifamily housing projects. From other program groups, few offices, hotels, and schools are present, while the mixed-use group in panel systems consists of purely housing and commercial programs. *Green House* and *WoodTek HQ* office have a panelized structure, but are also smaller footprint buildings.

In 3-D module construction, the even distribution between commercial and residential occurs due to a high number of hotels and hostels counted as commercial spaces, 22.2% and 7.4%, respectively, with a smaller number of office spaces. From residential programs, the highest number of projects are social and affordable housing projects, 14.8%. Apartments, collective housing, multi-family housing, and retirement homes are also present. A total of 11.1% of space module projects are schools. Only one mixed-use project *FOGO* is present. It is a temporary development that combines housing for refugees, trainees, and students with studios and spaces for courses and workshops.

Combination systems consist of primarily residential programs, with an equal ratio of mixed-use and commercial programs. Civic programs comprise 17.4% of combination systems and are dominantly school programs.

3.2.4. Categorization: Massing

Analysis of floor plans and massing outlines in XY shows that the majority of projects overall are rectangles. As Figure 17 shows, the rectangle is the only dominant group of outlines, comprising 53.1% of the projects. The only other form that appears in a significant proportion is 'L', or orthogonal rectangular-based L. At a more detailed look, an additional 16% of the projects have the word rectangle within the form description, such as the qualitative description of *Cowan Court* as a 'rectangular courtyard with curved sides'. Other form descriptions account for up to 2% of the projects and consist of variations of polygon geometries, bent strips, curved strips, right trapezoids, right triangles, quads, blobs, and so on.

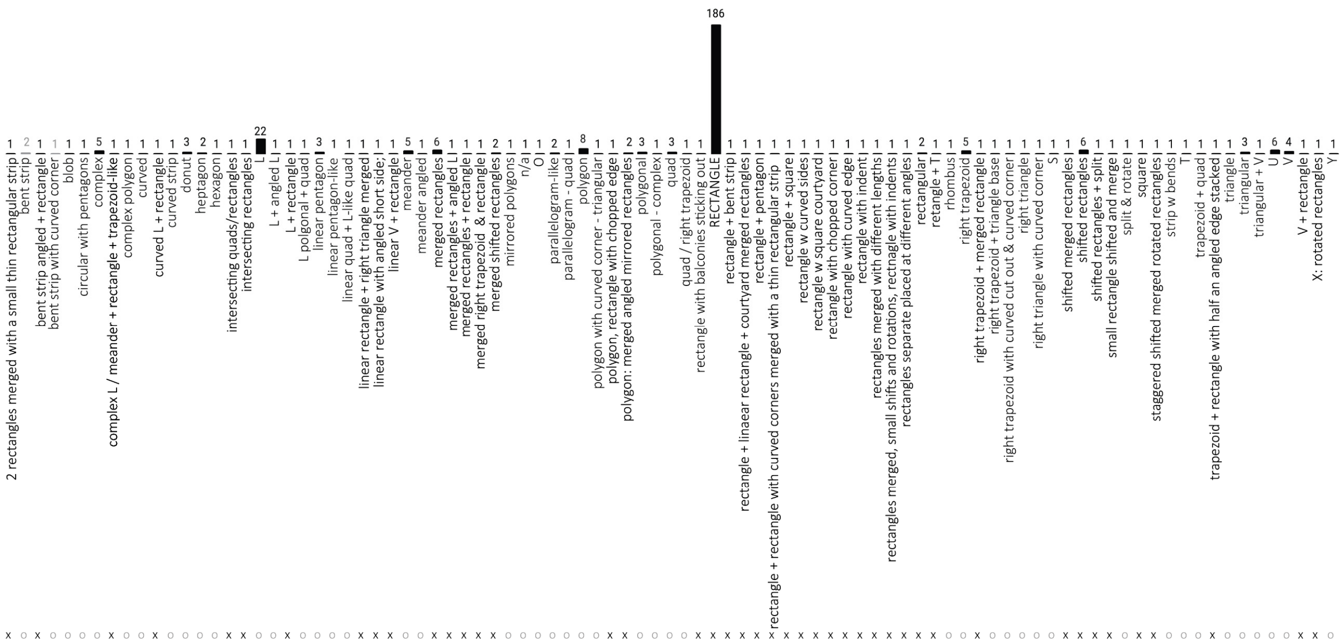


Figure 17. Number of projects per geometry description. (Geometry descriptions containing the word "rectangle" are marked with "x" at the bottom of the figure.)

Results of the XY categorization into typologies confirm this. Rectangles comprise 52.3% of the typologies, while linear (16.57%), rectangle-based (8.8%), and rectangle operations (8.6%) are the other largest groups. Polygons are one exception as they appear in 6.8% of the projects, while courtyard typologies account for only 2.8% of the projects. The rest of the typologies appear in percentages of less than 1% and are mostly combinations.

Figure 18 shows the results within the individual structural groups. Rectangles, rectangle-based, and rectangle operation types are dominant in every structural category. No other subcategories are present in a significant percentage.

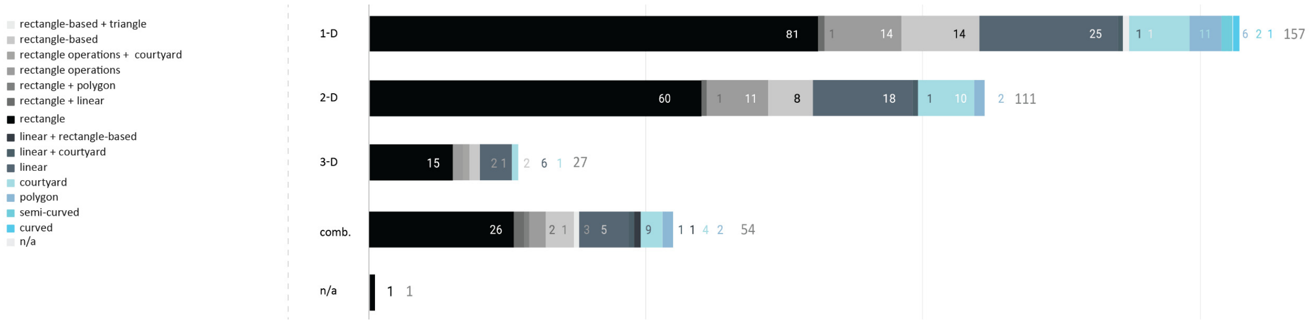


Figure 18. Number of projects per structural system by floorplan outline geometry type.

The 3-D module projects exhibit the smallest range of typologies. Only rectangle, rectangle-based, rectangle operations, and linear projects appear. Project *Gymnasium Nord in Frankfurt am Main* is one exception, where rectangle operations and a courtyard are present. The scale of the courtyard is small, and it is also rectangular. Panel and frame projects on the other hand both exhibit a similar number of typology groups, eight and ten, respectively, while combination system projects have the largest number, eleven typology groups. In contrast to panel systems, frame system projects contain curved and semi-curved forms. These forms do not appear in combination systems either. There, the difference in typologies accounts for combinations of rectangles and polygons, as well as combinations of rectangle-based forms with triangles or linear strips. Therefore, frame projects *Triodos Bank* and design study *Seattle Mass Timber Tower* by Fast + Epp are the only instances of classified curved and semi-curved projects among the 350 projects.

Purely orthogonal outlines account for 76.3% of total projects, with semi-orthogonal at 19.7%, and only 4% non-orthogonal outlines, as can be seen in Figure 19.

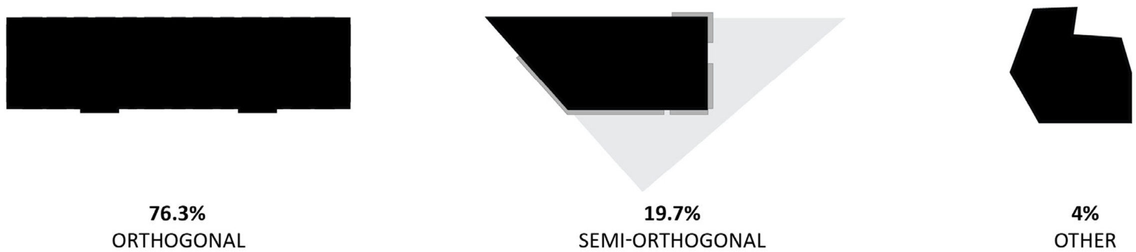


Figure 19. Overall ratio of projects based on their orthogonality. Project outlines not to scale (from left to right: Brock Commons, Haut, Mazarin House).

Figure 20a shows the ratio of orthogonal, semi-orthogonal, and non-orthogonal projects across the structural systems.

Panel projects contain the most non-orthogonal outlines, 6.3%, followed by combination systems with 5.4%, frame projects with 2.5%, while volumetric projects have no instances of non-orthogonal outline projects. The 3-D module projects are in fact composed of dominantly orthogonal outlines, with only 18.5% semi-orthogonal massings. *Immeuble de bureaux Opalia* and *Valla Berså* are both examples of semi-orthogonal and curved linear projects that appear in the panel systems.

Figure 20b shows the degree of symmetry in the projects. A total of 82.8% of projects are symmetrical. This percentage is roughly equal to the distribution of projects across the structural system categories. Again, 3-D modules have the lowest amount of non-symmetrical projects, which account for only 7.4%. Combination systems, on the other hand, contain the most non-symmetrical projects, at 25.5%.

As can be seen from Figure 20c, 12.6% of projects are classified as irregular, at a total of 43 projects. The ratio is highest in frame projects and accounts for 16% of the projects and lowest in the 3-D module group with 0 irregular projects.

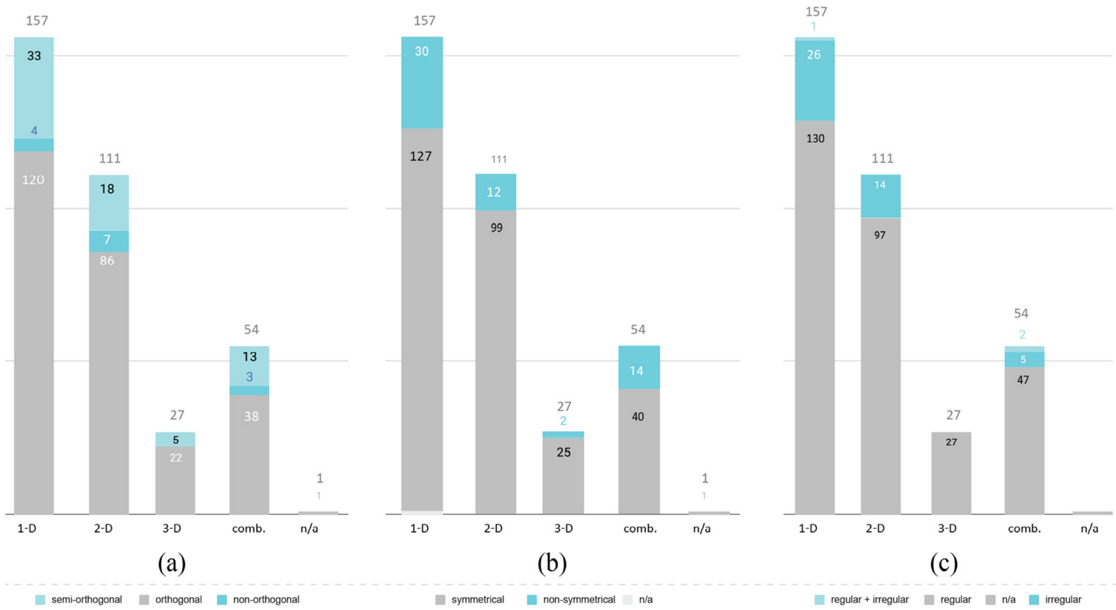


Figure 20. Massing analysis results (XY). Number of projects per structural system by: (**a**) orthogonality; (**b**) symmetry; (**c**) regularity and irregularity of form.

Among the 43 irregular projects, three are of courtyard typologies (*Samling, Hôtel de Région Auvergne*, and *wooden parking in Aarhus*), one curved (*Triodos Bank*), one semi-curved (*Seattle Mass Timber Tower*), six projects are variations of the linear typology with either complex intersections or polygonal outlines (*Woody, Royal Shakespeare Theatre, Opalia, Wälderhaus Place*, *Ternes Villiers*, and *Woodland Trust*), and three are a combination of concave–convex polygonal courtyards with elements of linear typology (*Groupe Scolaire Pasteur, Dalston Works*, and *Green Office Enjoy*). These polygonal courtyard projects nevertheless still retain orthogonal elements. The largest group of irregular projects overall are polygons (20 projects), while smaller numbers of projects consist of more complex rectangle operations (4) and rectangle-based projects (4). An example is project *Forte*, which is composed of staggered, shifted, and merged groups of rectangles, which are connected at a different angle to create a joint massing outline. The polygonal project on the other hand consists of pentagonal and heptagonal projects, as well as of more complex right triangular projects. Several polygonal projects are both convex and concave.

The analysis of the project volumes shows similar results. A total of 79.7% of all projects are regular extrusions, 16.6% are incremental extrusions, and only 3.4% of projects show a floor plate variation in Z (across stories), as can be seen in Figure 21.

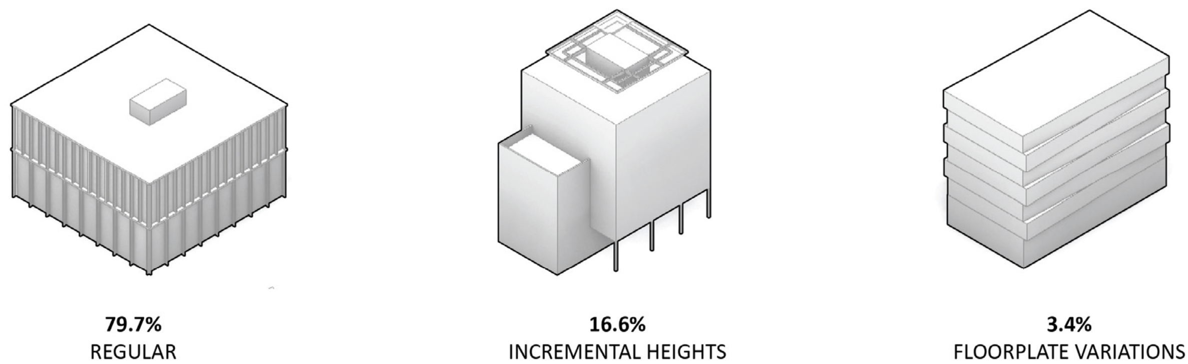


Figure 21. Overall ratio of projects based on volumetric extrusion strategy. Project volumes not to scale (from left to right: BOKU, Skaio, Patch 22).

As can be seen in Figure 22a, regular extrusions are dominant across all structural systems. Figure 22b shows that regular extrusions with a flat roof are most common overall, as a little over 60% is the average, with the exception of space module projects, at 70%. Figure 22b also shows that there is least variation in volume massing in 3-D module projects. Only a few different descriptions appear. In the regular extrusion there are only two projects with a terraced top floor, and one project with a rotated module on the top floor positioned as a semi-cantilever. Incremental extrusion shows height differentiation, and floorplate variation in one project, *WDF 53*, where modules are slightly shifted in X, Y, and Z in a way that creates a more dynamic facade.

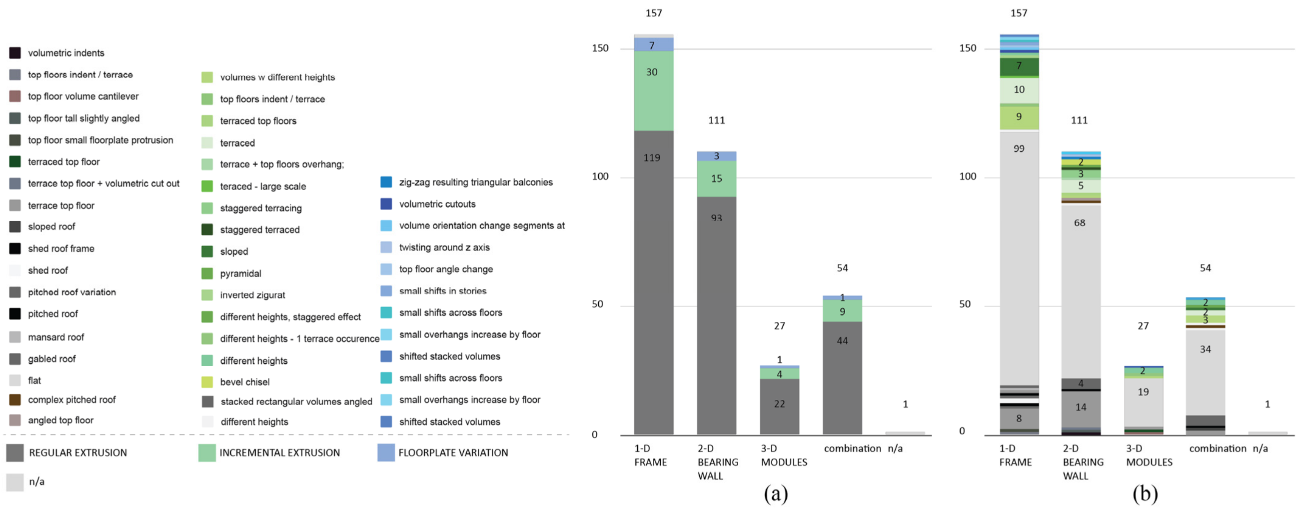


Figure 22. Number of projects by massing volume (Z) per structural system: (**a**) overall typologies; (**b**) detailed geometric forms.

In contrast, frame and panel projects show a much greater degree of volumetric variations. Even within regular extrusions, pitched roof and terracing top floor variations are more common. Frame project *Adohi Hall*, for example, is a set of regular extrusions stacked differently across each other to form a long strip, creating areas of free ground floor passage. *Nodi*, a frame project in Gothenburg, on the other hand is the only case of an inverted ziggurat in volume. Floorplan variations happen mostly at a smaller scale. In project *Bürohaus Holzbau Küng*, a ring of balconies increases in size across the stories creating a wider volume at the top. Projects *Green Office Enjoy, Patch 22*, and *Albina Yard* all exhibit small shifts between floor plates that create greater volumetric differentiation of stories through overhangs. In contrast, *Ki-Etude* and *105 Punt Road* have a high level of repetition of zig zag overlapping balconies. *Shimouma Apartment, Flatiron PDX*, and *Additional Storeys in Wood Construction in Zurich* exhibit variation through larger volumetric indents and angle change between floorplates. The *Daramu House* project consists of a symmetrical set of overlapping stories that appear to cantilever above ground on steel columns. Project *Wenlock Cross* is the only one that exhibits large-scale floorplate variation as each floor rotates around the core at significantly large and different angles.

Figure 23 shows that overall among the projects, 24% of volumes were affected by balconies as a strategy to create dynamics, 8% of projects had a core that affected the massing volume, and 7.4% of projects had instances of a dynamic façade. Most of the balconies were sticking out, with a smaller percentage of indent, angled, and curved balconies.

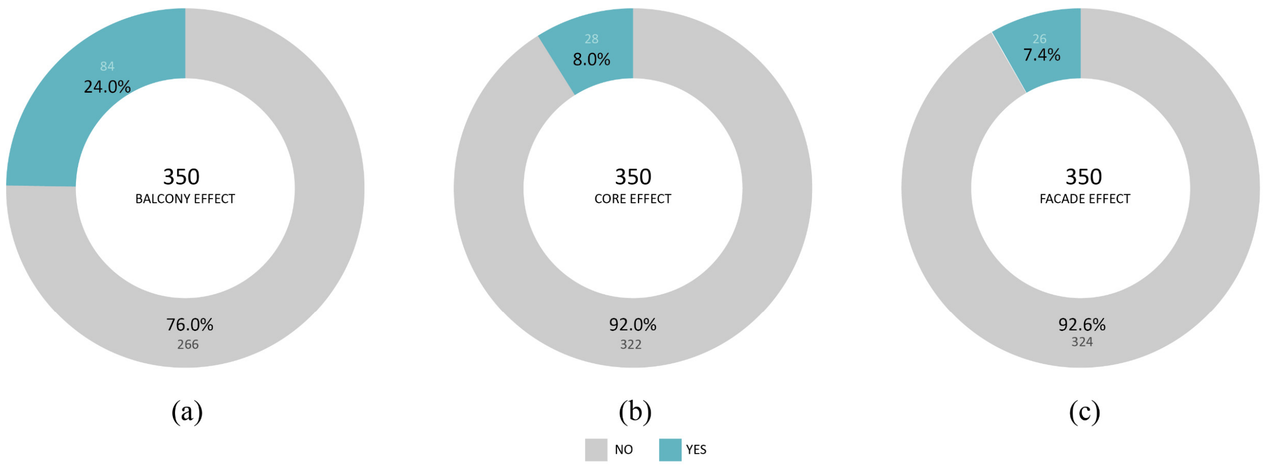


Figure 23. Number of projects by additional features: (**a**) balcony variations, (**b**) core effect, (**c**) façade effect.

3.2.5. Categorization: Classification by Ordering System

Overall, grid is the most dominant ordering system, comprising 40.1% of the total projects. Linear array follows with 30.8% of projects. A total of 13.4% of projects are based on a grid, and 9.1% have a linear ordering strategy. In addition, there are also few instances of a combination of grid and a linear array ordering system. Irregular non-raster-based ordering systems appear only in 1.14% of all projects, as can be seen in Figure 24. A total of 3.6% of the projects had no sufficient visual data on the interior to determine the exact ordering system or did not have sufficient footprint area for ordering system determination. However, based on partial data, these projects are most likely organized on raster-based strategies.

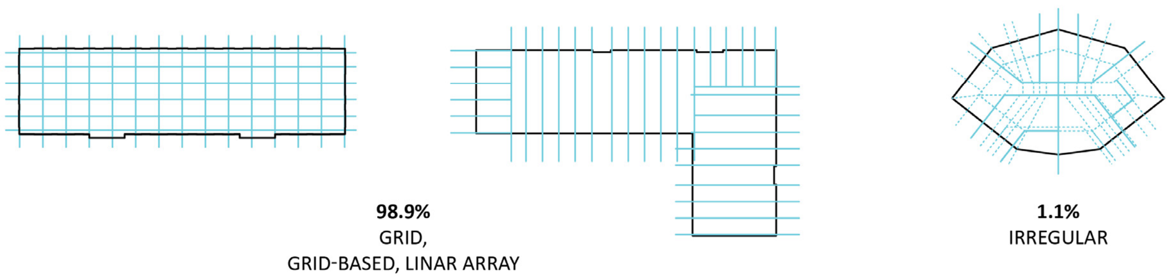


Figure 24. Overall ratio of projects based on internal ordering system. Project outlines not to scale, (from left to right: Brock Commons, Senior Citizen Home Wabern, Rundeskogen).

As can be seen in Figure 25a, frame projects consist of 69.2% grids and 12.8% linear arrays. These two are the two most dominant ordering systems. Other raster-based system variations have small percentages, while 0.64% of projects are classified as irregular.

Panel projects consist primarily of linear arrays as an ordering strategy (43.2%), followed by linear and grid-based ordering systems (both at 18%). Pure grids comprise only 12.6% of panel projects. A total of 1.8% of projects have irregular ordering systems.

The 3-D module projects have a dominant strategy with 81.48% of projects based on a linear array. Both grid and linear arrangements comprise only 3.7% of projects each. There are no instances of projects with an irregular ordering system.

Combination systems have two dominant strategies, grid and linear array, and both account for almost one third of the project each. A total of 1.8% of projects are classified as having a non-raster-based irregular ordering system.

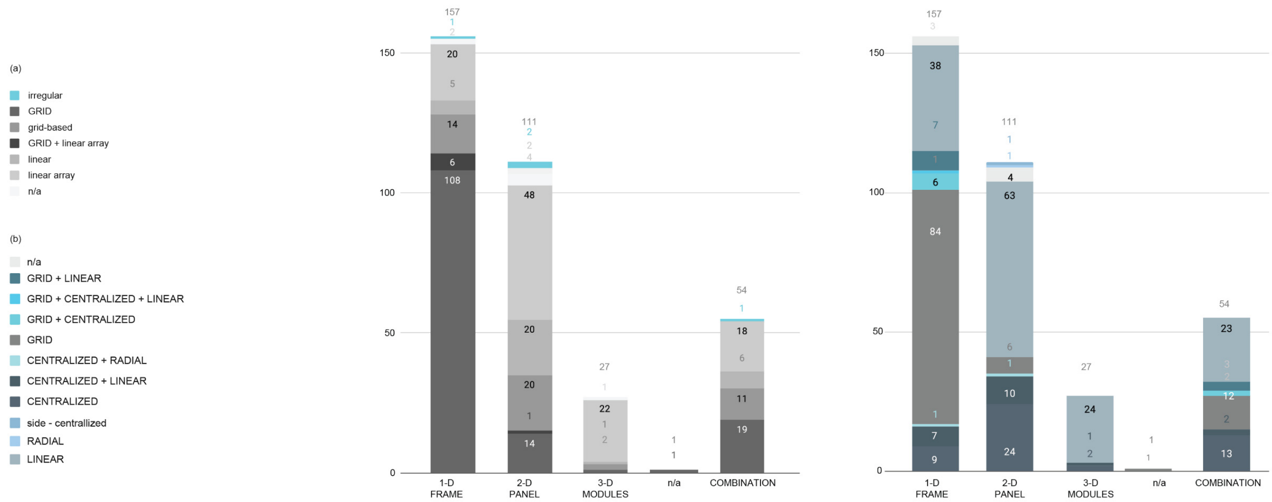
Figure 25b shows the internal spatial organization strategies of the projects. Linear organization with 42.3% is the most dominant, while grid organization appears in 29.4% and centralized organization in 13.7%.

Frame system projects consist mostly of projects organized based on a grid (53.8%). *Triodos Bank* is one example of a combination of centralized and radial organization, in which three centralized segments are connected.

Panel systems consist of 56.7% projects organized linearly. Centralized projects are the next largest group with 21.6%, followed by a combination of centralized and linear organizations, with grid organization only at 5.4%. *Wenlock Cross* is the only example that shows a combination of centralized radial organization with spaces rotated differently in each story around a central core (Figure 6d). *Mazarin House* project can also be classified as semi-radial as spaces of different forms and sizes are oriented in different directions from a core located along the edge of the floorplan.

The 3-D module projects have the most predominant composition in terms of spatial organization. A total of 88.9% of projects are arranged based on a linear circulation, while 7.4% projects have a centralized organization. There are no instances of a grid in terms of organization of circulation in the projects.

Combination systems, on the other hand, exhibit all organization strategies. Linear is still predominant at 41.8%, and centralized and grid both occur in roughly 20% of the projects.



(a) (b)

Figure 25. Number of projects by ordering system per structural system: (**a**) per ordering system classification; (**b**) per spatial organization.

Figure 26 shows the results of the analysis of the variations among the ordering system. It is visible that overall there are very few variations. A total of 3.4% of projects showcase shifts in the grid, modules, or panels. A total of 22% of projects exhibit some sort of spacing variation. From the data, it is clear that the two largest variations in this group refer to projects with different sizes of regular grid bays, usually two to maximum of three bay sizes (14 projects), module size variation, and combination of modules (12 projects), as well as grid-based spacing variation for spatial divisions. Only 1.4% of projects exhibit length variation in the ordering system, which accounts to a total of five projects. In *Samling* this variation occurs due to an irregular massing form, while in project *Mineroom Leoben*, this occurs due the design of an irregular zig-zaggy internal corridor. A total of 8% of projects showcase an orientation change in the ordering system. This is mostly an orthogonal change of orientation; however, angled orientation changes also occur. A total of 8.5% of projects have an irregular atrium, core, or an open area as a strategy to maintain the simplest layout in construction. A total of 10% have grid variations, most common of which are deviated grids that adapt in certain areas to the massing form (usually in one direction) and intersecting grids or grid rotations. A total of 2% of projects have other variations such as presence of irregular transition areas and use of different ordering systems in different volumes and program areas of the projects. Multiple variations can occur per project.

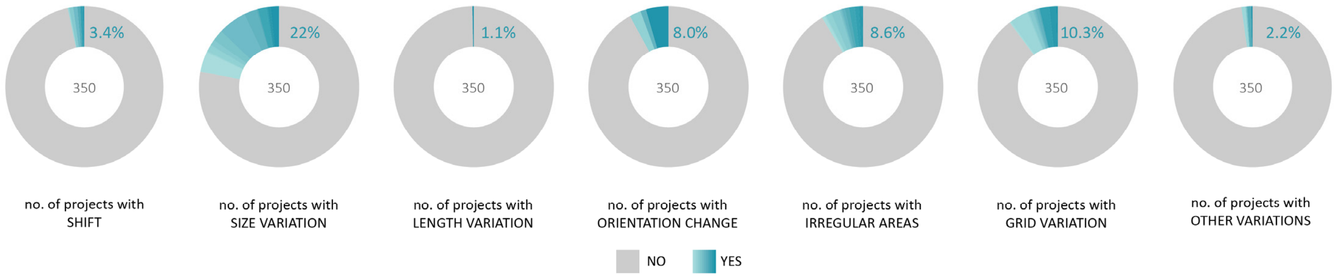


Figure 26. Number of projects with ordering system variations. (The color range illustrates the range of variations within the analyzed categories.)

4. Discussion and Conclusions

This paper presented an analysis of 350 multi-storey timber projects built between 2000 and 2021, and building proposals. The main goal was to examine the range of typologies and morphologies in current multi-storey timber construction in relation to structural and material aspects.

Based on the analysis of structural systems, material, program, massing, and ordering system of the projects, the results show that a great majority of multi-storey timber buildings are grid-based rectilinear volumes with regular flat extrusions. However, steel and concrete, as well as additional structural elements such as beams or combinations of structural systems, are present in the buildings not only to fulfill unsolved technical challenges such as loads or spans, but also in cases where greater design freedom was needed.

Few projects do exhibit non-rectangular and non-orthogonal footprints and show strategies to achieve less regularity in grid-based ordering systems. In frame projects, this is achieved by distorting, removing, or rotating some of the grid lines, in modular systems by reorienting or varying the size of the 3-D modules, while panel projects showcase the most instances of non-orthogonal wall placement. Overall, a common strategy was to position cores or open areas such as atriums at transitional or irregular locations in the buildings, as well as to use concrete or steel, to achieve a greater degree of design freedom. This may suggest a strategy to maintain a high level of repetition within timber structural systems.

The analysis resulted in classification of projects into four structural system groups, four material groups, four program groups, eight massing outline and three massing volume groups, and five ordering system groups (three raster-based), as well as more detailed subgroups.

A more in-depth study is needed on possibilities and limitations of timber construction in regard to design versus structural and spanning capabilities to confirm the results of the study.

The current range of typologies in MSTBs so far does not exhibit novel morphological expressions. This raises broader questions on development of new technologies, pre-fabrication, and material products in relation to architectural expression and their manifestation in the built environment. The study brings up questions on how currently relatively rigid architectural designs may adjust to the multi-faceted boundary conditions within urban contexts and the value of geometrically flexible building systems. As current EWPs and prefabrication machines in timber are based on either linear or rectangular geometries, which may mean that all deviations from this occur at additional costs, an analysis of the larger context of the main stakeholders involved in the design, engineering, and construction of MSTBs is needed to understand the reasons behind the current morphological range in mass timber construction and to identify opportunities for innovation. Due to global challenges, the trends suggest that the number of timber buildings will keep increasing. The relative novelty of timber in multi-storey construction means that future morphologies will highly depend on the available technologies, design knowledge, building physics, construction methods, and regulatory requirements.

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Appendix A

Project list.

Table A1. Project list.

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
1	Trähus 2001	4	4	Malmö	Sweden	built	2000
2	Housing Block in Merano	4	4	Merano	Italy	built	2003
3	Spöttlgasse	5	4	Vienna	Austria	built	2004
4	Altenpflegeheim Höchsterstraße (Pflegeheim Dornbirn, Dornbirn Nursing Home)	4	3	Dornbirn	Austria	built	2005
5	Svartamoen Place	5	4	Trondheim	Norway	built	2005
6	Fairmules House	5	5	London	UK	built	2006
7	Holzhausen	6	6	Zug	Switzerland	built	2006
8	WHA am Mühlweg Bauteil A (Wohnanlage Mühlweg)	4	3	Mühlweg	Austria	built	2006
9	WHA am Mühlweg Bauteil C	5	5	Vienna	Austria	built	2006
10	Wohnanlage Samer Mösl	3	3	Mösel	Austria	built	2006
11	Casa Montarina	6	5	Lugano	Switzerland	built	2007
12	E3	7	6	Berlin	Germany	built	2008
13	Limnologen	8	7	Växjö	Sweden	built	2008
14	Wohnanlage Kiefernweg (housing complex Kiefernweg)	3	3	Gantschier	Austria	built	2008
15	Condos at Lost Rabbit, Phase II	3	3	Madison, MS	USA	built	2009
16	Gemeindezentrum St. Gerold	4	4	St. Gerold	Austria	built	2009

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
17	Hotel Ammerwald (BMW—Hotel Alpenhof)	5	3	Reutte	Austria	built	2009
18	Office building	3	3	Wabern	Switzerland	built	2009
19	Portvakten	8	7	Växjö	Sweden	built	2009
20	Russel STreet	4	4	Cambridge	UK	built	2009
21	Stadthaus (Murray Grove)	9	8	London	UK	built	2009
22	H4	4	4	Bad Aibling	Germany	built	2010
23	Lauriston Primary School	3	3	London	UK	built	2010
24	Prenzlauer Berg	5	4	Berlin	Germany	built	2010
25	Royal Shakespeare Theatre	3	3	Stratford-upon-Avon	UK	built	2010
26	The Open Academy	3	3	Norwich, Norfolk	UK	built	2010
27	Wohn- und Geschäftshaus Badenerstrasse	7	6	Zurich	Switzerland	built	2010
28	Woodland Trust	3	3	Grantham	UK	built	2010
29	Agrarbildungszentrum Salzkammergut	3	3	Altmunster	Austria	built	2011
30	Bridport House	8	8	London	UK	built	2011
31	Centre for Interactive Research on Sustainability (CIRS)	4	4	Vancouver	Canada	built	2011
32	Gewerbehalle Sääga	3	3	Balzers	Liechtenstein	built	2011
33	Holz8	8	8	Bad Aibling	Germany	built	2011
34	Kasukabe Convention Hall	6	2	Kasukabe City, Saitama Prefecture	Japan	built	2011
35	Sozialzentrum Pillerseetal	3	3	Fieberbrunn	Austria	built	2011
36	Terraced Houses	3	3	Munich	Germany	built	2011
37	Wälderhaus Place	5	3	Hamburg	Germany	built	2011
38	Wohnanlage Unterfeldstrasse	3	3	Ludesch	Austria	built	2011
39	Wohnhaus Habsburgstrasse	5	5	Zurich	Switzerland	built	2011
40	3xgrün- Wohnen im Holzhaus	6	5	Berlin	Germany	built	2012
41	Bürohaus Laur-Park	3	3	Brugg	Switzerland	built	2012
42	De Karel Doorman	21	16	Rotterdam	Netherlands	built	2012
43	Forte	10	9	Melbourne, Vic	Australia	built	2012
44	Hilden Grange Prepatory School	3	3	Tonbridge, Kent	UK	built	2012
45	Housing block in WeimarPlatzhaus,	4	4	Weimar	Germany	built	2012
46	Life Cycle Tower ONE (LCT One)	8	7	Dornbirn	Austria	built	2012
47	LignoAlp Office Building	4	4	Bressanone	Italy	built	2012
48	Marina Verde	6	6	Caorle	Italy	built	2012
49	Mühlebachstrasse/Hufgasse	6	6	Zurich	Switzerland	built	2012
50	Residenza Sirio	6	6	Lugano	Switzerland	built	2012
51	Te Ara Hihiko	5	3	Wellington	New Zealand	built	2012
52	UBC Earth Sciences	5	5	Vancouver, BC	Canada	built	2012
53	Whitmore Road	6	5	London	UK	built	2012
54	Züri Modular Pavillon (modular schools)	3	3	Zurich	Switzerland	built	2012
55	Bullitt Centre	6	4	Seattle, WA	USA	built	2013
56	C13	7	6	Berlin	Germany	built	2013
57	Giesserei	6	5	Winterthur	Switzerland	built	2013
58	Groupe Scolaire Pasteur	3	3	Limeil-Brevannes	France	built	2013
59	Gymnasium OMG	3	2	Neufahrn	Germany	built	2013
60	Ickburg School	3	3	London	UK	built	2013
61	Illwerke Zentrum Montafon	5	5	Vandans	Austria	built	2013
62	Leonhard Ragaz Weg	5	5	Zurich	Switzerland	built	2013
63	Les Cadolles	7	7	Neuchâtel/Neuenburg	Switzerland	built	2013

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
64	Lintuviita	6	5	Seinäjoki	Finland	built	2013
65	Osaka Timber Association	3	2	Osaka	Japan	built	2013
66	Panoramma Giustinelli	7	7	Trieste	Italy	built	2013
67	Pentagon II	8	7	Oslo	Norway	built	2013
68	Residential complex	4	3	Ansbach	Germany	built	2013
69	Senioren Wohnheim Hallein (Senior Citizen´s Home)	5	4	Hallein	Austria	built	2013
70	Shimouma Apartment	5	4	Tokyo	Japan	built	2013
71	Student Hostel	5	5	Heidelberg	Germany	built	2013
72	SZU-Betriebsgebaude (Pile Up Giessehübel)	6	4	Zurich	Switzerland	built	2013
73	Tamedia New Office Building	7	7	Zurich	Switzerland	built	2013
74	The Maison de l'Inde	8	7	Paris	France	built	2013
75	Via Cenni residential complex (Cenni di Cambiamento)	9	9	Milan	Italy	built	2013
76	Wagramerstrasse	7	6	Vienna	Austria	built	2013
77	Wälder Versicherung	4	4	Andelsbuch	Austria	built	2013
78	Wood Cube	5	5	Hamburg	Germany	built	2013
79	698 Wohnüberbauung Sihlbogen Areal B	7	7	Zurich	Switzerland	built	2014
80	Ark Brunel Primary Academy	3	3	London	UK	built	2014
81	Contralaminada (Edifici de Fusta Cavallers)	5	5	Lleida	Spain	built	2014
82	Diesel Benelux HQ	5	5	Amsterdam	Netherlands	built	2014
83	Gemeindezentrum Kuchl	4	3	Kuchl	Austria	built	2014
84	Holztechnikum Kuchl	3	3	Kuchl	Austria	built	2014
85	Hôtel de Région Auvergne	5	3	Clermont-Ferrand	France	built	2014
86	Hotel Saentispark	5	4	Abtwil	Switzerland	built	2014
87	IBA apartment building	4	4	Hamburg	Germany	built	2014
88	Kampa administration building (Kampa K8)	7	7	Aaalen	Germany	built	2014
89	Kingsgate House	7	5	London	UK	built	2014
90	Mayfield School	3	3	London	UK	built	2014
91	Mazarin House	4	4	London	UK	built	2014
92	Mossbourne Victoria Park Academy	4	4	London	UK	built	2014
93	Rundeskogen	14	13	Sandnes	Norway	built	2014
94	School in Orsonnens	3	3	Orsonnens	Switzerland	built	2014
95	Sky UK: Believe in Better Building	4	4	London	UK	built	2014
96	St. Die-des-Vosges (Residences J.Ferry)	8	8	St. Die-des-Vosges	France	built	2014
97	Strandparken	7	6	Stockholm	Sweden	built	2014
98	The Radiator buildings	5	5	Portland, OR	USA	built	2014
99	William Perking Church of England School	4	4	London	UK	built	2014
100	Wood Innovation and Design Centre	7	7	Prince George, BC	Canada	built	2014
101	WoodTek HQ	5	4	Taichung	Taiwan	built	2014
102	CANDLEWOOD Candlewood Suites Hotel on Redstone Arsenal Base	4	4	Huntsville, AL	USA	built	2015
103	Cobalt Place	6	6	London	UK	built	2015
104	Curtain Place	6	5	London	UK	built	2015
105	Egger headquarters	4	4	St. Johann in Tirol	Austria	built	2015
106	Eskolantie	7	6	Helsinki	Finland	built	2015
107	European School	3	3	Frankfurt am Main	Germany	built	2015
108	Frame Work 6th Ave	5	4	Portland, OR	USA	built	2015

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
109	Hummelkaserne Graz	6	6	Graz	Austria	built	2015
110	MEC Head Office (Mountain-Equipment. Cp-Op Head Office)	4	4	Vancouver, BC	Canada	built	2015
111	Mehr als Wohnen Haus I+ J	5	4	Zurich	Switzerland	built	2015
112	Mehrfamilienhaus Gapont	3	3	Triesen	Liechtenstein	built	2015
113	Nachverdichtung Speyer	5	5	Speyer	Germany	built	2015
114	Puukuokka	8	8	Helsinki	Finland	built	2015
115	Reininghaus Sud	5	4	Graz	Austria	built	2015
116	Residential Complex in Toulouse (résidence sociale Toulouse)	4	4	Toulouse	France	built	2015
117	Schmuttertal Gymnasium	3	3	Diedorf	Germany	built	2015
118	Schorenstadt	4	4	Basel	Switzerland	built	2015
119	Siloah	7	6	Bern	Switzerland	built	2015
120	Sky Health and Fitness Center Sky UK	3	3	London	UK	built	2015
121	Social housing in Saint-Denis	6	5	Saint-Denis	France	built	2015
122	Solhöjden i Visättra	4	4	Huddinge	Sweden	built	2015
123	Sørhauggata Student Housing (Sørhauggate)	5	4	Haugesund	Norway	built	2015
124	St Clare's College	3	3	Oxford, Oxfordshire	UK	built	2015
125	Studentboliger Remmen	6	5	Halden	Norway	built	2015
126	Suurstoffi Areal, Baufeld 3	4	4	Rotkreuz	Switzerland	built	2015
127	Trafalgar Place	5	3	London	UK	built	2015
128	Treet Tower	14	14	Bergen	Norway	built	2015
129	Vallen Part B	9	7	Växjö	Sweden	built	2015
130	Wenlock Cross (the Cube/Wenlock Road 21)	10	9	London	UK	built	2015
131	Ywood Les Docks Libres	6	5	Marseille	France	built	2015
132	Albina Yard	4	4	Portland, OR	USA	built	2016
133	Arbora Complex	8	7	Montreal QC	Canada	built	2016
134	Barretts Grove (Nordic Lofts)	5	5	London	UK	built	2016
135	Cowan Court	3	3	Cambridge	UK	built	2016
136	Direction Départementale des Territoires et de la Mer (DDTM)	6	5	Vannes	France	built	2016
137	H7	7	6	Munich	Germany	built	2016
138	Holzwohnbau Rosenstraße	5	4	Linz	Austria	built	2016
139	International House	7	6	Sydney, NSW	Australia	built	2016
140	Mineroom	5	5	Leoben	Austria	built	2016
141	Moholt 50/50	9	8	Trondheim	Norway	built	2016
142	Patch 22	7	6	Amsterdam	Netherlands	built	2016
143	Rue des Ardennes	5	4	Paris	France	built	2016
144	Synergia	6	5	Saint-Hyacinthe, QC	Canada	built	2016
145	T3	7	6	Minneapolis, MN	USA	built	2016
146	UEA Blackdale	5	5	Norwich, Norfolk	UK	built	2016
147	Wohnen 500	3	3	Mader	Austria	built	2016
148	Wohnhaus am Dantebad	5	4	Munich	Germany	built	2016
149	Wohnsiedlung in Rive de Gier	5	5	Rive de Gier	France	built	2016
150	Woodberry Down	5	5	London	UK	built	2016
151	Zollfreilager housing complex	6	6	Zurich	Switzerland	built	2016
152	106 Lewes Road	5	4	Brighton	UK	built	2017
153	Additional Storeys in Wood Construction	6	3	Zurich	Switzerland	built	2017
154	Arvida Livingwell Park Lane	4	4	Christchurch	New Zealand	built	2017

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
155	Bacton Low Rise	5	5	London	UK	built	2017
156	Cite U Lucien Cornil (Lucien Cornil Student Residence)	8	8	Marseille	France	built	2017
157	Dalston Works (Dalston Lane)	11	10	London	UK	built	2017
158	Edge Olympics	5	2	Amsterdam	Netherlands	built	2017
159	Geschosswohnungsbau Kamorstraße	3.5	3.5	Konstanz	Germany	built	2017
160	Holzwohnbauten im Dragoner-Quartier	6	6	Wels	Austria	built	2017
161	Hotel Katharinenhof	4	3	Dornbirn	Austria	built	2017
162	Hotel Nautilus	8	7	Pesaro	Italy	built	2017
163	Hotel Revier	5	4	Lenzerheide	Switzerland	built	2017
164	I Valla (Integralen 6)	4	4	Linköping	Sweden	built	2017
165	Immeuble de bureaux R+7 (Opalia)	8	8	Paris	France	built	2017
166	Origine Condos	13	12	Quebec City, QC	Canada	built	2017
167	Östra Sala Backe	6	5	Uppsala	Sweden	built	2017
168	Penticton Lakeside (Lakeside Resort Expansion)	6	5	Penticon, BC	Canada	built	2017
169	Schwarzensteinhütte	6	6	San Giovanni Valle Aurina	Italy	built	2017
170	Träloftet	6	6	Linköping	Sweden	built	2017
171	UBC Brock Commons	18	17	Vancouver, BC	Canada	built	2017
172	Valla Berså	5	4	Linköping	Sweden	built	2017
173	Wohnen Offenbach	5	4	Offenbach	Germany	built	2017
174	Woodie	7	6	Hamburg	Germany	built	2017
175	25 King	10	9	Brisbane, Qld	Australia	built	2018
176	Carbon 12	8	8	Portland, OR	USA	built	2018
177	Daramu House	7	6	Sydney, NSW	Australia	built	2018
178	Fagerlund studenthybler	6	4	Horten	Norway	built	2018
179	Flatiron PDX	6	4	Portland	USA	built	2018
180	Frostaliden apartments	8	6	Skövde	Sweden	built	2018
181	Gibraltar Guest House	6	6	Gothenburg	Sweden	built	2018
182	Green Homes (Sanctuary Ellerslie Road, Ellerslie Crescent)	7	7	Glasgow	UK	built	2018
183	HoHo Next	6	6	Vienna	Austria	built	2018
184	Holzhaus am Waldpark	3	3	Berlin	Germany	built	2018
185	Hotel Jakarta	9	8	Amsterdam	Netherlands	built	2018
186	Illot Bois et Biosource (Sensations)	12	11	Strassbourg	France	built	2018
187	Import Building, Republic at East India/Studio RHE	10	9	London	UK	built	2018
188	Karantanika	4	4	Domžale,	Slovenia	built	2018
189	Ki-Etude	6	6	Namur	Belgium	built	2018
190	La Borda	7	6	Barcelona	Spain	built	2018
191	Lighthouse Joensuu	14	13	Joensuu	Finland	built	2018
192	M12 Max-Mell-Allee	4	4	Graz	Austria	built	2018
193	Maskinparken TRE	6	8	Trondheim	Norway	built	2018
194	Pitfield Street Cinema	6	5	London	UK	built	2018
195	Sue & Til	6	5	Winterthur	Switzerland	built	2018
196	SUURSTOFFI 22 (S22)	10	9	Rotkreuz	Switzerland	built	2018
197	Temporäre Wohn- und Gewerbesiedlung Fogo Ost	5	5	Zurich	Switzerland	built	2018
198	Tereneo (Euratech Capgemini)	5	5	Lille	France	built	2018
199	Theaterturm am Julierpass	5	5	Bivio	Switzerland	built	2018
200	Valle Wood	7	7	Oslo	Norway	built	2018
201	Virtuoso	6	6	Vancouver, BC	Canada	built	2018
202	Vogelkamp Neugraben	4	3	Hamburg	Germany	built	2018
203	Whythe I and II 320 and 360 Wythe	5	5	New York City, NY	USA	built	2018

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
204	111 East Grand Office	4	4	Des Moines, IA	USA	built	2019
205	55 Southbank (Adina Hotel)	17	10	Melbourne, Vic	Australia	built	2019
206	Adohi Hall	5	4	Fayetteville, NC	USA	built	2019
207	Asylunterkunft Rigot (Rigot collective dwelling centre)	5	5	Geneva	Switzerland	built	2019
208	bercahaus	5	5	Berlin	Germany	built	2019
209	Bjergsted Financial Park	7	7	Stavanger	Norway	built	2019
210	Blindenschule	4	3	Zollikofen	Switzerland	built	2019
211	Bouwupdate Bouwdeel D (emontabel)	4	4	Delft	Netherlands	built	2019
212	Bureaux Perspective	7	6	Bordeaux	France	built	2019
213	Cederhusen	13	13	Haninge	Sweden	built	2019
214	Eisberg	7	7	Berlin	Germany	built	2019
215	Famju	5	4	Heilbronn	Germany	built	2019
216	Freebooter	4	4	Amsterdam	Netherlands	built	2019
217	Frostaliden 5	9	9	Skövde	Sweden	built	2019
218	Gare Maritime	4	4	Brussels	Belgium	built	2019
219	Gesundheits. Quartiers	7	6	Vienna	Austria	built	2019
220	Gillies Hall	6	5	Melbourne, Vic	Australia	built	2019
221	Gleis 21	6	5	Vienna	Austria	built	2019
222	Green Office Enjoy	8	5	Paris	France	built	2019
223	Gymnasium Frankfurt Nord	3	3	Frankfurt am Main	Germany	built	2019
224	Hotel Bergamo	5	4	Ludwigsburg	Germany	built	2019
225	Jo & Joe	8	7	Paris	France	built	2019
226	Kajstaden	9	9	Västerås	Sweden	built	2019
227	Kreativquartier Lattich	3	3	St. Gallen	Switzerland	built	2019
228	Lot 1 Suurstoffi (Arbo)	16	16	Rotkreuz	Switzerland	built	2019
229	Lynar 38–39 Gemeinschaftswohnen im Wedding	7	6	Berlin	Germany	built	2019
230	Maierhof housing estate	3	3	Bludenz	Austria	built	2019
231	MaxAcht	4	4	Stuttgart	Germany	built	2019
232	Mjøstårnet	18	18	Brumunddal	Norway	built	2019
233	Omega Factory HQ	5	4	Biel	Switzerland	built	2019
234	Oregon Conservation Center	3	2	Portland, OR	USA	built	2019
235	Palazzo Nice Meridia	10	9	Nice	France	built	2019
236	Platte 15	5	4	Denver, CO	USA	built	2019
237	Pont de Flandres Batiment 007	8	7	Paris	France	built	2019
238	Pulse	7	6	Saint-Denis	France	built	2019
239	Sideyard	5	5	Portland, OR	USA	built	2019
240	Skaio	10	9	Heilbronn	Germany	built	2019
241	SOTO	6	4	San Antonio, TX	USA	built	2019
242	T3 Midtown West	7	6	Atlanta, GA	USA	built	2019
243	The Green House	7	7	London	UK	built	2019
244	trikåfabriken Extension (Styrpinnen 15)	7	5	Stockholm	Sweden	built	2019
245	Triodos Bank	5	5	Driebergen	Netherlands	built	2019
246	Trummens Strand, Kv Geologen	8	6	Växjö	Sweden	built	2019
247	WA 15 West Holzbausiedlung Prinz-Eugen-Park	7	6	Munich	Germany	built	2019
248	WDF 53—Office building in Walldorf	4	4	Walldorf	Germany	built	2019
249	Wohnen am Kleinen Wannsee	3	3	Berlin	Germany	built	2019
250	Wohnüberbauung Moos L	3	3	Cham	Switzerland	built	2019
251	Wohnüberbauung Moos S	3	3	Cham	Switzerland	built	2019
252	Wood City Residential Building	8	7	Helsinki	Finland	built	2019
253	Woody (Santé Publique France Office)	3	3	Paris	France	built	2019
254	WA 14 West Holzbausiedlung Prinz-Eugen-Park	7	6	Munich	Germany	built	2020
255	6 Orsman Road (Storey 6)	6	6	London	UK	built	2020

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
256	6×6 block	6	6	Girona	Spain	built	2020
257	73 Saint Mande Housing	4	4	Paris	France	built	2020
258	Adidas North American Headquarters	6	6	Portland, OR	USA	built	2020
259	BOKU (Ilse Wallentin Haus der Universität für Bodenkultur)	5	4	Vienna	Austria	built	2020
260	Bürohaus Holzbau Küng	4	4	Alpnach	Switzerland	built	2020
261	Casa di Ringhiera	3	3	Bellinzona	Switzerland	built	2020
262	Catalyst	5	5	Spokane, WA	USA	built	2020
263	District Office	6	6	Portland, OR	USA	built	2020
264	Entrepatios Las Carolinas	4	4	Madrid	Spain	built	2020
265	FE Home Office	4	4	Vancouver, BC	Canada	built	2020
266	HoHo (Hoho Wien)	24	24	Vienna	Austria	built	2020
267	HOLZSTUDENT SIEBEN—Ellener Hof	7	6	Bremen	Germany	built	2020
268	Kilströmskaj	7	7	Karlskrona	Sweden	built	2020
269	Klapgat health center	4	3	Haacht	Belgium	built	2020
270	Klein Veldekens (Astor)	10	9	Geel	Belgium	built	2020
271	Kunskapshuset	6	6	Gällivare	Sweden	built	2020
272	La Trobe University Student Dormitory	7	n/a	Melbourne, Vic	Australia	built	2020
273	Massivholzhäuser Neuruppin	4	4	Berlin	Germany	built	2020
274	ÖGK Turm II (Erweiterung der Österreichische Gesundheitskasse)	9	8	Salzburg	Austria	built	2020
275	Quartier Wir	5	5	Berlin	Germany	built	2020
276	Remise Immanuel kirch straße	4	4	Berlin	Germany	built	2020
277	Samling	3	3	Sand	Norway	built	2020
278	School near Geneva	3	3	Geneva	Switzerland	built	2020
279	Schulraumprovisorium, temporäre Schulgebäude in Biel	3	3	Biel	Switzerland	built	2020
280	Supercell HQ	8	7	Helsinki	Finland	built	2020
281	the AA "Red" Emmerson Advanced Wood Products Laboratory (AWP), Oregon Forest Science Complex Peavy Hall	3	3	Corvalis, OR	USA	built	2020
282	The Canyons	6	6	Portland, OR	USA	built	2020
283	Timber Lofts	4	3	Milwaukee, WI	USA	built	2020
284	Üstra-Siedlung	5	5	Hannover	Germany	built	2020
285	WA 16 West Holzbausiedlung Prinz-Eugen-Park	7	7	Munich	Germany	built	2020
286	Walden48	7	7	Berlin	Germany	built	2020
287	Wellnesshotel Malis Garten	5	5	Zell am Ziller	Austria	built	2020
288	ZEB laboratory	4	3	Trondheim	Norway	built	2020
289	1 de Haro	4	3	San Francisco, CA	USA	built	2021
290	Abelia	5	4	Bry sur Marne	France	built	2021
291	Aparthotel DAS BLEIBT	5	4	Schladming	Austria	built	2021
292	Cirrus	9	7	Denver, CO	USA	construction	2021
293	Erweiterungsbau Führungsakademie BW	3	3	Karlsruhe	Germany	built	2021
294	Haut	21	21	Amsterdam	Netherlands	built	2021
295	HOAS Tuuliniitty	13	12	Espoo	Finland	built	2021
296	Hyperion	18	15	Bordeaux	France	built	2021
297	InnoRenew CoE	3	3	Livade	Slovenia	built	2021
298	Nodi	5	5	Gothenburg	Sweden	built	2021
299	Sara Cultural Centre (Sida Vid Sida)	19	19	Skellefteå	Sweden	built	2021
300	Stories	13	13	Amsterdam	Netherlands	built	2021

Table A1. *Cont.*

	Project Name	No. of Stories	Wood Stories	City	Country	Status	Year
301	Wood City Supercell	8	7	Helsinki	Finland	built	2021
302	Althea	7	6	Velizy	France	in construction	2022
303	Ascent	10	19	Milwaukee, WI	USA	construction	2022
304	Cirerers	8	7	Barcelona	Spain	construction	2022
305	Cradle	10	5	Düsseldorf	Germany	construction	2022
306	FILAO	7	7	Clichy la Garenne	France	in construction	2022
307	Qbika	4	4	Madrid	Spain	in construction	2022
308	Shelves House	3	3	Madrid	Spain	in construction	2022
309	Wittywood	5	5	Barcelona	Spain	construction	2022
310	T3 Bayside	10	10	Toronto, ON	Canada	construction	2023
311	Arbour (Limberlost Place, George Brown College)	12	10	Toronto, ON	Canada	moving into construction	n/a
312	Terrace House (Port Living)	18	18	Vancouver, BC	Canada	construction	n/a
313	78–90 Mounts Bay Road	10	10	Perth	Australia	proposal	2023
314	Burrard Exchange	16	n/a	Vancouver, BC	Canada	proposal	2023
315	Silva	18	18	Bordeaux	France	proposal	2023
316	Novum Research Park	10	10	Stockholm	Sweden	proposal	2024
317	'WeXO'	18	18	Växjö	Sweden	proposal	n/a
318	105 Punt Road	9	n/a	Melbourne, Vic	Australia	proposal	n/a
319	2150 Keith Drive	10	9	Vancouver, BC	Canada	proposal	n/a
320	40TEN	5	n/a	Baltimore	USA	proposal	n/a
321	475 West 18th Street	10	n/a	New York City, NY	USA	proposal	n/a
322	77 Wade	7	7	Toronto, ON	Canada	proposal	n/a
323	Academic Wood Tower UofT Patkai	15	14	Toronto, ON	Canada	proposal	n/a
324	Atlantic Hotel	14	13	Erfurt	Germany	proposal	n/a
325	Atlassian HQ	40	n/a	Sydney, NSW	Australia	proposal	n/a
326	Boston PassivHaus Model-C prototype "kit of parts"	5	5	Boston, MA	USA	proposal	n/a
327	Canopia	14	n/a	Bordeaux	France	proposal	n/a
328	Clichy Batignolles	9	9	Paris	France	proposal	n/a
329	Development House	9	9	London	UK	proposal	n/a
330	Dutch Mountains	8	8	Eindhoven	Netherlands	proposal	n/a
331	Earth Tower	37	37	Vancouver, BC	Canada	proposal	n/a
332	Framework	12	12	Portland, OR	USA	proposal	n/a
333	Frihamnen Towers	20	20	Stockholm	Sweden	proposal	n/a
334	Green Square, Red Tower	16	n/a	Sydney, NSW	Australia	proposal	n/a
335	Holzhochhaus Pi	27	n/a	Zug	Switzerland	proposal	n/a
336	HSB Vasterbroplan	34	34	Stockholm	Sweden	proposal	n/a
337	hybrid Dutch Mountains	39	n/a	Eindhoven	Netherlands	proposal	n/a
338	Kaj 16/Kromet	15	12	Gothenburg	Sweden	proposal	n/a
339	Le Campus Seine	7	7	Nanterre	France	proposal	n/a
340	Life Cycle-Tower	18	18	Dornbirn	Austria	proposal	n/a
341	Magasin X	7	7	Uppsala	Sweden	proposal	n/a
342	Neues Stadtviertel in Lille (Archiborescence)	7	7	Lille	France	proposal	n/a
343	Newark's Riverfront Square commercial offices	11	11	Newark, NJ	USA	proposal	n/a
344	Oakwood Timber Tower	80	80	London	UK	proposal	n/a
345	River Beech Tower	80	80	Chicago, IL	USA	proposal	n/a
346	Seattle Mass Timber Tower	12	12	Seattle	USA	proposal	n/a
347	Ternes Villiers	9	n/a	Paris	France	proposal	n/a
348	Zünd Montage- und Logistikhalle, Altstätten	4	n/a	Altstätten	Switzerland	proposal	n/a
349	Wooden parking	6	6	Aarhus	Denmark	proposal	n/a
350	WoHo tower	29	29	Berlin	Germany	proposal	n/a

Appendix B

Sources

Table A2. List of books.

Book	Author	Year
Holzbau Atlas	Herzog et al.	2003
best of DETAIL Holz/Wood	ed. Schittich	2014
Solid Wood: Case Studies in Mass Timber Architecture, Technology and Design	Mayo	2015
Manual of Timber Construction	Kaufmann et al.	2018
CLT 100 UK	Waugh Thistleton Architects	2018
Naturally Wood—British Columbia	Brandt	2019
Building in Timber—Room Modules	Huß et al.	2019
Tomorrow's Timber	van der Lugt	2020

Table A3. List of relevant grey literature and reports.

Publication	Type	Year
Timber Structures in Voralberg	special edition DETAIL	2017
The Development of a Tall Wood Building	master thesis, Salvadori	2017
Mass Timber Methods	fellowship report	2018
25 Cases of Nordic Good Practice	report	2019
Structural Systems of Swedish Mass Housing	university course report	2020
Multi-Storey Timber-Based Buildings: An International Survey of Case-Studies with Five or More Storeys Over the Last Twenty Years	PhD dissertation, Salvadori	2021 [1]
World Conference on Timber Engineering (WCTE)	conference articles	
International Forum Holzbau (IHF)	conference papers	

[1] Due to publication in late 2021, most of the projects and data from Salvadori's dissertation were not included. It served as a reference for comparison and confirmation of some of the previously collected data from the project list.

Table A4. List of main magazines, newspapers, and media article publishers.

Media	Related Media Article Publisher
Archello	-
Archdaily	-
Bauenmitholz	-
Designboom Timber Online	-
Detail	-
Dezeen	-
Divisare	-
FIRST—Bauen und leben mit Holz	-
forest.fi	-
Holz-zentralblatt	-
Holzkurier	-
Holzbulletin/Bollettino Legno	Lignum
Mikado	-
Timber Design and Technology Middle East	-
Trä!	Swedish Wood

Table A5. List of online timber project databases.

Database Website	Project Status
bauen-mit-holz.nrw	built
baunetzwissen.de	built
dataholz.eu	built
Holzbau Atlas Berlin Brandenburg	built
holzbauaustria.at	built and planned
holzbau-schweiz.ch	built
holzbauoffensivebw.de	built and planned
holzbaukunst.at	built
makeitwood.org	built
nextroom.at	built
nordic.ca	built and in construction
proholz.at	built
puuinfo.fi	built
swedishwood.com	built
thinkwood.com	built
timberarchitecture.com	built and planned
triplewood.eu	built
woodskyscrapers.org	built and planned
woodforgood.com	built
woodsolutions.com.au	built
woodworks.org	built

Appendix C

Material composition.

Table A6. Number and % of projects based on material composition of different structural elements and within the total project list.

	Frame		Panel		3-D Modules		Combination		All	
	No.	%	No.	%	No.	%	No.	%	No.	%
podium	**76**	**48.41%**	**49**	**44.14%**	**12**	**44.44%**	**21**	**38.89%**	**159**	**45.43%**
concrete	58	36.94%	49	44.14%	12	44.44%	16	29.63%	136	38.86%
steel	1	0.64%		0.00%		0.00%		0.00%	1	0.29%
concrete (partial)	2	1.27%		0.00%		0.00%	2	3.70%	4	1.14%
timber–steel	1	0.64%		0.00%		0.00%		0.00%	1	0.29%
n/a	14	8.92%		0.00%		0.00%	2	3.70%	16	4.57%
steel-concrete		0.00%		0.00%		0.00%	1	1.85%	1	0.29%
core	**96**	**61.15%**	**42**	**37.84%**	**9**	**33.33%**	**14**	**25.93%**	**161**	**46.00%**
concrete	70	44.59%	40	36.04%	7	25.93%	11	20.37%	128	36.57%
steel frame core	4	2.55%		0.00%		0.00%		0.00%	4	1.14%
concrete stairs and landings	1	0.64%		0.00%		0.00%		0.00%	1	0.29%
timber–concrete (0–1/2/n)	1	0.64%	1	0.90%		0.00%		0.00%	2	0.57%
n/a	20	12.74%	1	0.90%	2	7.41%	3	5.56%	26	7.43%
slab	**24**	**15.29%**	**3**	**2.70%**	**4**	**14.81%**	**8**	**14.81%**	**37**	**10.57%**
composite	20	12.74%	1	0.90%	3	11.11%	3	5.56%	29	8.29%
concrete topping	1	0.64%	1	0.90%		0.00%	1	1.85%	1	0.29%
concrete ceilings		0.00%		0.00%	1	3.70%	1	1.85%	2	0.57%
concrete slab areas	2	1.27%		0.00%		0.00%	2	3.70%	3	0.86%
concrete (not all slabs)	1	0.64%		0.00%		0.00%	1	1.85%	1	0.29%
concrete		0.00%	1	0.90%		0.00%		0.00%	1	0.29%.

Table A6. *Cont.*

	Frame		Panel		3-D Modules		Combination		All	
	No.	%	No.	%	No.	%	No.	%	No.	%
additional elements	**35**	**22.29%**	**14**	**12.61%**	**2**	**7.41%**	**15**	**27.78%**	**66**	**18.86%**
concrete beams	2	1.27%	1	0.90%		0.00%		0.00%	3	0.86%
concrete bracing, columns	2	1.27%		0.00%		0.00%		0.00%	2	0.57%
concrete columns	3	1.91%		0.00%		0.00%	1	1.85%	4	1.14%
concrete frame		0.00%	1	0.90%		0.00%		0.00%	1	0.29%
concrete shear walls	1	0.64%	1	0.90%		0.00%		0.00%	2	0.57%
steel bracing	5	3.18%		0.00%		0.00%		0.00%	5	1.43%
steel frame bracing	3	1.91%		0.00%		0.00%		0.00%	3	0.86%
steel frame		0.00%	1	0.90%	1	3.70%	2	3.70%	4	1.14%
steel columns	1	0.64%	1	0.90%		0.00%	3	5.56%	5	1.43%
steel beams	9	5.73%	4	3.60%		0.00%	2	3.70%	15	4.29%
steel beams and columns	4	2.55%	1	0.90%		0.00%	3	5.56%	8	2.29%
steel rods		0.00%	3	2.70%		0.00%		0.00%	3	0.86%
hidden steel el. (n/a)	2	1.27%	1	0.90%	1	3.70%	2	3.70%	6	1.71%
hybrid timber–steel el.	2	1.27%		0.00%		0.00%	2	3.70%	4	1.14%
steel exoskeleton	1	0.64%		0.00%		0.00%		0.00%	1	0.29%
other	**4**	**2.55%**	**6**	**5.41%**	**3**	**11.11%**	**3**	**5.56%**	**16**	**4.57%**
concrete prefab corridors	0	0.00%	0	0.00%	1	3.70%	0	0.00%	1	0.29%
exterior concrete structure	2	1.27%	1	0.90%	0	0.00%	0	0.00%	3	0.86%
exterior steel structure	1	0.64%	4	3.60%	2	7.41%	3	5.56%	10	2.86%
exterior concrete-steel str.	1	0.64%	1	0.90%	0	0.00%	0	0.00%	2	0.57%

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