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Advanced Timber Construction Industry: A Quantitative Review of 646 Global Design and Construction Stakeholders

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Abstract: There has been a multi-storey timber construction boom since the start of the millennium. While there is now a body of research on trends, benefits, and disadvantages of timber construction, there is not yet literature on the wider market or the impact of stakeholders on it. This research investigates the (i) architects, (ii) engineers, and (iii) manufacturers involved in the realization of 300 contemporary multi-storey timber buildings from an existing survey. The analysis is based on data sourced from stakeholder websites and the building survey. It evaluates the perceived level of timber expertise of stakeholders based on service categorization and stakeholder type and relates them to the buildings they worked on. The research uses quantitative methods to answer qualitative questions on the connection between architectural variety in timber construction and the stakeholders involved. Interconnectivity between stakeholders and projects is visualized in an interactive network graph. The study shows a segmented mass timber market with relatively few impactful design and construction stakeholders, mostly located in central and northern Europe. It also identifies fabricators as the largest group of innovators advancing the industry and enabling the construction of more complex projects. It reveals the importance of collaboration and knowledge sharing for the industry's growth.

Keywords: stakeholders; innovation; industry analysis; multi-storey timber construction; mass timber construction; timber industry; timber buildings; wood buildings

1. Introduction

There has been a global increase not only in the number [1] but the height of multi-storey timber buildings (MsTBs) since the early 2000s [2]. This growth has been technically enabled by the development of new engineered wood products [3–5], increased levels of automation [3–8], and new prefabrication strategies with different levels of assembly [8–10]. This growth has also been driven by commercial forces. A broad range of studies have investigated the construction industry's newfound interest in MsTBs. These have looked at the market penetration potential of MsTBs overall [11], drivers and potentials for wood frame MsTBs in particular [12], recommendations to policymakers [13], relevance of R&D programs [14,15], motivations and barriers to using timber in construction [16,17], and how policies and initiatives can favor the construction of MsTBs [18,19]. In general, these studies observe that regulations posed the main barrier to MsTBs for many years and that their relaxation has allowed developers to build more [11,20–24].

Much analysis has already been performed on the buildings resulting from this construction boom [25,26]. The design and construction process, however, is less explored than the preceding factors or the resultant buildings. The literature on construction stakeholders, especially those directly involved in construction, is therefore relatively scarce.

1.1. Aim of the Study

As engineered timber products and construction technologies evolve, it is important to understand factors influencing MsTB construction and how they impact, enable, and limit building designs. This study will examine the qualities of the "project delivery stakeholders" involved in the design and construction of MsTBs, specifically, architects, engineers, and fabricators. Most importantly, it will classify these stakeholders by their perceived Level of Expertise in timber construction. This study asks whether a stakeholder's expertise relates to their impact within the MsTB construction industry. It does so through two research inquiries. First, this study aims to better understand and identify trends in the construction of MsTBs by relating stakeholders' expertise and the architectural variety found in their built projects. Secondly, this study aims to identify trends and relations between stakeholders and their interconnectivity, thus producing insight into the current state of the mass timber construction industry. The outcomes of this study are a dataset and a network graph that further allows readers to identify impactful MsTB stakeholders.

Section 1, Introduction, ends with a literature review in Section 1.2. The specific data collected about stakeholders and how it was collected is described in Section 2.1. How these data were analyzed and compared is described in Section 2.2. Section 3 describes the results of the data collection and analysis, including results from raw data in Section 3.1, the results of the General Stakeholder Analysis in Section 3.2, and the results of the Level of Expertise Analysis in Section 3.3. Section 3.3 also includes the building data analysis. The network graphs resulting from the Interconnectivity Analysis are described in Section 3.4. Section 4, Discussion, describes the limitations of the study and how its results compare to similar studies from the literature review. An overview of the key findings of the paper is given in Section 5, Conclusions.

1.2. Literature Review

Recently, there has been a growing number of studies on multi-storey timber construction and the stakeholders impacting its realization. Most studies analyze the perception of wood through interviews [22,27–29]. Surveys of the interviews also exist [30]. For example, Wiegand and Ramage [24] collect data based on document review and interviews with policymakers and professionals involved in 37 projects across eight countries. However, these surveys usually focus on a specific global region or a select group of countries [24,31,32].

Studies that focus on buildings only mention some of the key project delivery stakeholders without any analysis when surveying or listing projects [25,32–36]. Online databases survey timber production companies and compare data on them as well [37]. Some studies focus on residents or potential users as stakeholders rather than project delivery stakeholders [31,38–40]. Along these lines, the 2014 Perkins + Will timber buildings report by Holt and Wardle [32] summarizes the experiences and challenges of different stakeholder groups completing ten international MsTBs by interviewing them. These studies, though insightful, are less relevant to this research. Studies relevant to this research and their focus are shown in Table 1. The categories listed under "Types of Stakeholders" are those used by the surveys themselves.

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

Study	Year	Scope	Stakeholder #	Types of Stakeholders	Focus/Analysis
Araujo and Christoforo	2023 [41]	global	97	CLT manufacturers	stakeholder qualities
Architect's Newspaper	2019 [42] 2021 [43] 2022 [44]	North America	43 58 59	schools organizations manufacturers planned factories	research and development
Bysheim and Nyrund	2008 [45]	Norway	285	architects (unrelated to use of timber, names not disclosed)	perceptions of structural timber and attitudes
Karjalainen et al.	2021 [46]	Finland	21	builders principal designers structural designers construction supervisors contractors wood suppliers city planners (names not disclosed)	views of key professionals on boundary condition effects design parameters affected issues that need development barriers and measures to tall timber
Roos et al.	2008 [47] 2010 [48]	Sweden	23 26	architects engineers (names not disclosed)	perceived benefits/motivations attitudes perceived norms hampering factors facilitating Factors
Salvadori	2021 [49]	global	701	architects engineers timber engineers general contractors timber suppliers developers clients	clients and influences types of commission motivation stakeholder analysis
Tykkä et al.	2010 [50]	Europe	6	firms (names not disclosed)	innovations in timber construction

Relevant studies emphasize stakeholders in the MsTB industry. The categories listed under "Types of Stakeholders" are those used by the surveys themselves. Studies by Roos et al. and Karjalainen et al., among others, focus on the attitudes of architects and engineers towards power in multi-storey timber construction. Roos et al. [47,48] identify architects, structural engineers, timber suppliers, contractors, developers, authorities, and end-users as the key stakeholders relevant to MsTB completion. Karjalainen et al. [46] produce a wide range of insights about the MsTB industry but from a limited sample of stakeholders, entirely qualitatively and only for Finland. Tykkä et al. [50] identify timber frame innovators and interview them to determine what level of R&D support they receive. Bysheim and Nyrud [45] use a theoretical model to link architects' attitudes to the projects they produce but neglect other types of stakeholders. Recently, some websites have offered yearly overviews of companies in the industry and list basic information such as name and location [42–44]. They describe stakeholders' expertise qualitatively but lack quantitative statistics. Although some studies mention project delivery stakeholders, only two analyze these stakeholders in depth: Salvadori in addition to Araujo and Christoforo. Araujo and Christoforo analyze the websites of 97 CLT manufacturers for information about the companies [41]. They identified a lack of information about the CLT industry and aimed to rectify that. They employed a data collection strategy similar to the one used in this study. However, they did not perform a further qualitative analysis of that data.

Salvadori's 2021 doctoral dissertation provides a survey of 197 MsTBs and a related contextual analysis of the stakeholder networks involved [49]. This includes clients, developers, architects, engineers, contractors, and suppliers ranging from universities and city councils to the firms that manufacture and supply timber elements. Salvadori's study is one of the rare global analyses. It provides an analysis of the stakeholders' interconnected relationship networks by country as a result. It also identifies some of the "key-players" that strongly influenced some case studies' realization, R&D, and design properties. The dissertation also provides a literature review and analyzes the regulatory framework, type of commission, influential factors, and motivations behind the realization of MSTBs. It, however, does not relate context analysis to building design analysis.

So far, research on stakeholders in the MsTB industry is focused on interviews and perceptions [48,50], national networks between stakeholders [49], or describing the unique qualities of individual stakeholders [42–44]. There is no specific research on the global stakeholder network that focuses on their expertise in timber construction or that relates stakeholder roles to building designs. While Salvadori did draw networks between stakeholders, they were diagrammatic and restricted nationally. This misses the international interconnectivity in the globalized timber market.

2. Materials and Methods

The following section explains the methods for data collection and analysis in detail. This research was conducted as a comparative global survey (Figure 1) of 646 stakeholders. These stakeholders were involved in the design and construction of the 300 built works included in the survey by Svatoš-Ražnjević et al. [26] and the related dataset [51]. This dataset was chosen because the variety of construction methods, functions, and locations of the buildings provides a wide image of the MsTB industry. The complete dataset of stakeholders is available under the following accession number: DOI: 10.18419/darus-2740 (accessed on 14 August 2023) [52]. An interactive map of both projects and stakeholders is available online at https://archstakeholders.github.io/ (accessed on 14 August 2023). The analysis is restricted to regions with available data from the preceding study: Europe, North America, Asia, and Australia and Oceania.

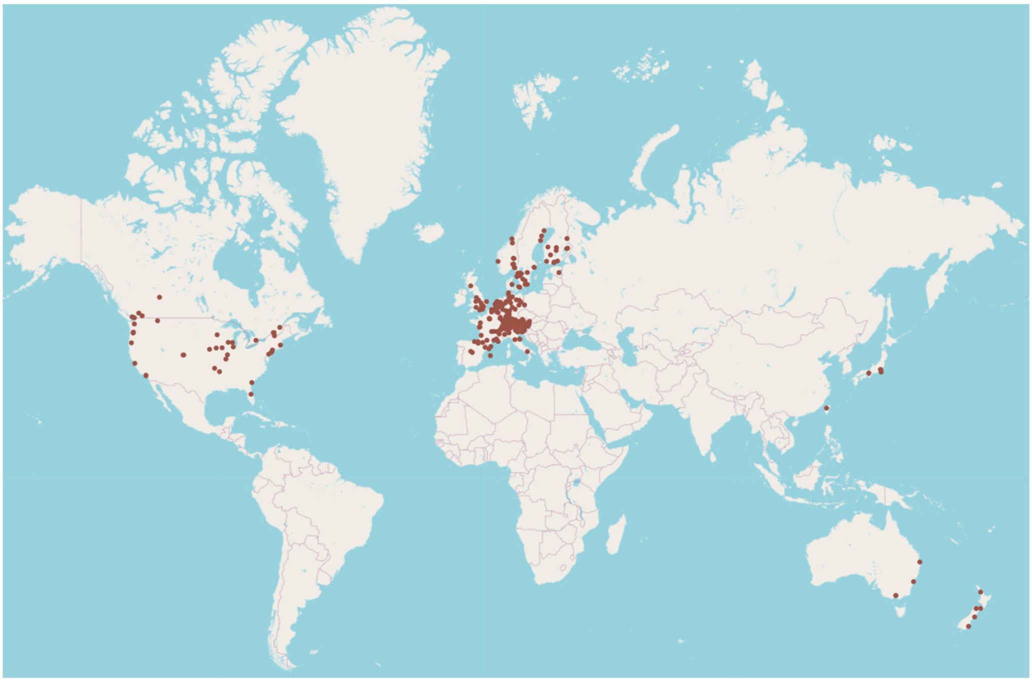

Figure 1. Map of stakeholder locations. Dots represent cities where at least one stakeholder is headquartered.

2.1. Data Collection Methods

Project delivery stakeholders, namely architects, general and timber-specific structural engineers, fabricators, manufacturers, contractors, and, where possible, timber suppliers, were found for each built project in the buildings dataset. Buildings of "Status Category", "in construction", "moving into construction", or "proposal" in the buildings dataset were not included as a source for this study. The buildings dataset contained at least one architect per project, as well as at least one online source for information about the project. Sources included in the buildings dataset, as well as online search results, were used to identify the projects' stakeholders. In most cases, multiple sources were needed, including websites from the other project stakeholders. Developers, general contractors, and clients who surfaced during these searches were not included unless they also fit into one of the earlier categories. Table 2 shows a representative example of the extracted stakeholders.

Table 2. Representative sample of stakeholder data extracted from the project list.

Project ID	Project Name	Country	City	Website	Stakeholders
143	Rue des Ardennes	FR	Paris	https://www.woodskyscrapers.org/projects.html (accessed on 3 November 2021) https://www.construction21.org/case-studies/fr/the-ardennes,es.html (accessed on 3 November 2021)	Aimeric Audebeau Fokkema & Partners Engenuity Price & Myers B&K Structures binderholz Rubner Holzbau

The role stakeholders played on each project was regularly listed along with their names in online sources about their projects. Often, multiple stakeholders played the same role. For example, two architecture firms collaborated on the design of *UBC Brock Commons*: *Acton Ostry Architects* and *Hermann Kaufmann + Partner ZT GmbH*. In other cases, a single stakeholder took multiple roles on the same project. One example is *Arup*, who did both the architectural and structural design of *Sky UK: Believe in Better Building*.

The authors independently developed the data collection methodology. Which data to collect was iteratively decided alongside the criteria for determining the perceived Level of Expertise. Data about the stakeholders themselves was gathered from their individual websites. When stakeholders' websites were not part of the stakeholder-gathering process, a thorough web search was conducted. The manual online data collection method has inherent risks and biases as companies' fortunes, priorities, or online presence are in constant flux. If the website could not be found, or if it was inaccessible, blocked, or under construction, the stakeholder remained in the dataset for the network analysis but was excluded from all other analyses. Due to a lack of publicly available data at the time of collection, engineers were not found for 62 projects, and fabricators for a different 62.

When a stakeholder was mentioned with different naming variations, the naming from their website or logotype was used. "Contact" and "impressum" pages were the source for the stakeholder's country and city. For firms with multiple offices, the location of their corporate headquarters or main office was used. ISO 3166-1 alpha-2 country codes [53] are used throughout this study and in the stakeholders dataset.

2.2. Analysis Methods

The developed stakeholder analysis consists of three parts: (I) a general stakeholder analysis, (II) an analysis based on perceived Level of Expertise in timber construction, and (III) an interconnectivity analysis.

The general analysis classifies stakeholders based on (I.a) what Service Categories they offer and (I.b) their stakeholder type. These results are combined with an overview of the stakeholder's project portfolio from their website to derive (II.a) their perceived Level of Expertise in timber construction.

Additionally, (II.b) a project/stakeholder analysis compares the results of the stakeholder analyses to a selection of data from the project database: project location, year of completion, architectural program, and massing data [51]. General stakeholder analysis results are compared to project location and year. Level of Expertise analysis results are related to year, program, and massing.

Finally, (III) an interconnectivity analysis of stakeholders' involvement and relations within the mass timber construction industry is performed using network visualization. Figure 2 illustrates the analysis methodology, as well as each analysis's inputs and results.

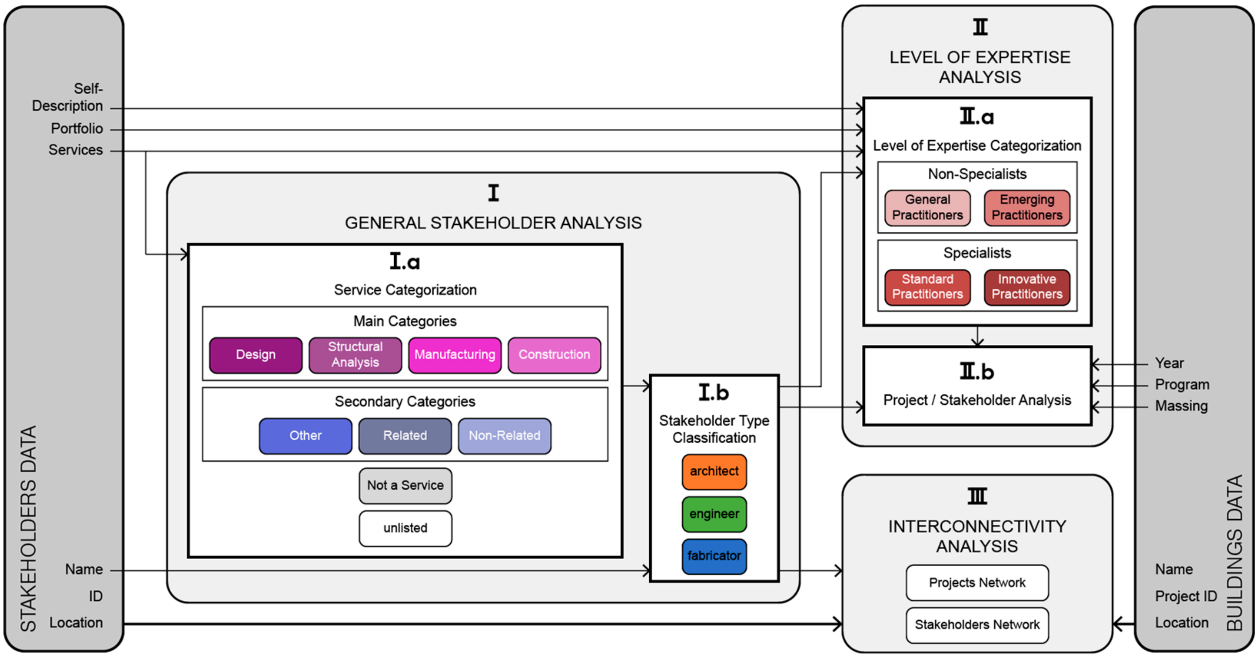

Figure 2. Analysis methods inputs and results.

2.2.1. General Stakeholder Analysis

In addition to basic information like company name and headquarters location, the general stakeholder analysis considers the services offered by stakeholders and their project roles.

(I.a) Service Categories

All services listed by stakeholders on their websites are collected, regardless of their relevance to timber construction. The exact naming of services is retained, resulting in similar services such as "acoustic", "acoustics", "acoustical engineering", and "acoustics & sound" being recorded separately.

Many stakeholders' websites have a dedicated "services" page. If not, a service list can often be found on the "about" page as part of their self-description. For tiered service lists with many services under a few groups, only the service group titles are collected. Stakeholders whose websites do not list services are marked as "unlisted". Service lists consisting of exclusively products or building types, such as "commercial, residential, high rise", were not collected and also marked "unlisted". "Unlisted" stakeholders were not included in further Service Category analysis.

Services are classified into seven Service Categories. Any descriptions of the services, if included alongside the list, are used in this classification. If there is no description, the common, conventional definition for the service is used. The four main Service Categories were created by the authors before coding based on the tasks that architects, engineers, or timber engineers/fabricators/manufacturers/contractors would perform during design and construction. They are the following:

1. Design (implementation of the structural system);
2. Structural Analysis (analysis and simulation of the structural system);
3. Manufacturing (prefabrication of the structural system);
4. Construction (on-site assembly and construction of the structural system).

Services not pertaining to the design and manufacturing of the load-bearing components are merged into three secondary Service Categories. These categories were developed by the authors as part of the coding process based on the services' relation to the construction process. These are:

5. Other (part of the construction process);
6. Related (related to construction but not part of the construction process);
7. Non-related (not related to the construction process).

The Other category includes parts of the construction process that do not fit into the four main categories. Physical tasks, such as excavation, are classified as Other. So, too, are objects that are permanent and remain as part of the construction, such as facades.

The Related category includes services that are not part of the construction process but still related to it. Non-physical tasks that did not fit into the four main categories, such as tertiary services and consulting, are classified as Related. Physical objects that did not remain as part of the finished construction, such as scaffolding, are also classified as Related.

If products or building typologies are captured as part of larger service lists, they are categorized as "Not a Service". This includes any non-timber materials. Timber materials, however, are included in the Manufacturing category. In many cases, the material itself, such as a glue-laminated beam, is the prefabricated element that is assembled on-site.

Services that fit into multiple categories, primary or secondary, are classified into all their applicable categories. For example, "design & engineering", offered by *ARGE raumwerk*, is put into both the Design and Structural Analysis categories. It, therefore, counts twice in statistical analyses.

The definitions alongside some services resulted in services with the same title being classified differently. For example, "value engineering", offered by *Aronsohn* [54], has a description that classifies it as Construction. In contrast, the text accompanying "value engineering" on the webpage of *SmartLam NA* [55] classifies it as Manufacturing.

(I.b) Stakeholder Type

Though there are many roles in the realization of a building, including contractor or developer, stakeholders are reclassified into one of three types: architect, engineer, or fabricator. These three types were chosen to simplify further analysis. A stakeholder's type is set based on their role, with support from their names, promotional text, or services. For example, 62% of architects have a variation of the word "architect" or its translation in their company names. Others, such as *GG-loop*, begin their "about" page [56] with the sentence "GG-loop is [an] architectural practice".

The architect type includes stakeholders involved in spatial and architectural design of buildings. The engineer type includes stakeholders offering analysis and simulation of buildings and their structures, including civil, MEP (mechanical, electrical, and plumbing), structural, and timber engineering. The fabricator type includes companies that primarily involve themselves in the physical construction of buildings, including material suppliers and timber contractors.

2.2.2. Level of Expertise Analysis

Level of Expertise in timber construction, within the context of this study, is a qualitative, interpretive metric based on a stakeholder's projects, their engagement with new products, and their level of digitization.

(II.a) Level of Expertise

Stakeholders' websites, particularly their (a) self-description, (b) services offered, and (c) curated project list, were analyzed to determine their perceived Level of Expertise. The analysis looked for timber- and timber-construction-related wording in text, headings, and photo descriptions.

Four categories were developed during the coding process. Free categories were first assigned on a small dataset. The authors attempted to combine these categories, which led to the categories' redefinition. The final categories were chosen because each stakeholder fit into only one of the four subcategories. Stakeholders are divided into two main categories and four subcategories:

- Non-specialists
  a. General Practitioners;
  b. Emerging Practitioners.
- Specialists
  c. Standard Practitioners;
  d. Innovative Practitioners.

Non-specialists are stakeholders who worked on few timber projects. Specialists include stakeholders that built most or all their projects in timber. Specialists also include stakeholders with a special timber department despite their more general material focus.

a. General Practitioners do not focus on timber construction but still have timber buildings in their portfolios. They concentrate on other materials or other aspects of the built environment.

b. Emerging Practitioners, though their portfolios do not feature exclusively timber construction, have made their mark on the mass timber construction industry. The few timber projects they have designed or built are experimental and forward-looking.

c. Standard Practitioners include architecture and engineering firms who work with established wood products and timber construction techniques. They also include highly experienced fabricators, such as traditional carpenters.

d. Innovative Practitioners include companies that are attempting to disrupt the established practices of timber construction by innovating in material use, building systems, or fabrication processes. Oftentimes, architecture companies included in this category self-describe as "pioneers of timber" or have had a long history of timber use, producing "demonstrator" projects that showcase variations and possibilities in timber construction. Engineering companies in this category have a deep understanding of timber as a material and its properties, enabling them to design and certify, through additional testing, novel details and assemblies that would not otherwise be permitted by building code. Innovative fabricators either use state-of-the-art techniques, materials, or processes or pursue new ones, perhaps for their own development.

(II.b) Project/Stakeholder Analysis

The study examines whether stakeholders' level of expertise is correlated with their architectural output. It tracks their levels of expertise across their projects' completion dates to identify trends. To gauge building complexity, the study uses a project's massing and program variety from the projects database. The uses of all the projects in the buildings database are classified into one of four program groups: residential/housing, commercial, mixed-use, and public and civic. Massing is defined by analyzing the outlines of the building's form in plan. If they are orthogonal and symmetrical, or mostly orthogonal with a small degree of non-symmetry, the building is "regular". If the outlines are complex, non-orthogonal, or non- or semi-symmetrical, the building is "irregular". Some buildings have both regular and irregular components and are noted as such.

2.2.3. Interconnectivity Analysis

A global analysis of stakeholders is conducted through network visualization. The focus is to identify repetitive stakeholders, patterns of stakeholder interdependence, clusters of collaboration, and interrelated projects, as well as potential levels of international exchange and how they relate to perceived Level of Expertise in timber.

Node-link diagrams (NLs) are one of the most common network visualization techniques. In NLs, graph vertices are visually depicted as circular nodes. Graph edges are represented by straight lines connecting the nodes. The stakeholder dataset contains two entities (i.e., projects and stakeholders), leading to two NLs to visualize the relationships for each entity. The Projects NL depicts the relationships between projects, whereas the Stakeholders NL visualizes the relationships between stakeholders (see Section 3.4. Interconnectivity Results). To reduce visual clutter, a common problem in NL, d3-force algorithms [57] are used to lay out the nodes. In the case of Stakeholders NL, the network layout is further enhanced by grouping [58] the stakeholders based on the "country" attribute and, therefore, highlighting the countries with most stakeholders.

Other network representations, such as adjacency matrix and alternative layouts for NLs, such as the radial layout, were evaluated. Nevertheless, NL with force-directed layout was found to be the most suitable to the characteristics of the dataset (i.e., network density and size) and the easiest to understand for laypersons. All stakeholders are included in the network visualization, even those for whom no additional data was available.

3. Results

3.1. Collected Data Results

3.1.1. Stakeholder Location

A total of 646 Stakeholders were identified in the initial data collection. After exclusions for lack of data, 614 stakeholders from 22 countries based in 352 cities remain in the general analysis. The distribution of stakeholders by country and by global region is shown in Figure 3b.

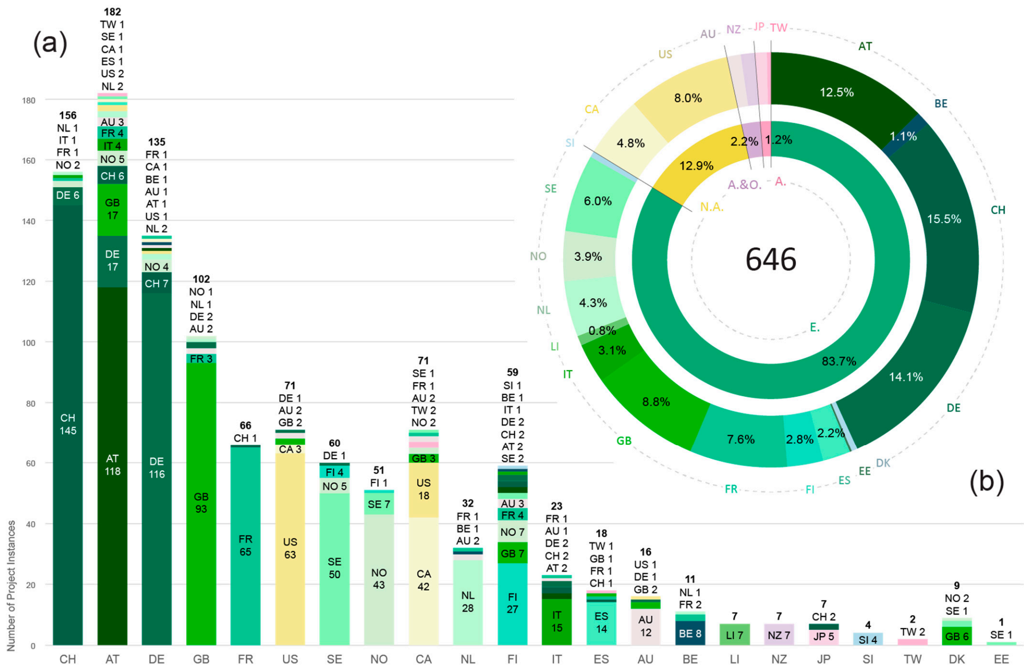

Figure 3. (**a**) Number of times stakeholders worked on a project, grouped by stakeholder location, colored by project location, sorted from highest to lowest number of matching stakeholder and project locations. (**b**) Ratio of stakeholders by country and continent, sorted alphabetically. Not all country percentage labels are shown.

3.1.2. Project Locations

The MsTB industry is fragmented and local in nature, as can be seen in Figures 3a and 4. Stakeholders work mostly, but not always, in their own country (Figure 3a). In total, 52% of projects (152) have exclusively national stakeholders, and 101 of the 143 projects with multinational teams only have one foreign partner. Conversely, 92% of stakeholders work only in their own country. Proportionally, French stakeholders work abroad the least. A total of 24 of their 25 projects are located in France. British stakeholders are next (36/43), and then Swiss ones (38/49). Conversely, stakeholders from Denmark (0/9), Finland (8/39), and Austria (36/91) work on foreign projects the most.

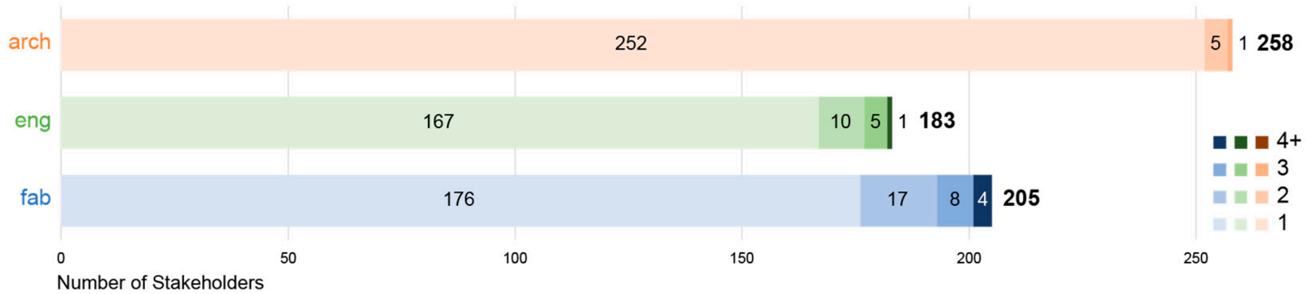

Figure 4. Number of stakeholders, by type, categorized by the number of countries they worked in, where darker tones represent more countries (legend at right).

Figure 4 shows how many countries stakeholders worked in. Fabricators work internationally the most: 29 fabricators (14%) worked in two or more countries, compared to only 2% (6) of architects and 9% (16) of engineers. Therefore, over 93% of stakeholders worked in only one country. All stakeholders with one project have it in their own country. Of those with two or more, only 32% work internationally. However, these statistics undermine the internationality of certain stakeholders. Eighteen architects built exclusively abroad, with *Shigeru Ban* from Japan being the only one to do so twice, in Switzerland. Eleven engineers built exclusively abroad, with *Arcadis* from the Netherlands doing so twice in Australia. Of the 15 fabricators who built exclusively abroad, *StructureCraft*, from Canada, who built all four of their projects in the US, was the only one to do so multiple times. Tables of the most international stakeholders by type can be found in Appendix A. While most international architects and engineers are from a variety of countries and regions, half of the most international fabricators were from Austria, and two-thirds were from majority German-speaking countries.

3.1.3. Recurrent Stakeholders

In general, stakeholders did not work on multiple case study projects. Most stakeholders (75%) worked on only one project. Of the 160 stakeholders who worked on multiple projects, just over half (52%) worked on only two. The DACH region (DE—Germany, A—Austria, CH—Switzerland) has the most recurrent stakeholders, possibly due to their robust local market for timber buildings or high representation in this study. Regardless, they only account for 22%, 31%, and 26% of their totals, respectively. Figure 5 shows which countries have the most recurrent timber companies. Proportionally, Belgium, Austria, and Canada have the most recurrent stakeholders at 57%, 57%, and 35%, respectively. Austria (8 stakeholders), Canada (5), Switzerland (4), and the UK (4) have the most stakeholders who worked on five or more projects.

Figure 5. Number of stakeholders, grouped by location, categorized by number of projects worked on, where darker colors represent more projects.

3.2. General Analysis Results

3.2.1. Service Categories

Ninety-four stakeholders (15%) are marked "unlisted" and excluded from the Service Category analysis. A total of 2218 services were gathered from the remaining stakeholders and categorized. The greater number of secondary Category services highlights how much AEC work is not related to the structure of a building. A total of 1040 services (44.3%) are in the four main Service Categories, while 1152 services (49.1%) fall under the three secondary Service Categories. Of the main Service Category, Construction is the most common. Of the secondary, services not related to the construction process were the most prevalent. Figure 6 shows a breakdown of how many services belong to which Service Category.

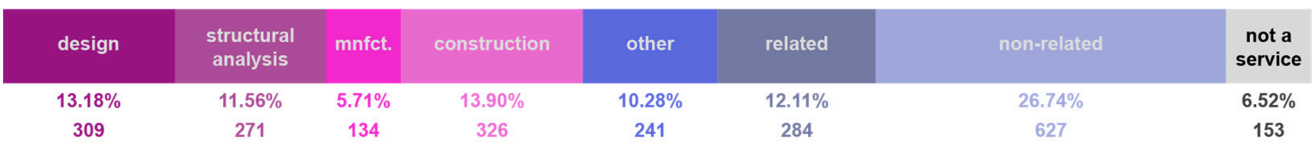

Figure 6. Detailed ratio of services by Service Category. Main Service Categories are purple; secondary Service Categories are blue; services marked "not a service" are grey.

Design services account for almost half of those offered by architects. Engineers and fabricators offer them much more rarely. The proportion of Service Categories offered by each type of stakeholder is shown in Figure 7. Over 40% of services offered by fabricators are in the Construction and Manufacturing categories. Less than a quarter of engineers' services belong to the Structural Analysis category. Instead, engineers cover the spectrum of Service Categories. They offer more secondary Category services than either architects or fabricators. They, therefore, offer, on average, the most Service Categories, at 3.3. *Thornton Tomasetti*, an engineer, is the only stakeholder who offers all eight Service Categories. The Service Category least offered by both architects and engineers is Manufacturing. Conversely, fabricators offer Design services the least. For example, fabricators *A-Z Holzbau Zimmerei* and *Laube SA* both offer seven service categories (all except Design).

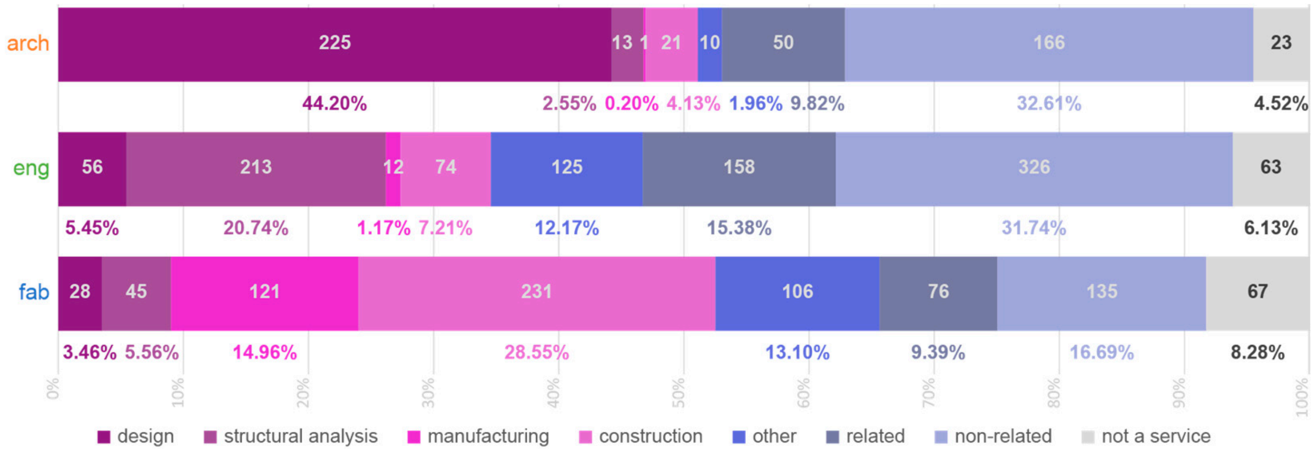

Figure 7. Detailed ratio of services categories offered by stakeholder type.

3.2.2. Stakeholder Type

The 258 architects, 183 engineers, and 205 fabricators captured by this study (Figure 8b) are unevenly globally distributed. Switzerland, Germany, and Austria have the most stakeholders, mirroring the distribution of projects in the building survey. Still, fabricators are overrepresented in the DACH region: 45% of fabricators are headquartered there, more so than architects and engineers. Figure 8a shows that certain types are more prevalent in certain countries. For example, there are proportionally fewer fabricators in the UK than there are architects and engineers. This results in the two top fabricators, *Eurban* and *B&K Structures*, working on over half (19) of the 36 British projects. Conversely, the United States has proportionally more architects. This study includes stakeholders of all three types from almost every country included but does not capture any fabricators from Australia, Denmark, or Estonia, any engineers from Slovenia or Taiwan, or any architects from Estonia.

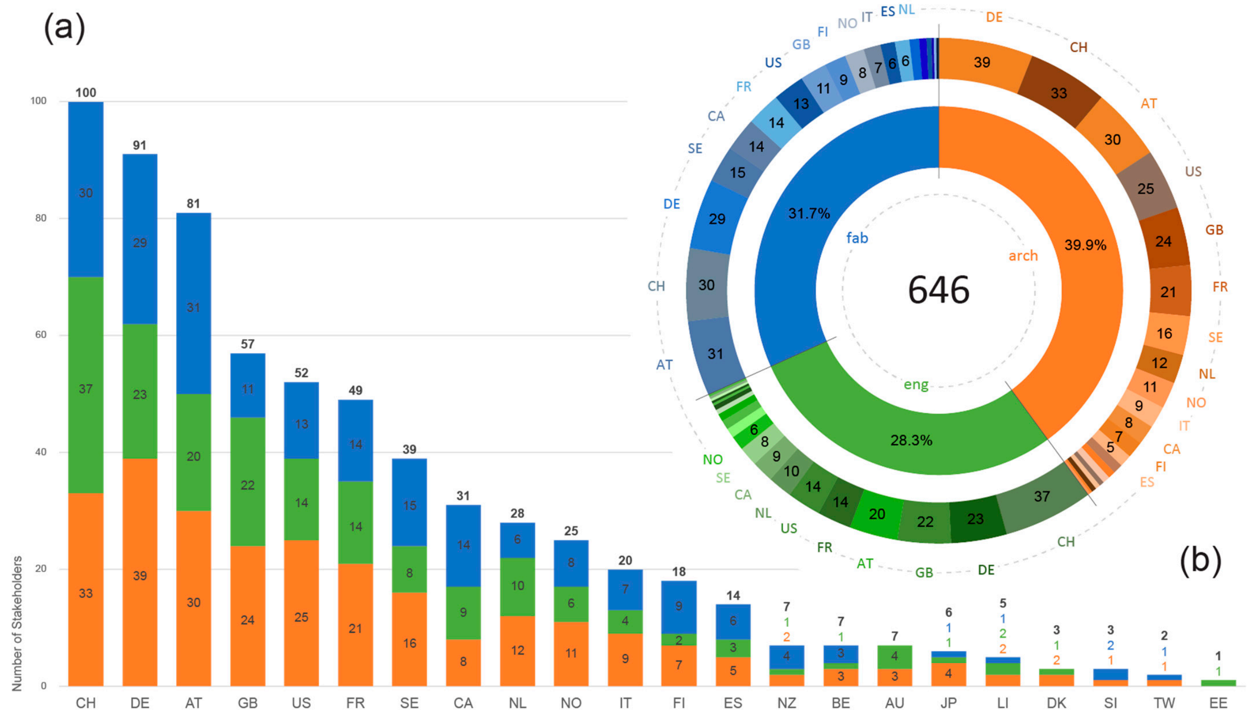

Figure 8. Breakdown of stakeholders by type and country: (**a**) Number of stakeholders per country, categorized by type. (**b**) Proportion of stakeholder types, with concentration by country.

3.2.3. Recurrent Stakeholders

Fabricators are more likely to work on multiple projects at a rate of 30%, compared to 28% of engineers and 18% of architects. Stakeholders worked on anywhere between one and 35 projects, with 160 stakeholders, about 25%, working on two or more (Figure 9). Architects are the least recurrent, working on average on only 1.3 projects. Engineers recurred more often, at 1.7, but less than fabricators, at 2.1.

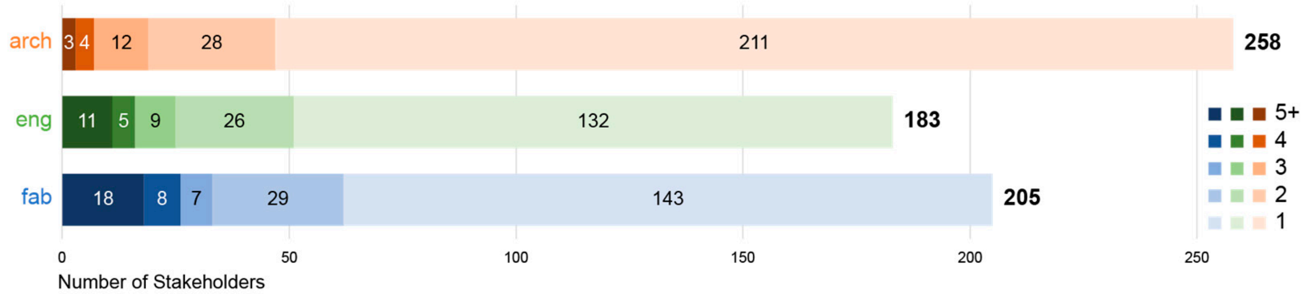

Figure 9. Number of stakeholders, grouped by type, categorized by the number of projects they worked on, where darker tones represent more projects (legend at right).

The most prolific architect in the survey is *Waugh Thistleton Architects*, whose nine buildings are all in the UK. The most prolific stakeholder in the survey was a fabricator, *Stora Enso* from Finland, who contributed to 35 buildings across twelve countries, including seven projects in Finland. The most prolific engineer was *Merz Kley Partner*, from Austria. They built 11 of their 17 projects in Austria, 5 in Germany, and one in Switzerland. A table of the most prolific stakeholders by type can be found in Appendix B. While the most prolific architects and fabricators were Specialists, more than half of the engineers were Generalist practitioners. Except for *Lendlease DesignMake* from Australia and *Michael Green Architects* and *WSP* from Canada, all of the most prolific architects were European.

There is no correlation between a stakeholder's number of projects and the variety of services they offer. Of the 111 stakeholders offered five or more Service Categories, only *B&K Structures*, from the UK, was in the top 10 recurrent stakeholders, with nine projects.

3.3. Level of Expertise Results

There are proportionally many more Specialist fabricators (65.6%) than Specialist architects (18.6%) or engineers (23.3%). This becomes even more pronounced when looking at Innovative Practitioners: 20.0% of fabricators are Innovative, compared to 6.1% of architects or 6.4% of engineers. This is representative of how specialized the MsTB industry is at the high level and how it is still being filled out.

Figure 10 shows the breakdown of stakeholders by Level of Expertise and type. About 65% of stakeholders (400) were Non-specialists, with 321 General Practitioners and 79 Emerging Practitioners. The other 35% of stakeholders (214) were Specialists, consisting of 149 Standard Practitioners and 65 Innovators.

Across all three stakeholder types, the lower subcategories (General Non-specialists and Standard Specialists) are more common than the higher ones (Emerging Non-specialists and Innovative Specialists). The breakdown of architects shows a discipline that is only starting to specialize in timber as a material: 64.4% of architects are General Practitioners, with fewer at higher Levels of Expertise. Engineers show a more mature split, with stakeholders who work completely in timber construction, the Standard Practitioners, outnumbering those who are getting into the material, the Emerging Practitioners. However, given the propensity for engineers to offer a wide and varied array of services (Section 3.2.1), it is not surprising to see that they have the highest proportion of Generalists at 66.9%. Engineers also have the least Innovators, only 11 out of 172.

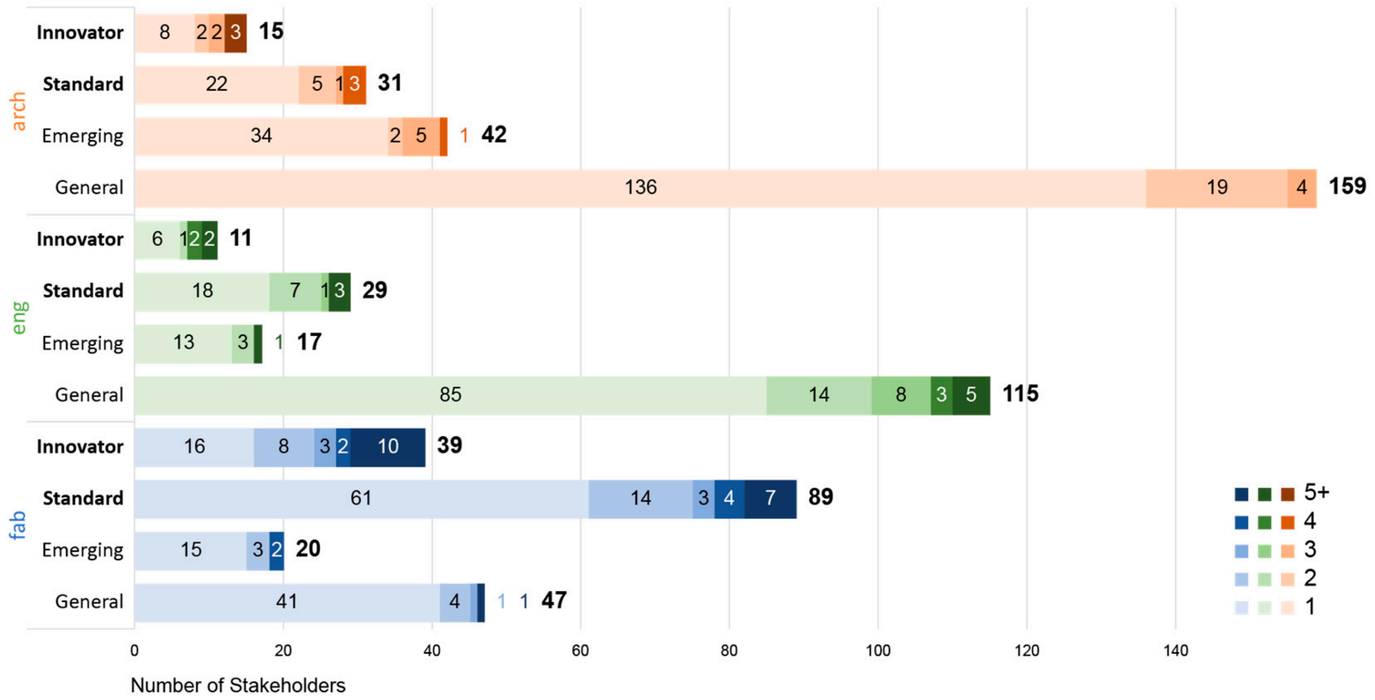

Figure 10. Number of stakeholders grouped by type, divided by Level of Expertise, and colored by the number of projects they worked on, where darker tones represent more projects (legend at right). Specialist categories in bold type. Non-specialist categories in regular width.

Figure 10 further partitions the stakeholders by the number of projects they worked on. In general, a higher Level of Expertise correlates with more projects. Apart from six engineers (*Woschitz Group, Sweco, Lendlease DesignMake, Price & Myers, WSP*, and *Ramboll*) and one fabricator (*Veidekke ASA*), all stakeholders who worked on five or more projects were Specialists.

The appendices contain tables of the stakeholders who were the most international, prolific, interconnected, internationally connected, and linked. In total, 28 of the 44 of the stakeholders thus highlighted were Specialists, and all 17 fabricators were Innovative Practitioners. This shows a link between the Level of Expertise and prominence in the MsTB industry. It also underscores the outsized influence innovative fabricators have on the industry. A total of 23 stakeholders appeared on more than one table, 16 of which were Specialists, reinforcing that collaboration fosters innovation.

3.3.1. Project Program Analysis

Innovative Practitioners are leading the MsTB industry by working on projects across multiple program types. Most Generalists (74%) only worked on projects of a single program, either residential/housing (51%) or commercial (32%). Inversely, 74% of Innovators worked on projects across multiple programs. The data for Figure 11 consider four program groups: residential/housing, commercial, mixed-use, and public and civic. Almost half of all stakeholders who worked on projects across three or four programs were Innovators. Except for two General Practitioners, all stakeholders who worked on four different programs were Specialists. These exceptions were *Arup* and *Engenuity*, both engineering firms from London with broad expertise beyond mass timber construction.

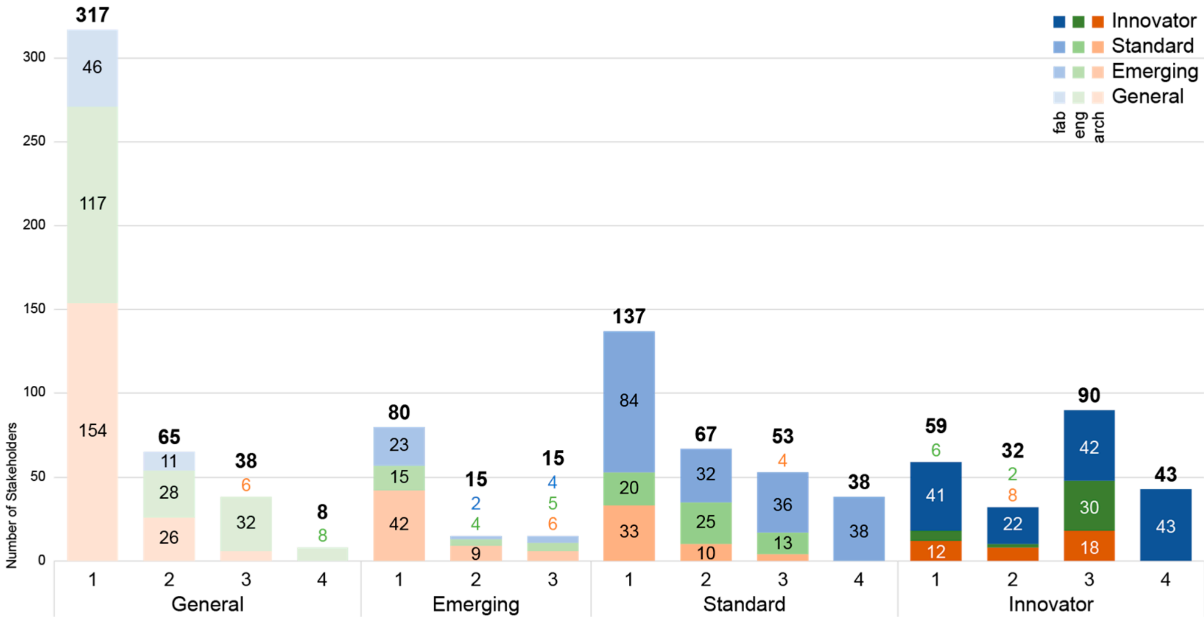

Figure 11. Number of stakeholders who worked on projects across multiple programs, grouped by Level of Expertise, where darker tones represent higher timber expertise, categorized by type (legend at right).

3.3.2. Project Massing Analysis

Innovative Practitioners are also driving forward volumetric architectural variety. Most projects are fabricated by Specialist stakeholders, but an even higher proportion of irregular projects are. Only 9 of the 129 irregular projects (7.0%) were fabricated by Non-specialists. Innovative architects work on an equal proportion, about 16%, of irregular projects as Innovative fabricators do. The fabricators simply work on more of them. In contrast, General Practitioners, not Specialists, perform the design and structural engineering of both regular and irregular projects alike, as seen in Figure 12.

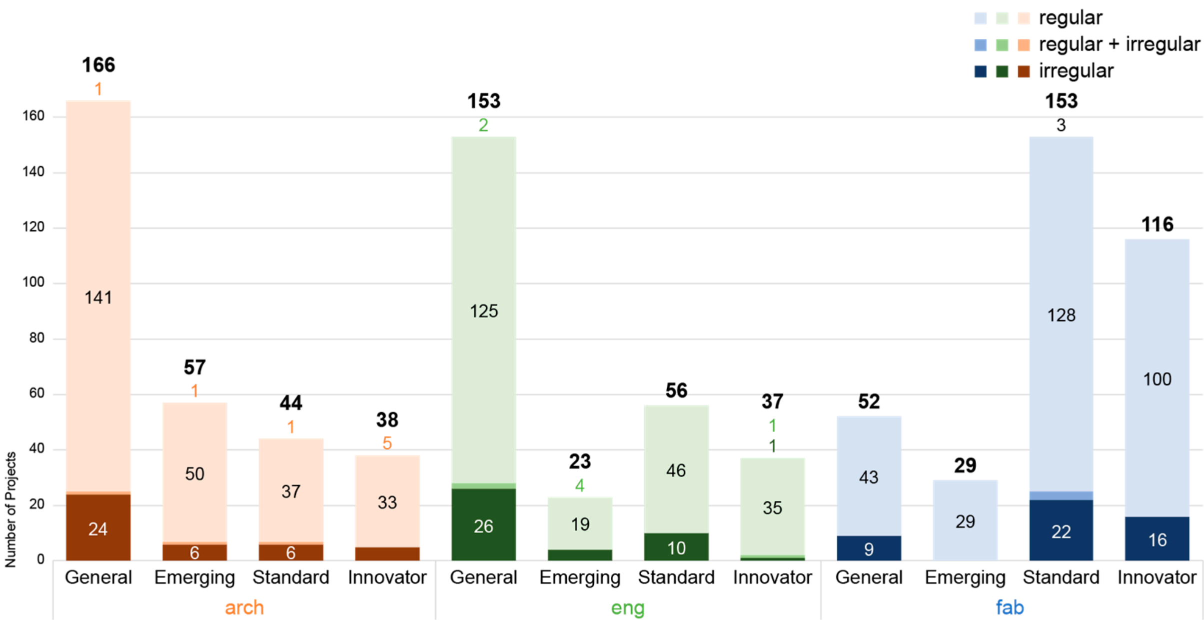

Figure 12. Number of projects categorized by geometric complexity, where darker tones represent greater complexity (legend at top-right), grouped by the type and divided by the Level of Expertise of the stakeholders who worked on them.

3.3.3. Project Year Analysis

The consistently high proportion of General Practitioners working on MsTBs shows that the larger AEC industry continues to show interest in timber as a construction material. This level of interest and involvement is increasing, as shown by the decrease in Specialists building MsTB case studies in recent years.

Figure 13 counts stakeholders by the years in which projects they worked on were built. Due to the low number of projects included in the project survey before 2008, it is difficult to analyze trends from this period. After 2008, General Practitioners make up, on average, 39% of all stakeholders, peaking in 2016 at 48.8% and never falling below 33.1% in 2021. There is a slight downward trend in the proportion of Specialist stakeholders per year, starting at 63% in 2010 and decreasing to 44% in 2021.

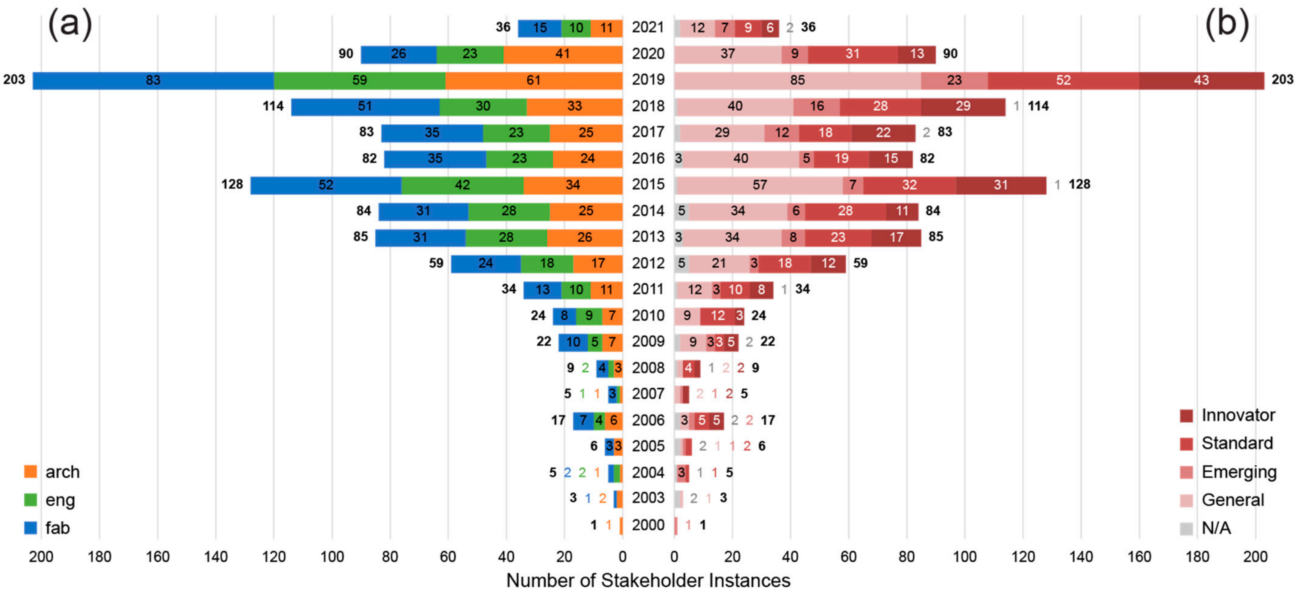

Figure 13. Number of stakeholders who worked on projects completed in each year: (**a**) Categorized by stakeholder type (legend at left). (**b**) Categorized by Level of Expertise, where darker tones represent higher timber expertise (legend at right).

3.4. Interconnectivity Results

A web application prototype using a node-link diagram was built to visualize and analyze the stakeholders [52] and buildings [51] datasets. The application can be found online at https://archstakeholders.github.io/ (accessed on 20 April 2023), along with an interactive user guide. A description and brief user guide for the web application is in Appendix C.

3.4.1. Projects Network

The Projects Network (PN) depicts the relationships between projects as an NL. Figure 14 shows the PN based on the MsTB projects dataset. Each project in the network is depicted by a ring. The stakeholders involved in that project are depicted as circles attached to the project ring (Figure 14a). Projects become connected when they share one or more stakeholders. In that case, links are drawn as straight lines to connect the same stakeholder's circles on each ring (Figure 14c). The projects that have the most stakeholders are *Bjergsted Financial Park* in Norway (12) and *Asylunterkunft Rigot* (11), as well as *Suurstoffi Areal Baufeld 3* (10), both in Switzerland.

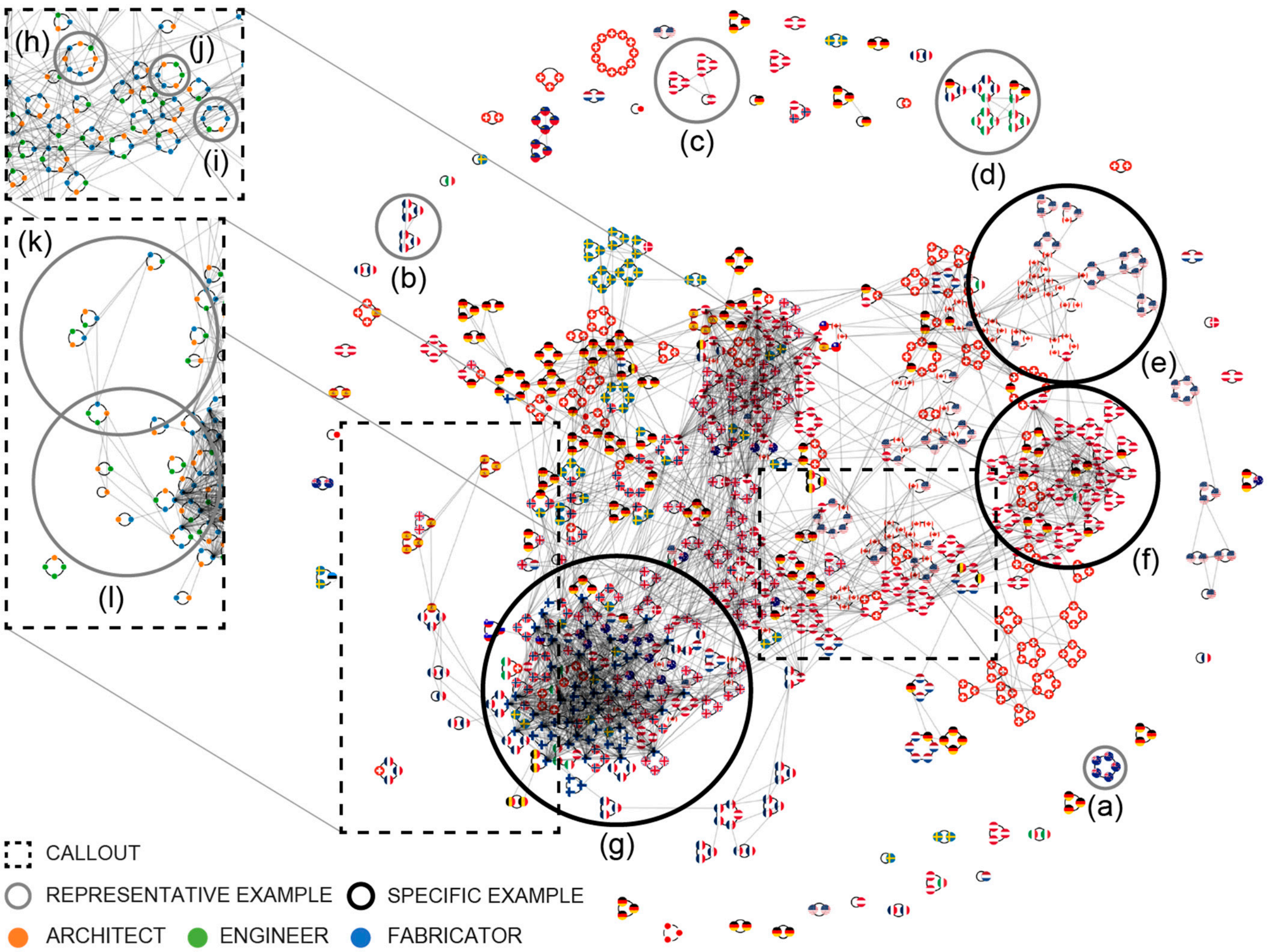

Figure 14. Projects Network. Projects are ring nodes. Flags are stakeholder headquarters locations. Colored dots are stakeholder type. (a) example of single-project island. (b) example of two-project island. (c) three-project island. (d) five-project island. (e) North American cluster. (f) Austro-German cluster. (g) *Stora Enso* cluster. (h) Project: *Adohi Hall*. (i) Project: *Patch 22*. (j) Project: *Arbora Complex*. (k) *Egoin* cluster. (l) *Jean-Paul Viguier* cluster.

Projects are grouped into "clusters" by their shared stakeholders. Most (248) projects are in one large cluster, called the "central cluster". The remaining 52 are in clusters disconnected from the central cluster, called project "islands". Of these, 47 consist of a single project (Figure 14a), three are project pairs (Figure 14b), one has three projects (Figure 14c), and one has five (Figure 14d). Some islands are clusters centered around a single stakeholder, such as Swiss engineers *LP architektur ZT GmbH* (Figure 14c). Other islands are collaborative clusters where multiple stakeholders have collaborated on multiple projects, such as in Figure 14b. Project islands are indicative of the distributed and disconnected nature of part of the mass timber construction industry.

Encoding stakeholders by their country's flag is useful for identifying interconnected national timber industries. Examples include a cluster of Canadian and American stakeholders in Figure 14e, an Austro-German cluster in Figure 14f, and an international cluster centered around Finnish stakeholder *Stora Enso* in Figure 14g. The number of connections a project has is calculated by counting the number of unique projects its stakeholders also worked on. This highlights the projects on which the most prolific stakeholders collaborated. *Rue des Ardennes* in France and *The Green House* and *Woodbury Down* in the UK are the most connected, with 54, 50, and 46 connections, respectively.

The stakeholder breakdown per project becomes visible when stakeholders are encoded by type. As representative examples, one can see that *Adohi Hall* has as many architects as fabricators and engineers combined (Figure 14h), whereas *Patch 22* has more fabricators than architects or engineers (Figure 14i), and *Arbora Complex* has an equal split of stakeholder types (Figure 14j). This encoding also highlights the common stakeholder in clusters along the periphery of the network. Representative examples are one cluster around *Egoin* from Spain (Figure 14k) and another around *Jean-Paul Viguier* from France (Figure 14l).

3.4.2. Stakeholders Network

The Stakeholders Network (SN) depicts the relationships between stakeholders as an NL. Figure 15 shows the SN based on the stakeholder dataset. Each stakeholder in the network is depicted by a circular node. The stakeholders' projects are shown as black dots along the edge of the stakeholder node (Figure 15e). The larger the number of projects the stakeholder has worked on, the larger the stakeholder node. Stakeholders become connected when they have collaborated on at least one project. In that case, links are drawn as straight lines to connect the respective project dots.

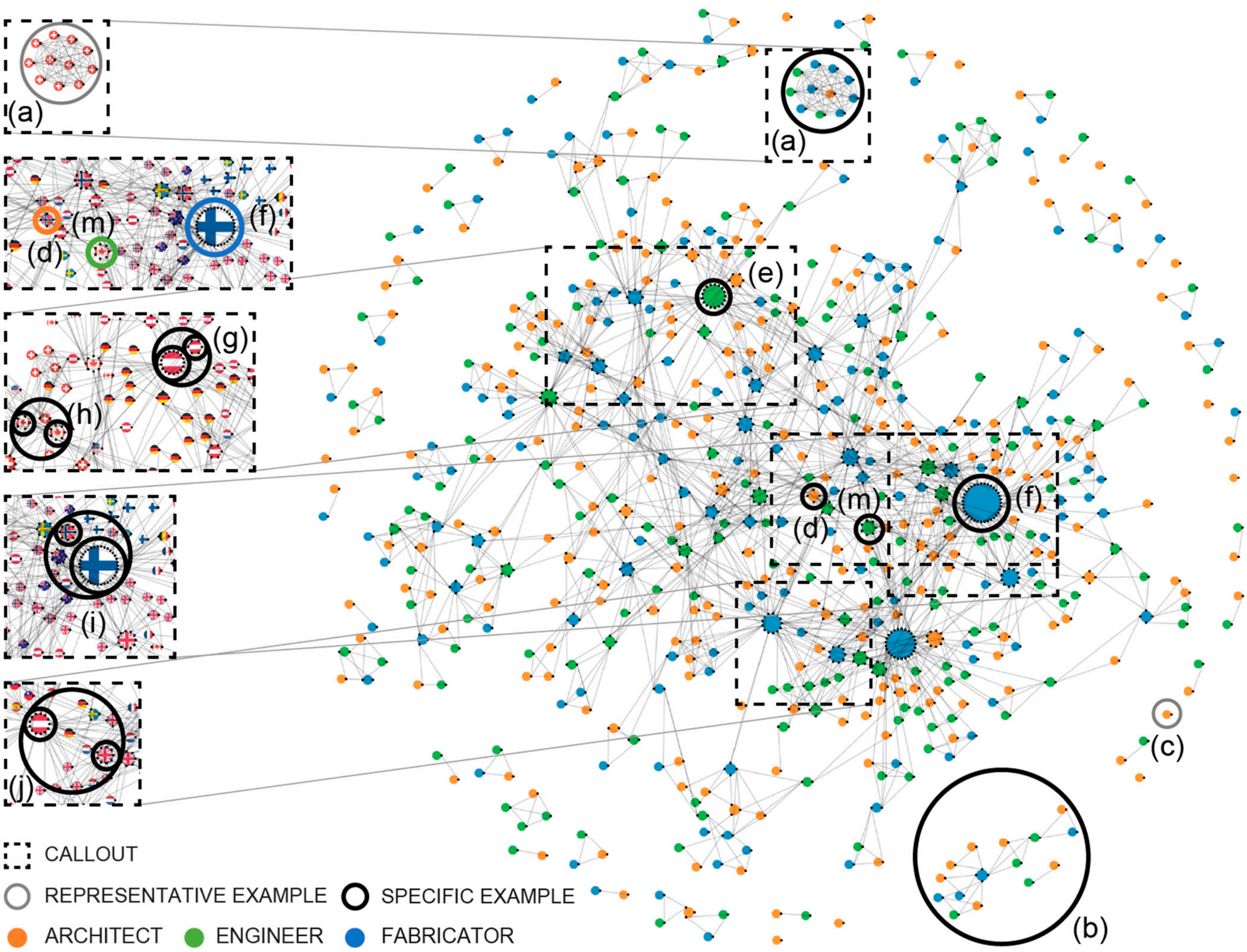

Figure 15. Stakeholders Network. Projects are nodes. Flags are stakeholder headquarters locations. Colored dots are stakeholder type. (a) eleven-stakeholder island. (b) thirteen-stakeholder island. (c) example of project with unlisted collaborators. (d) Stakeholder: *Helen & Hard*. (e) Stakeholder: *Merz Kley Partner*. (f) Stakeholder: *Stora Enso*. (g) Linked Stakeholders: *Merz Kley Partner* and *Hermann Kaufmann + Partner ZT GmbH*. (h) Linked Stakeholders: *Nordic Structures* and *FGP Construction*. (i) Linked Stakeholders: *Stora Enso* and *Woodcon*. (j) Linked Stakeholders: *binderholz* and *B&K Structures*.

Like the PN, the SN can also be divided into stakeholder islands and a central cluster. The largest project islands have 11 and 13 stakeholders each (Figure 15a,b). The 11 architects whose collaborators were not listed publicly appear as individual nodes without any connections. Figure 15c shows a representative example. The most interconnected stakeholders are those who have worked directly with the most other stakeholders. The most interconnected architect, engineer, and fabricator are *Helen & Hard*, *Merz Kley Partner*, and *Stora Enso*, with 19, 38, and 93 connections, respectively (Figure 15d–f). Tables of the most interconnected stakeholders by type can be found in Appendix D. They are spread across a wide range of countries, with almost no overlaps by type.

Depending on the number of shared projects, two stakeholders might have one or more links between them. A table of the most linked stakeholders is in Appendix E. Among the ten most linked stakeholders, there are four collaborative pairs (Figure 15g–j). It is easier to identify collaborative pairs of stakeholders in the web interface by encoding stakeholders by type and toggling which stakeholder types are visible. The majority of most linked stakeholders are linked with their compatriots, with the exception of *binderholz* and *B&K Structures* from Austria and the UK and *Stora Enso* and *Lendlease DesignMake* from Finland and Australia.

International collaborations between stakeholders are visible when they are encoded by their nationality. In total, 45 of the 52 project islands have a consistent nationality, as shown by the representative example in Figure 15a. The most internationally connected stakeholders are those who have collaborated with stakeholders from the most countries. The most internationally connected architect, engineer, and fabricator are *Helen & Hard*, *WSP*, and *Stora Enso*, with 7, 8, and 16 countries, respectively (Figure 15d,m,f). Tables of the most internationally connected stakeholders by type can be found in Appendix F. The most internationally connected architects and engineers come from all over the world, including North America and Australia. Conversely, the most internationally connected fabricators, except for *Stora Enso*, are all from the DACH region.

3.4.3. Stakeholder Countries Network

A variant of the SN that rearranges the stakeholder nodes so that stakeholders from the same country appear close to each other in the network is called the Stakeholder Countries Network (SCN). While the SN solely uses connectivity information to lay out the network nodes (i.e., nodes placed close to each other if they are connected), the SCN also considers country information when deciding on the final placement of nodes. The SCN, therefore, further highlights international connections in the mass timber construction industry. National clusters connect to each other through the stakeholders that worked abroad and in multiple countries (Section 3.1.2. Project Locations). Stakeholders closer to the center of the chart are likely to have worked with the most international partners. The three most connected stakeholders, *Stora Enso*, *KLH Massivholz GmbH*, and *binderholz* (Table D3 and Section 3.4.2. Stakeholders Network), are close to the center of the network (Figure 16a–c). A total of 19 of the 22 countries represented in the study appear in the central cluster (all but Estonia, Lithuania, and New Zealand) (Figure 16d–f).

The stakeholder islands that appeared in the periphery of Figure 15 are now clustered, rendering visible the proportion of a country's stakeholders that formed part of the central cluster. Representative examples of this national clustering are visible in Figure 15g,h. This reinforces the findings of Figure 4 that stakeholders mostly collaborated with their compatriots. The isolation of some timber markets from the rest of the global industry is especially apparent in this view: all stakeholders from New Zealand and Liechtenstein (Figure 16e,f) had no international connections, and from Japan, only *Shigeru Ban* did (Figure 16i).

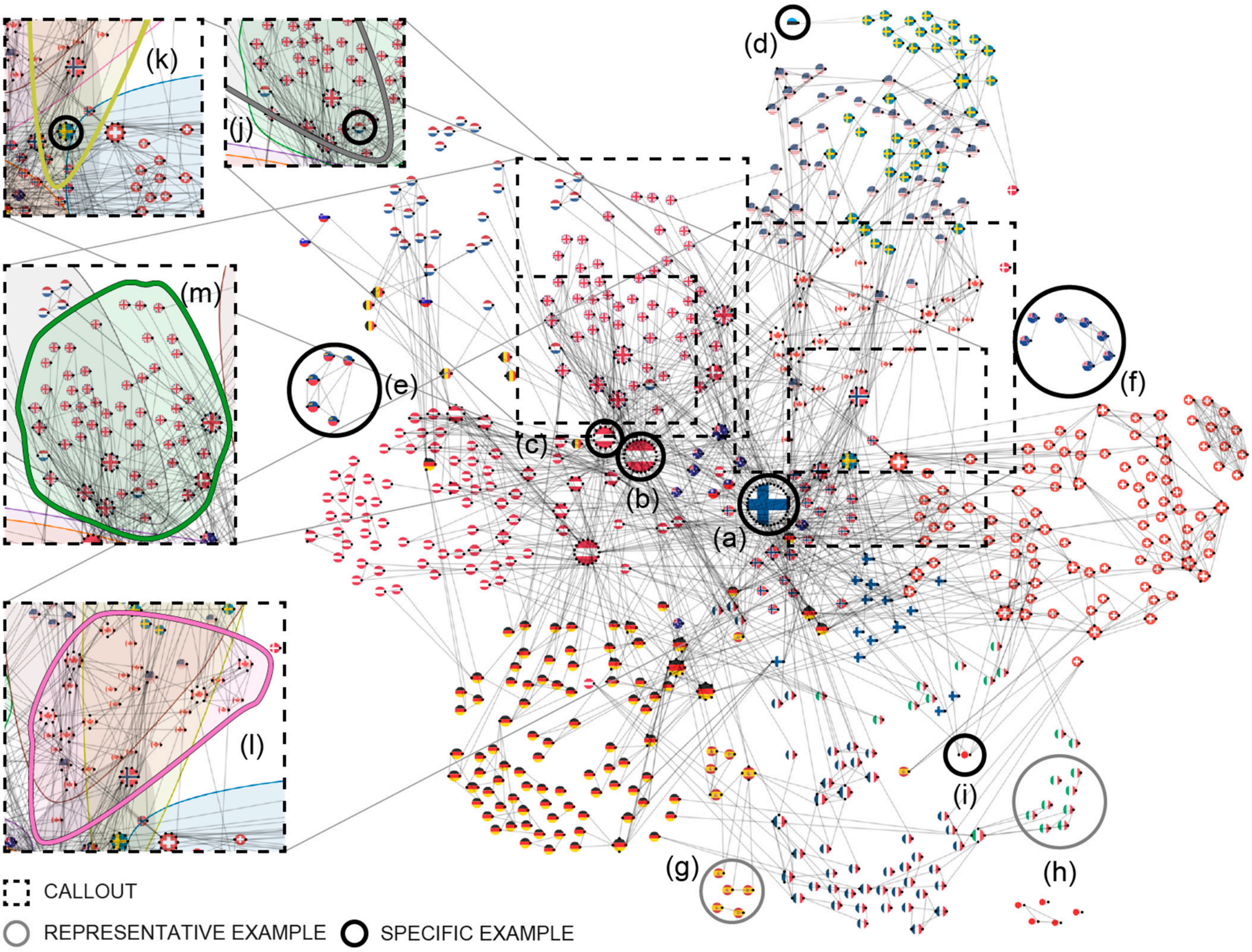

Figure 16. Stakeholders Countries Network. Projects are nodes. Flags are stakeholder headquarters locations. Colored contours bound national clusters. The force-directed layout favors national cohesion. (a) Stakeholder: *Stora Enso*. (b) Stakeholder: *KLH Massivholz GmbH*. (c) Stakeholder: *binderholz*. (d) Estonia cluster. (e) Lithuania cluster. (f) New Zealand cluster. (g) Non-international Spanish cluster. (h) Non-international Italian cluster. (i) Stakeholder: *Shigeru Ban*. (j) Stakeholder: *Arcadis*, in grey Netherlands countour. (k) Stakeholder: *Sweco*, in yellow Sweden contour. (l) Canada cluster, with pink contour. (m) United Kingdom cluster, with green contour.

Adding colored contours around national clusters helps identify the most internationally collaborative stakeholders by country: they are the ones that most deform the national clusters. Representative examples include *Arcadis* from the Netherlands (Figure 16j) and *Sweco* from Sweden (Figure 16k). Some nations' timber industries, with Canada as a representative example, are closer to the center of the network (Figure 16l) because of their propensity for working on multiple projects (42%, Figure 5) or for building abroad (47%, Figure 3a). Alternatively, representative examples like the United Kingdom (Figure 16m) or Norway are closer to the center of the network because their stakeholders worked with stakeholders from at least one other country at such a high rate: 93% and 100%, respectively.

4. Discussion

This study focuses on stakeholders who built multi-storey timber buildings, three stories and above, using mass timber. This sector of the market is centered in Europe (Figures 1 and 3). This geographic focus would be elsewhere if this study took a wider view of the timber building industry, such as shorter buildings or stick frame construction: 92% of singlefamily homes built in 2021 in the United States were wood-framed [59], compared to a fraction of that in Europe.

The data collection process used in this study will have skewed its quantitative results. Though there are known centers of research and construction in timber elsewhere in the world, such as in Chile, there is a lack of stakeholders from continental Asia, Africa, and South America. The original study [26] suffered from sampling bias due to the sources used to gather project information. Observer bias might have affected the measurement of the perceived Level of Expertise in timber, as the company names were not blinded, and the authors had prior knowledge about some of the stakeholders. The results could be distorted by omitted variable bias, as factors such as company size, number of employees, or number of offices were not accounted for in this study. Moreover, the openly accessible online data published by the stakeholders themselves might be influenced by self-serving bias since this information often serves as marketing material. An incomplete dataset also introduced analytic bias, as some information on the stakeholders was missing, especially regarding the network relationships. Furthermore, this study employed a qualitative analysis to address quantitative questions. Finally, this study is a snapshot of stakeholders at the end of 2022 based on projects built before the end of 2021. As the MsTB industry continues to change, future studies may choose to continue this observation in order to gain insight as to how the industry continues to develop and spread globally.

One of this work's main contributions is collecting data and making them available digitally. This is a starting point that enables future analysis and visualization. The various steps of processing, validation, and visualization were applied to ensure the accuracy and completeness of the data. However, the possibility of human error, which is fairly common in data collection and entry stages, cannot be eliminated. Readers are advised to verify the data sources and the visualizations for further validation. The web-based visualization provides an analysis tool that facilitates the access to and analysis of the dataset. Regardless, as stated in Section 2.1, some stakeholders who worked on projects in the survey were not captured. This missing data reflects the different priorities and policies of the stakeholders regarding information disclosure. This is particularly evident in Figure 13, which shows the inconsistency of data from before 2008. These missing stakeholders may have skewed statistical data throughout the paper.

Some trends and relations demonstrated in this study's results are corroborated by earlier research by Salvadori. In his dissertation, Salvadori establishes that "timber design knowledge is still strongly linked to timber engineers, contractors, and suppliers" [49]. This agrees with the high proportion of Specialists found in this study. Salvadori concluded that "only a few architectural offices [are] . . . capable of influencing the final outcome" of timber buildings. This may explain why so few architects worked across multiple programs and why those who did were mostly Innovative Practitioners. If architects were unable to greatly affect their buildings, the design of these buildings may have been left to engineers or fabricators, who this study shows are highly unlikely to offer Design category services. This may explain why Svatoš-Ražnjević et al. found that many of their case studies lacked architectural interest [26].

Prevalence in this study could signify the potential economic success of the stakeholders. The most prevalent stakeholders are those who are most open to collaborations, especially across borders. Sharing best practices, knowledge, and expertise internationally leads to a healthier industry that is more effective at addressing today's urban and environmental issues. Salvadori corroborates this when he concludes that "the cooperation between [stakeholders] often determines how MTBs will evolve" [49]. The positive network effect felt by prevalent stakeholders will improve as the broader construction industry builds more in timber. This growth is already underway, as the number of General Practitioners in this study demonstrates.

5. Conclusions

This study reveals patterns and trends in the MsTB industry. The fragmented and highly local nature of the industry is evident from the number and geographic distribution of stakeholders. This creates hotspots of timber knowledge, often dominated by certain players with high Levels of Expertise and numbers of projects. The DACH region, with its robust local market for timber buildings, is prevalent in this study and has the most companies working on multiple projects. Timber-building knowledge seems to come from fabricators, of whom there are fewer to begin with and who, therefore, work on more projects. This may be because MsTB construction requires high specialization and because this sector of the timber industry is still filling out. These fabricators and their high Level of Expertise are mostly located in the DACH region, with a few noteworthy exceptions in Scandinavia. High Level of Expertise fabricators work the most internationally due to the increased need for engineered timber products and assembly knowledge. The high proportion of Innovative fabricators, 20%, when compared to architects and engineers, indicates that they are leading the MsTB industry forward. Regardless, although MsTB construction is relatively digitized when compared to conventional steel or concrete construction, a low proportion of timber construction is highly automated.

There is an uneven distribution of Level of Expertise between stakeholder types in certain geographies. Regardless, Innovative designers work on geometrically challenging projects at the same rate as Innovative fabricators do, regardless of where they are. Design expertise is more evenly distributed globally, though it still, like this study, has a European focus. The high proportion of General stakeholders and the trend towards proportionally fewer Specialist stakeholders in recent years indicates the increased interest of the larger AEC industry in timber construction. The high number of services in secondary Service Categories highlights just how much of the work carried out in the AEC industry takes place around or off the building site.

This study evaluates hundreds of international stakeholders based on a newly developed classification of the perceived level of timber expertise. This classification helps show that stakeholders with a high level of expertise in timber construction have the most impact on the MsTB industry, both through the complexity of the buildings they design and the networks of stakeholders they collaborate with. This study suggests that increased collaboration and knowledge sharing among stakeholders across regions and disciplines in the face of a fragmented industry fosters innovation. It also shows that there is a gap between design and fabrication expertise in some regions, which may affect the quality of timber buildings without further international collaboration. Finally, it highlights the need for more timber fabricators worldwide, lest the environmental advantages of timber be undermined by international logistics. Because of their effect on the industry, a future study could focus on fabricators' business models and fabrication setups and how they relate to the buildings they produce.

Supplementary Materials: The network diagram derived from the Stakeholder in Multi-Storey Timber dataset can be accessed at https://archstakeholders.github.io/ (accessed on 20 April 2023).

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Data Availability Statement: The Multi-Storey Timber Buildings dataset from which the stakeholders were collected can be downloaded at DOI: 10.18419/darus-2733 (accessed on 14 August 2023). The dataset containing the complete list of Stakeholders in Multi-Storey Timber can be downloaded at DOI: 10.18419/darus-2740 (accessed on 14 August 2023).

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Appendix A

International Stakeholders

Table A1. Most international architects.

ID	Name	Country	City	LoE	# of Projects	# of Proj. Countries
259	Hermann Kaufmann + Partner ZT GmbH	AT	Schwarzach	Inn	6	3
311	Jean-Paul Viguier	FR	Paris	Eme	4	2
400	Michael Green Architects	CA	Vancouver	Sta	4	2
180	dRMM	GB	London	Inn	3	2
453	Perkins & Will	US	Chicago	Eme	3	2
212	Fokkema & Partners	NL	Delft	Gen	2	2

Table A2. Most international engineers.

ID	Name	Country	City	LoE	# of Projects	# of Proj. Countries
634	WSP	CA	Montreal	Gen	7	5
398	Merz Kley Partner	AT	Dornbirn	Inn	17	3
457	Pirmin Jung	CH	Rain	Sta	10	3
356	Lendlease DesignMake	AU	Melbourne	Gen	7	3
196	Equilibrium Consulting	CA	Vancouver	Sta	5	3
64	ARUP	GB	London	Gen	4	3

Table A3. Most international fabricators.

ID	Name	Country	City	LoE	# of Projects	# of Proj. Countries
555	Stora Enso	FI	Helsinki	Inn	35	12
334	KLH Massivholz GmbH	AT	Teufenbach	Sta	25	9
99	binderholz	AT	Fügen	Sta	13	7
248	Hasslacher Norica Timber	AT	Sachsenburg	Inn	5	4
394	Mayr-Melnhof Holz	AT	Leoben	Inn	8	3
631	Woodcon	NO	Brumunddal	Sta	8	3
646	Züblin Timber	DE	Stuttgart	Inn	8	3
328	Kaufmann Bausysteme	AT	Reuthe	Sta	6	3
186	Egoin	ES	Bilbao	Sta	4	3
260	Hess Timber	DE	Kleinheubach	Inn	4	3
503	Rubner Holzbau	IT	Kiens	Sta	4	3
627	Wiehag	AT	Altheim	Sta	3	3

Appendix B

Prolific Stakeholders

Table A4. Most prolific architects.

ID	Name	Country	City	LoE	# of Projects
616	Waugh Thistleton Architects	GB	London	Inn	9
259	Hermann Kaufmann + Partner ZT GmbH	AT	Schwarzach	Inn	6
321	Kaden + Lager	DE	Berlin	Inn	5
254	Helen & Hard	NO	Oslo	Sta	4
311	Jean-Paul Viguier	FR	Paris	Eme	4
315	Johannes Kaufman Architektur	AT	Dornbirn	Sta	4
400	Michael Green Architects	CA	Vancouver	Sta	4

Table A5. Most prolific engineers.

ID	Name	Country	City	LoE	# of Projects
398	Merz Kley Partner	AT	Dornbirn	Inn	17
457	Pirmin Jung	CH	Rain	Sta	10
85	bauart Konstruktions	DE	Lauterbach	Sta	8
564	Sweco	SE	Stockholm	Gen	8
356	Lendlease DesignMake	AU	Melbourne	Gen	7
471	Price & Myers	GB	London	Gen	7
484	Ramboll	DK	Copenhagen	Gen	7
634	WSP	CA	Montreal	Gen	7

Table A6. Most prolific fabricators.

ID	Name	Country	City	LoE	# of Projects
555	Stora Enso	FI	Helsinki	Inn	35
334	KLH Massivholz GmbH	AT	Teufenbach	Sta	25
99	binderholz	AT	Fügen	Sta	13
198	Eurban	GB	London	Inn	11
406	Moelven	NO	Moelv	Sta	10

Appendix C

Application User Guide

Figure A1 shows screenshots of the user interface and the effects of changing various parameters.

The "Graph Type" dropdown list (Figure A1a) changes the network's arrangement between five options. The options are

- "Projects NL", which shows the projects as ring nodes (Figure A1n). Projects each appear once. Stakeholders appear as circles on the ring node of the projects they worked on. Projects become connected when they share one or more stakeholders. In that case, links are drawn as straight lines to connect the same stakeholders on each ring node;
- "Stakeholders NL", which shows the stakeholders as nodes and projects as the black dots attached to the nodes (Figure A1g). The size of the node represents how many projects each stakeholder worked on. The "Show Ring Connectors" button toggles the visibility of project dots attached to the stakeholder node (Figure A1d,e);
- "Stakeholders NL (group by country)" is a variant of the "Stakeholders NL" where the nodes are rearranged so that stakeholders from the same country are placed close to each other. The "Show Contours" button toggles the visibility of contours that highlight each country's stakeholders (Figure A1j,k) based on the Gimenez grouping layout [58];

- "Stakeholders GeoMap" shows the location of all stakeholders on a world map (Figure 1). For each location, a brown circle is drawn to signify the existence of one or more stakeholders in that location (Figure A1l). The size of the circle reflects the total number of stakeholders in each location. By default, the circle counts stakeholders regardless of type. However, when the "Color by Stakeholder type" button is toggled, each location receives one, two, or three colored circles depending on the number of stakeholders by type at each location (Figure A1m);
- "Projects GeoMap" shows the location of all projects on a world map. For each location, a brown circle is drawn to signify the existence of one or more projects in that location. The size of the circle reflects the total number of projects in each location.

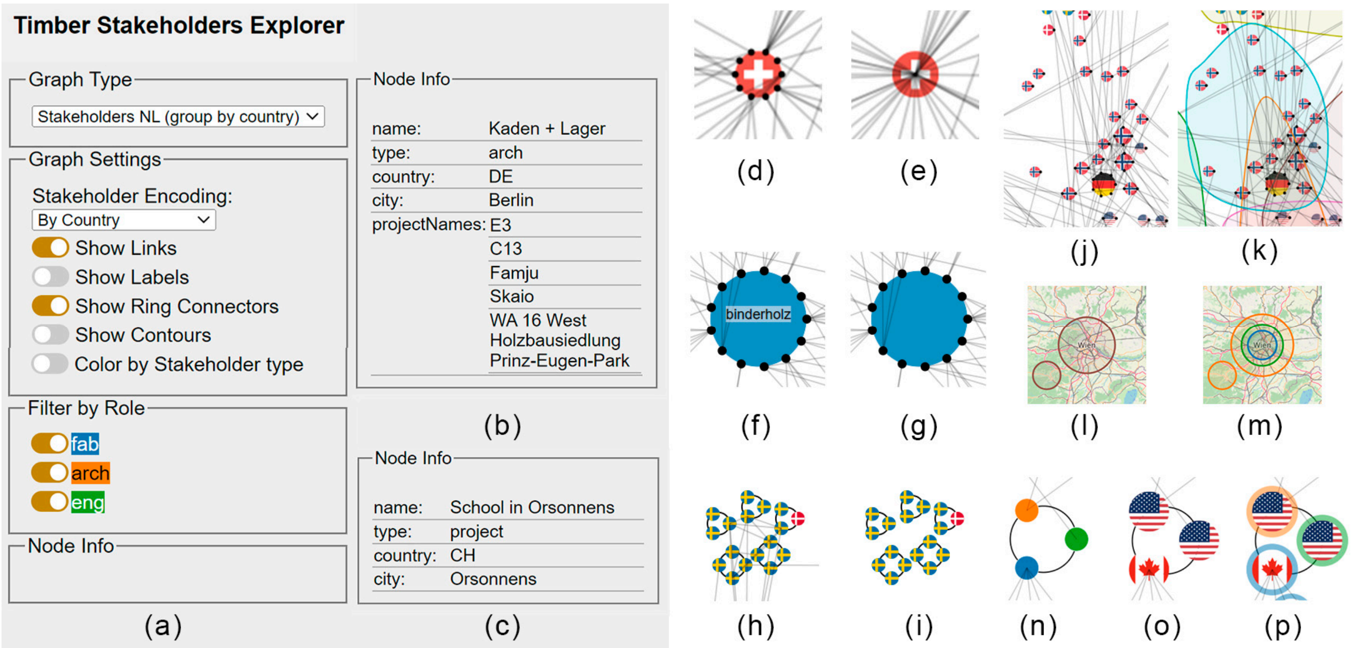

Figure A1. Timber Stakeholders Explorer user interface. (**a**) Graph controls, including Graph Type, Graph Settings, Filtering, and empty Info Panel. (**b**) Info Panel showing example stakeholder information. (**c**) Info Panel showing example project information. (**d**) Stakeholder node with Ring Connectors. (**e**) Stakeholder node without Ring Connectors. (**f**) Stakeholder node with Label. (**g**) Stakeholder node without Label. (**h**) example Project cluster with Links. (**i**) example Project cluster without Links. (**j**) SCN without Contours. (**k**) SCN with Contours. (**l**) Stakeholders GeoMap without Color by Stakeholder Type. (**m**) Stakeholders GeoMap with Color by Stakeholder Type. (**n**) Stakeholder Encoding by Type. (**o**) Stakeholder Encoding by Country. (**p**) Stakeholder Encoding Both (Type and Country).

Depending on the selected graph type, the settings panel on the left shows different options (Figure A1a). For example, when the users select "Stakeholder NL" from the "Graph Type" dropdown list, the "Stakeholder Encoding" dropdown list provides three options to visually encode the stakeholders: color-coded based on their type (Figure A1n), flag-coded based on their nationality (Figure A1o), or both a flag and a color-coded (Figure A1p). The "Show Links" button toggles the visibility of the network links (Figure A1h,i). The "Show Labels" button toggles the visibility of names on the graph nodes (Figure A1f,g). The "Filter by Role" buttons toggle the visibility of each stakeholder type.

Mousing over the network graph applies a lens effect to aid with navigation and legibility. Clicking on a node displays information about that node underneath the settings panel on the left side of the window, whether it is a stakeholder (Figure A1b) or a project (Figure A1c).

Appendix D

Interconnected Stakeholders.

Table A7. Most interconnected architects.

ID	Name	Country	City	LoE	# of Projects	# of Connections	# of Connection Countries
254	Helen & Hard	NO	Oslo	Sta	4	19	7
616	Waugh Thistleton Architects	GB	London	Inn	9	18	4
49	Archobau	CH	Chur	Gen	2	15	3
259	Hermann Kaufmann + Partner ZT GmbH	AT	Schwarzach	Inn	6	14	3
509	SAAHA architects	NO	Oslo	Gen	1	11	4

Table A8. Most interconnected engineers.

ID	Name	Country	City	LoE	# of Projects	# of Connections	# of Connection Countries
398	Merz Kley Partner	AT	Dornbirn	Inn	17	38	4
457	Pirmin Jung	CH	Rain	Sta	10	35	6
564	Sweco	SE	Stockholm	Gen	8	24	5
634	WSP	CA	Montreal	Gen	7	19	8
196	Equilibrium Consulting	CA	Vancouver	Sta	5	19	6
471	Price & Myers	GB	London	Gen	7	18	5

Table A9. Most interconnected fabricators.

ID	Name	Country	City	LoE	# of Projects	# of Connections	# of Connection Countries
555	Stora Enso	FI	Helsinki	Inn	35	93	16
334	KLH Massivholz GmbH	AT	Teufenbach	Sta	25	69	14
99	binderholz	AT	Fügen	Sta	13	50	10
406	Moelven	NO	Moelv	Sta	10	36	6
646	Züblin Timber	DE	Stuttgart	Inn	8	29	8

Appendix E

Linked Stakeholders

Table A10. Most linked stakeholders.

ID	Type	Name	LoE	# of Projects	Link #	Link ID	Link Name	LoE
555	fab	Stora Enso [1]	Inn	35	8	631	Woodcon [1]	Sta
631	fab	Woodcon [1]	Sta	8	8	555	Stora Enso [1]	Inn
198	fab	Eurban	Inn	11	6	555	Stora Enso	Inn
398	eng	Merz Kley Partner [2]	Inn	17	5	259	Hermann Kaufmann + Partner ZT GmbH [2]	Inn
259	arch	Hermann Kaufmann + Partner ZT GmbH [2]	Inn	6	5	398	Merz Kley Partner [2]	Inn
99	fab	binderholz [3]	Sta	13	5	77	B&K Structures [3]	Sta
77	fab	B&K Structures [3]	Sta	9	5	99	binderholz [3]	Sta
429	fab	Nordic Structures [4]	Inn	7	5	205	FGP Construction [4]	Inn
205	fab	FGP Construction [4]	Inn	5	5	429	Nordic Structures [4]	Inn
356	eng	Lendlease DesignMake	Gen	7	5	555	Stora Enso	Inn

[1] Stora Enso and Woodcon are a collaborative pair, as shown in Figure 15i; [2] Merz Kley Partner and Hermann Kaufmann + Partner ZT GmbH are a collaborative pair, as shown in Figure 15g; [3] binderholz and B&K Structures are a collaborative pair, as shown in Figure 15j; [4] Nordic Structures and FGP Construction are a collaborative pair, as shown in Figure 15h.

Appendix F

Internationally Connected Stakeholders

Table A11. Most internationally connected architects.

ID	Name	Country	City	LoE	# of Projects	# of Connections	# of Connection Countries
254	Helen & Hard	NO	Oslo	Sta	4	19	7
596	Tzannes	AU	Sydney	Gen	2	6	6
212	Fokkema & Partners	NL	Delft	Gen	2	10	5
180	dRMM	GB	London	Inn	3	9	5
24	Aimeric Audebeau	FR	Paris		1	8	5
530	SF Design	FR	Paris	Gen	1	8	5
81	BAS Arkitekter	NO	Sarpsborg	Gen	2	7	5

Table A12. Most internationally connected engineers.

ID	Name	Country	City	LoE	# of Projects	# of Connections	# of Connection Countries
634	WSP	CA	Montreal	Gen	7	19	8
356	Lendlease DesignMake	AU	Melbourne	Gen	7	17	8
19	AECOM	US	Los Angeles	Gen	3	11	8
457	Pirmin Jung	CH	Rain	Sta	10	35	6
196	Equilibrium Consulting	CA	Vancouver	Sta	5	19	6
484	Ramboll	DK	Copenhagen	Gen	7	15	6

Table A13. Most internationally connected fabricators.

ID	Name	Country	City	LoE	# of Projects	# of Connections	# of Connection Countries
555	Stora Enso	FI	Helsinki	Inn	35	93	16
334	KLH Massivholz GmbH	AT	Teufenbach	Sta	25	69	14
99	binderholz	AT	Fügen	Sta	13	50	10
260	Hess Timber	DE	Kleinheubach	Inn	4	23	9
646	Züblin Timber	DE	Stuttgart	Inn	8	29	8

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