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Trajectories from standard to incremental and pioneering innovation in timber construction: multi-storey timber buildings in Germany, Austria, and Switzerland

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ABSTRACT

This article examines innovation trajectories in multi-storey timber design and construction in the DACH region (Germany, Austria, and Switzerland) and the factors influencing them. The DACH region is at the forefront of timber innovation due to long-standing traditions in carpentry and timber construction, the development of pioneering products and projects, and the availability of fabrication facilities and wood resources. Combining an architectural design survey of 99 multi-storey buildings and the related timber building systems, an actor-networks analysis, and stakeholder interviews, the paper identifies three innovation trajectories: (1) standard innovation, (2) incremental innovation, and (3) pioneering innovation in timber construction. The results show the growth and prevalence of the incremental innovation trajectory across DACH due to the relatively low, efficiency-driven levels of digitalization in practice and an overwhelming variety of timber products as the main barriers to the wider adoption of the other trajectories.

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Introduction

Reduction of energy consumption and greenhouse gas emissions have become a priority for the construction sector as one of the world's largest consumers of energy and natural resources, calling for a more sustainable building culture. Simultaneously, urbanization and increased housing demand due to world's population growth demand more efficient design and construction processes. One answer to these issues, discussed in scientific literature and policy proposals (Churkina et al., 2020; Mishra et al., 2022), is increasing the use of renewable materials such as timber in multi-storey construction. Timber construction and multi-storey timber buildings (MSTBs), in particular, are regarded as relevant undertakings in the sustainable transition of architecture and construction. Additionally, timber construction is considered a forerunner in adopting digital technologies and automation (Bianconi & Filippucci, 2019).

Despite a long history of timber use in low-rise construction, MSTBs have experienced an increase in construction globally only in the last two decades, owing to advances in digital technology and engineered timber products, improved fire protection and acoustic qualities, changes in regulations, and growing public interest in

sustainability (Kuzmanovska et al., 2018; Salvadori, 2021). Germany, Austria, and Switzerland, also known as the DACH region, take up a key role in timber construction innovation due to long-standing timber construction and carpentry traditions, development of pioneering products and projects, higher number of fabrication facilities, and availability of local wood supplies. Today, the region accounts for 70% of the global production of cross-laminated timber (CLT) panels (Muszynski et al., 2020) and the majority of glulam production in Europe (Holzkurier, 2020), while several MSTBs built in the early 2000s acted as demonstrators for building code amendments. Even with the region's significance in timber construction and the increasing demand for sustainable buildings, local production of MSTBs is comparatively low (Kind et al., 2022). Additionally, previous research shows that the design of MSTBs remains limited architecturally as most building designs favour regular building typologies and hybrid structures despite a wide variety of engineered timber products and digitally enhanced design and fabrication processes (Salvadori, 2021; Svatoš-Ražnjević et al., 2022; Žegarac Leskovic & Premrov, 2021).

So far, each pilot project and taller timber construction are considered a breakthrough with innovation potentials

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in resolving fire resistance, acoustic properties, price, optimizing prefabrication, or controlling waste generation (Švajlenka & Pošiváková, 2023). Hence, suggesting that most MSTB developments are emerging innovations in themselves. At the same time, few studies have explored MSTBs as an innovation in the transition of architecture and construction to more sustainable practices from an architectural design and socio-organizational perspective (e.g. Fleming et al., 2014; Mahapatra & Gustavsson, 2008; Toivonen et al., 2021; Wiegand & Ramage, 2022; Xia et al., 2014). Further, given the role of the DACH region and its socio-technical contribution to timber architecture and construction innovation, it remains unexplored.

Understanding innovation in the built environment entails broadening perspectives through architectural, sociological and policy research to move away from traditional conceptualizations of linear, technology-driven and cost-benefit innovation models (Harty, 2005; Sage et al., 2021; Whyte & Sexton, 2011). Following science and technology studies and actor-network theory approaches to innovation (Akrich et al., 2002a, 2002b; Callon, 1986; Irwin, 2023), we understand innovation as dynamically co-produced by social and technical factors instead of only progressing according to market rules. Several studies on innovation in architecture and construction have emphasized the tight coupling of design, technical aspects and their socio-material and organizational structuring: for instance, the relevance and presence of tacit and context-specific knowledge in digital design and construction (Andersson & Eidenskog, 2023; Muldoon-Smith et al., 2021); the co-production of market standards and sustainability policies (Cass, 2018; Georg, 2015; Sage et al., 2021); or the expected path dependencies and actor implications due to BIM technology convergence (Boeva et al., 2024; Dainty et al., 2017).

Against this background, the aim of our study is to contribute to the existing analyses by exploring timber construction innovation trajectories on the basis of built MSTBs in DACH countries and the conditions informing those over the last 20 years. Innovation trajectories are shaped not only by technological developments but by the socio-cultural, regulative, and economic contexts in which they are co-constructed. Therefore, this paper combines architectural and social science perspectives and presents a qualitative, empirical analysis of the unfolding socio-technical transitions to more sustainable design and construction. It addresses the following research questions: What are the identifiable innovation trajectories of MSTBs in the DACH region? What factors (actor-networks, drivers, barriers) influence the trajectories? How are factors and trajectories interlinked? By examining the variety of

social, technical, and material factors, their dynamics and interactions, along with stakeholder perspectives on what drives or hinders developments, this study advances the understanding of MSTBs as an innovation.

Background literature and context

Stakeholder perspectives on multi-storey timber construction

The social studies turn in construction innovation has turned attention to the sector's stakeholders with 'their choices and motivations and the processes of taking up and using new technologies' by reviewing different complementary strands of theoretical frameworks from the sociology of technology and work, social practice theory, innovation theory, and science and technology studies (Whyte & Sexton, 2011, p. 480). Therefore, our literature review on MSTBs as an innovation focuses on stakeholder motivations and awareness about timber use and developments, user participation in innovation, actor-networks, institutional practices and policy measures, as well as studies with a DACH focus. While we acknowledge the relevance and intersection with studies exploring approaches such as business ecosystems and business models for industrialized timber construction highlighting costs as a barrier and higher levels of efficiency through strategic product-orientation (Brege et al., 2014; Lessing, 2015; Toppinen et al., 2022), or single case studies of MSTB innovation diffusion (Lindgren & Emmitt, 2017), particularly in the Nordic countries, we also discern noteworthy differences in the DACH construction sector's size, structure, heterogeneity, and traditions. Hence, a close comparison between these regions is beyond the scope of both paper's literature review and analysis.

As research on MSTBs keeps growing, more studies are exploring their uptake, barriers, and stakeholder experiences. Most studies on the socio-technical conditions of timber construction industry come from the Nordic countries due to earlier changes in building code enabling taller construction and wood's sociocultural significance in local design and architecture (Hemström et al., 2011; Jussila et al., 2022; Kylkilähti et al., 2020; Lindgren & Emmitt, 2017; Mahapatra & Gustavsson, 2008; Roos et al., 2010). A recent literature review-based study of 42 articles on MSTB development validates that: 37 articles concerned the Nordic countries, while only eight explored other areas (Jussila et al., 2022). This also reconfirms the need to broaden the geographical studies and research perspectives on MSTBs as innovations towards more sustainable architecture and construction.

Drawing on stakeholder interviews and surveys, several research papers continuously point out that lack of user knowledge and experience is a significant barrier to multi-storey timber construction despite the increased timber products availability and regulation changes (Mahapatra & Gustavsson, 2008; Markström et al., 2019; Riala & Ilola, 2014). Moreover, path dependencies such as user practices and traditions of building with concrete in multi-storey buildings or perceptions about timber's engineering properties, such as acoustics and fire safety, influence local architects and engineers' selection of construction materials (Hemström et al., 2011; Hurmekoski et al., 2015; Roos et al., 2010). In their critical review of mid- and high-rise timber buildings, Fleming et al. (2014) argue that such projects showcase that design with timber is pursued as if it were concrete or steel rather than designing with its inherent properties. Similar results can be found in interview- and survey-based studies with timber professionals in Finland (Karjalainen & Ilgin, 2021; Riala & Ilola, 2014), Australia (Marfella & Winson-Geideman, 2021; Xia et al., 2014), and Canada (Gosselin et al., 2016). Public perception of timber as an appropriate construction material compared to concrete or steel and lack of public awareness about MSTBs are also shown to hold back its diffusion in Europe (Dumler et al., 2020; Nyrud et al., 2024; Petruch & Walcher, 2021; Savolainen et al., 2022).

Main measures to counter barriers to timber construction's further development identified in this scholarship include changes to construction sector education, professionals' re-training, creation of information and exchange platforms on regulation, timber products, and fabricator networks, as well as economic and political incentives such as different taxation of materials and policies. Sectoral policy instruments and the regulatory context can shape both innovation and uptake of MSTBs. In their analysis of connections between policies and MSTBs, Wiegand and Ramage (2022) point out that only through a combination of different policy instruments (i.e. regulatory, economic, information, or voluntary types), MSTB projects are accomplished, while simultaneously each projects' development co-shapes policies and building code amendments. Interestingly, implemented policies in Austria influencing developments are either regulatory or voluntary, whereas economic, voluntary, and R&D measures prevail in Germany (ibid.). These instruments are not mutually exclusive but support each other's formation; for example, economic ones, such as subsidies, fund R&D ones, such as fire performance tests and simulations. Municipalities may also act as intermediaries in implementing policies to champion sustainability transitions and promote MSTBs for urban

densification through instruments such as building codes, zoning laws, or land-use plans, thereby shaping innovation trajectories (Lähtinen et al., 2019; Salmi et al., 2022; Viljanen et al., 2023).

Discourse and narratives affect innovation trajectories, too. Toivonen et al. (2021) identify four policy narratives of MSTBs (bioeconomy, wood industry, climate change, counter-narrative) to understand how they foster the innovation system by interviewing Finnish policymakers and public administrators. Despite three of the narratives being 'pro-wood', their differences and some incompatibilities in goals, measures, and challenges indicate reasons for the variations in MSTBs' uptake and trajectories applicable to other European contexts (ibid.). Similar results have been found in a comparative analysis of German and French timber discourses (Mast, 2022).

Research on MSTB developments in the DACH region regarding the uptake of timber construction, stakeholder experience, and requirements remains limited. While DACH countries have been included in multinational research studies on policies (Wiegand & Ramage, 2022), global actor-network analyses of MSTB projects (Salvadori, 2021), timber manufacturer perspectives on practice (Ilgin et al., 2024), market potentials (Hurmekoski et al., 2015), and public perceptions (Nyrud et al., 2024; Petruch & Walcher, 2021), they have rarely been studied individually or as a region, despite their strong presence as material supplier and timber technology developers.

By far, the most holistic study on timber construction in urban contexts in Germany provides an overview of the status quo and perspectives regarding trends, drivers, barriers, and the sector (Kind et al., 2022). This government-commissioned report highlights that the higher degree of preplanning, shifts in the design and fabrication process, and recent material price increases due to exogenous factors strongly influence the market entrance of mineral-based competitors into the MSTBs domain and the increase of timber hybrids. The challenges regarding early preplanning and process reorganization are reaffirmed by the results of a research project on BIM's role in timber construction in Germany (Kaufmann et al., 2019).

Research on innovation dynamics in the Austrian MSTB landscape is marginal. We identified only one research study exploring barriers and drivers based on interviews with local timber construction actors (Santana-Sosa & Kovacic, 2022). The results reveal similar patterns to Germany's perspectives. Apart from historical studies on timber materials or MSTB development (Adam, 2023; Wiederkehr, 2010), structural design-related studies aspects (Smith & Frangi, 2014), and

industry reports (e.g. Holzbau Schweiz, 2023), we could not identify scholarly research on contemporary timber construction transitions in Switzerland. This might be explained by their established and densely located timber actor-networks and more precedent projects, as we illustrate later in the analysis.

Timber innovations in Germany, Austria, and Switzerland

Since the early low-rise projects, multi-storey timber construction in the DACH region has reached new heights (Figure 1), partly due to the high level of timber expertise of local fabricators, the strong position of local stakeholders as global suppliers, and the construction of exemplary projects made possible due to ‘two centuries of [continued] EWP development and practice’ (Salvadori, 2021, p. 46).

The DACH region has a long-standing carpentry tradition and a maintained practice of timber construction, from early post-and-beam and ‘blockbau’ log houses to half-timbered construction (Dangel, 2009; Klein & Grabner, 2015). Sixteenth-century innovations in Germany of dividing vertical stilts enabled taller half-timber construction and transformed the role of the carpenter as it required a high level of advanced planning (Winter, 2002; Zügner, 2013). Despite industrialization bringing changes in production processes and timber’s replacement by other materials, timber construction in the region continued as timber products were modernized. In 1901, Otto Hetzer, the father of modern glulam, developed a patent for glued timber boards, while around 1920, two German companies – Deutsche Werkstätte Hellerau and Christoph & Unmack – started developing a new panel construction system, later simplified and standardized into early modern panel construction by Konrad Wachsmann (Müller, 2004; Sumi, 2007; Winter, 2002).

The development of two other Engineered Wood Products (EWPs), Dowel-Laminated Timber (DLT) and Cross-Laminated Timber (CLT), also showcases

this continuation. In the 1980s, German engineer Julius Natterer and his research at the Institute for Timber Construction (IBOIS), EPFL (Lausanne), led not only to the precursor of DLT panels but also formed the basis of hybrid floor slabs (Falk, 2005). A major impact on timber construction was the introduction of CLT in Austria and Germany in the 1990s, as it enabled greater material homogeneity, anisotropy, higher performance, and planarity of elements (Kaufmann et al., 2018; Quesada-Pineda et al., 2018). Its development resulted from combined research and industry efforts, particularly sawmills, to create products from low-quality leftover material (Brandner, 2013). Although there are different precursors of CLT globally, similar products were produced in the DACH countries.¹ Due to these developments and the availability of local resources and forest reserves, the DACH region maintains numerous timber production facilities. There are, of course, differences: Austria produces about two-thirds of CLT’s worldwide volume (Brandner, 2013), while Switzerland relies on local products, has low CLT production compared to Austria, and developers prefer glue-laminated timber (GLT)-based products (Salvadori, 2021).

These innovations were also accompanied by investment in automation technologies, starting in the 1980s with large-scale CNC cutting providing high precision, image-based quality assurance, and CT scanning (Vogel-Heuser, 2009). Technology investments continue today with construction start-ups like Gropys, CREE Buildings, Timbatec, or Design-to-Production, specializing in automated manufacturing and digital transformation.

Timber innovation in the region and the development of multi-storey timber construction are further accomplished through different networks and institutional frameworks shaping policies. Through changes in building regulations, several three-storey timber projects were built in the 1990s. Their success started off the promotion of timber with architects like Hermann Kaufmann and Hubert Rieß playing pioneering roles

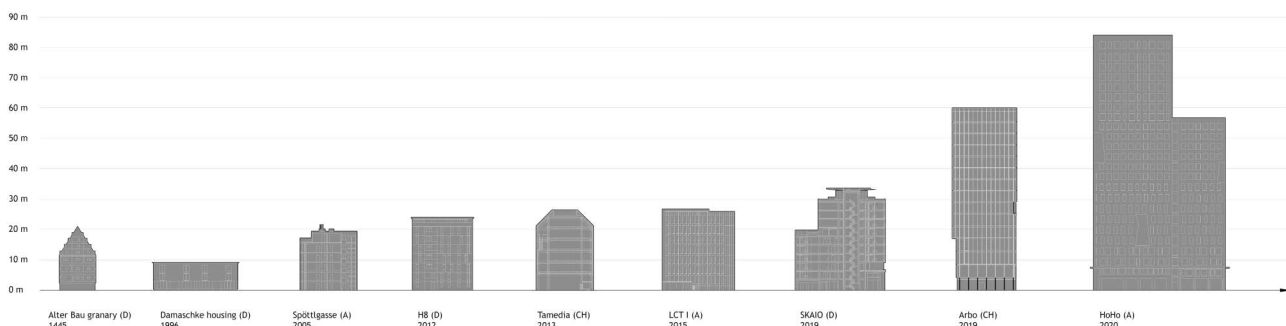


Figure 1. Development of multi-storey timber projects (selection).

Table 1. Fire regulations across DACH Region.

	Germany (D) Baden-Württemberg*	Austria (A)	Switzerland (CH)
Fire protection regulations, standards and directives	LBO BW § 26 Absatz 1,2	OIB guidelines	VKF 1–15 VKF 10–15, 28–15 SIA 265 (2012)
Prescribed number of stories or height (m)	5–6 13 m	≤ 6 (2015/17)	≤ 8 (since 2015) 30m
Timber fire rating (time) for mid-rise buildings	F 60–90	Structure R 90 and A2 R60–R120	Structure R 60 Sprinkler system R 30 Escape routes REI 60
Performance-based number of stories	no limit	no limit	no limit
Additional requirements	All building approvals discussed with the local authority, tests related to fire and building code standards	> 6 stories, proof of fire concept and level of protection, sprinklers in higher buildings	> 30 m K30-RF1 protection

Fire safety building heights in 2019. Sources: Interkantales Organ Technische Handelshemmnisse, 2015; Mayo, 2015; Mikkola, 2019; Ministerium für Wirtschaft, Arbeit und Wohnungsbau Baden-Württemberg, 2020; Österreichisches Institut für Bautechnik, 2019; Östman, 2022.

*Due to the building code variations in each federal state, we take Baden-Württemberg as example.

(Bogensberger, 2018; Zügner, 2013), while in the early 2000s, building code regulations were amended to allow greater heights with succeeding pilot projects, illustrating the importance of these projects as mechanisms of innovation and knowledge profusion.² Today, the main differences between countries' restrictions are the permissible number of storeys and visible wooden surfaces (Dumler et al., 2020; Östman et al., 2010; see Table 1).

Different lobby organizations (i.e. Timber Construction Europe, Swiss Wood Innovation Network, Holzforschung Austria, proHolzBW) continue promoting

and supporting timber development. At the same time, transnational research projects such as leanWood focus on optimizing organization and cooperation processes in timber construction (Schuster & Stieglmeier, 2018). While many timber construction programmes exist in Austria and Germany, multi-storey timber development is not promoted per se by public policy in Switzerland (Leyder et al., 2021). However, sustainability goals, climate protection policies, and different R&D programmes are strongly present across the DACH region, as well as country and regional building code differences (Tables 1 and 2).

Table 2. Policies, programmes, and sustainability certifications.

	Germany (D)	Austria (A)	Switzerland (CH)
Regional differences in building code	Yes (federal state level, 16)	Yes (federal state level, 9)	Yes (cantonal level, 26)
Timber-specific policies	<i>Holz Innovativ Programme</i> (Baden-Württemberg) <i>Berlin baut mit Holz</i> (Berlin) <i>IFB Hamburg</i> (Hamburg Investment and Promotional Bank) <i>Zusatzdarlehen Bauen mit Holz</i> (North Rhine-Westphalia)	<i>Holzbau in der Stadt</i> (Vienna, 2013, 2019) <i>Austrian Forest Strategy 2020+</i>	<i>Wood Resouce Policy</i> <i>Wood Action Plan 2021–2026</i>
Climate protection policies	<i>Climate Action Plan 2050</i> <i>Charter for Wood 2.0</i> <i>Klimabündnis Bauen in Rheinland-Pfalz – nachwachsende und kreislauffeffiziente Rohstoffe stärken</i>	<i>Bioökonomie-FTI-Strategie für Österreich 2018</i> <i>New Austrian bioeconomy strategy</i> (2019) <i>Klimaaktiv</i>	<i>2000-watt requirements</i> (Zürich, 2005)
R&D programmes	<i>From military wasteland to zero emission</i>	<i>Haus der Zukunft</i> (1999) <i>Smart City Vienna</i>	<i>National Research Programme NRP 66</i>
European Construction Product Regulation (EU Bauproduktrichtlinie) European Energy Performance of Building Directive (EU Gebäuderichtlinie) (EPBD) EU New Green Deal European Wood Policy Platform (woodPoP, 2022)			
Campaigns and interest groups	<i>Holzbau-Offensive</i> (Baden-Württemberg)	Proholz Austria	Swiss Wood Innovation Network
Sustainability certifications	Qualitätssiegel Nachhaltiges Gebäude (QNG) Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)	Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB through ÖGNI) PEFC Programme for the Endorsement of Forest Certification (PEFC)	Minergie Standard

Sources: Kollar, 2014; Mayo, 2015; Salvadori, 2021; Vihemäki et al., 2019, as well as the websites of certification organizations (<https://www.qng.info/>, <https://www.dgnb.de/en/dgnb/about-dgnb>, <https://www.ogni.at/projekte/page/29/?cn-reloaded=1>).

Methods and materials

The paper combines two analytical perspectives: an *architectural analysis* of multi-storey timber buildings (MSTBs) and a *social science analysis* of stakeholders' positions on current developments (Figure 2). The architectural analysis consists of a survey of 99 MSTBs in Germany, Austria, and Switzerland, built between 2004 and 2024, and the stakeholders involved in their design and construction (Figure 3). The social science analysis on stakeholder positions includes twelve semi-structured interviews with timber experts from the region, conducted between May 2020 and November 2021, and a group discussion from a stakeholder workshop in June 2022 based on the initial results of both analyses. Preliminary results were jointly analyzed after the initial data collection and individual disciplinary analyses.

For the architectural analysis, the first author systematically surveyed architectural variety and spatial possibilities in current serial and modular MSTBs on 350 international projects (Svatoš-Ražnjević et al., 2022). From this initial list, projects were filtered based on their location (126 in DACH region), height (99 with four storeys and above), and construction status (92 designed and built). After the initial screening, projects were eliminated based on the completeness of data and available project documentation (85). Another survey was conducted to update the data; thirteen additional

projects with sufficient technical documentation that fulfil the above criteria were added to the dataset, while one project was re-added to it as construction was completed in 2024 (99 in total).

Relevant data for analysis were project location, construction year, programme, type of timber structural system, the range of EWPs and non-timber materials used for the structure, classification of the design based on the form of the massing, and the organization principle of the floorplan. A total of 254 project stakeholders, their roles on the project as architects, engineers, timber engineers, general contractors, fabricators, and timber suppliers, the client type (public or private) and, when available, the motivation for the use of timber (e.g. sustainability) provided background data on involved companies and organizational interactions among them. Survey data were limited to publicly available materials and information in technical reports, books, papers, mass timber building databases, and project and stakeholder websites. Data for each project were triangulated across a variety of sources. In cases of contradicting data, the information from the technical documentation, i.e. detail sections, served as the primary source.

The second author conducted interviews to analyze stakeholder positions on current developments in the region. Interviewees were identified by desk research based on their expertise in timber construction and digital technologies. Sampling criteria included participation

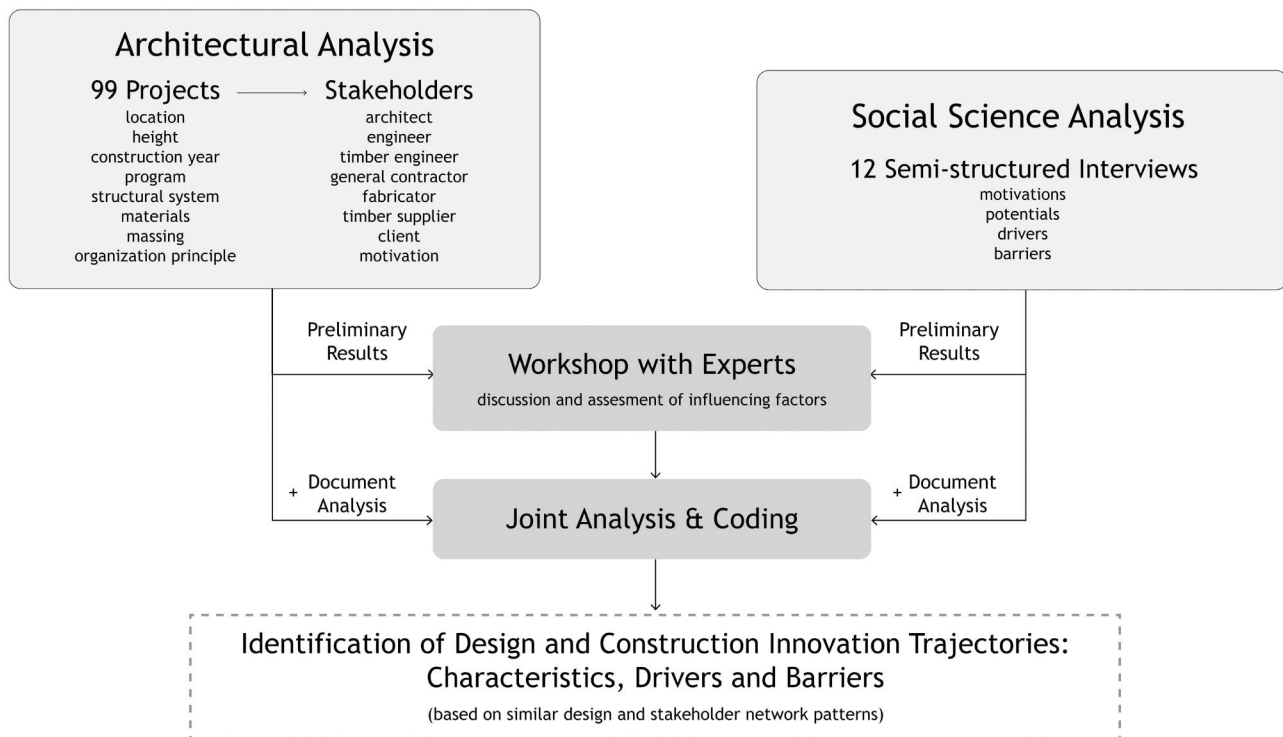
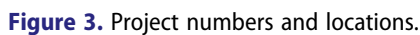
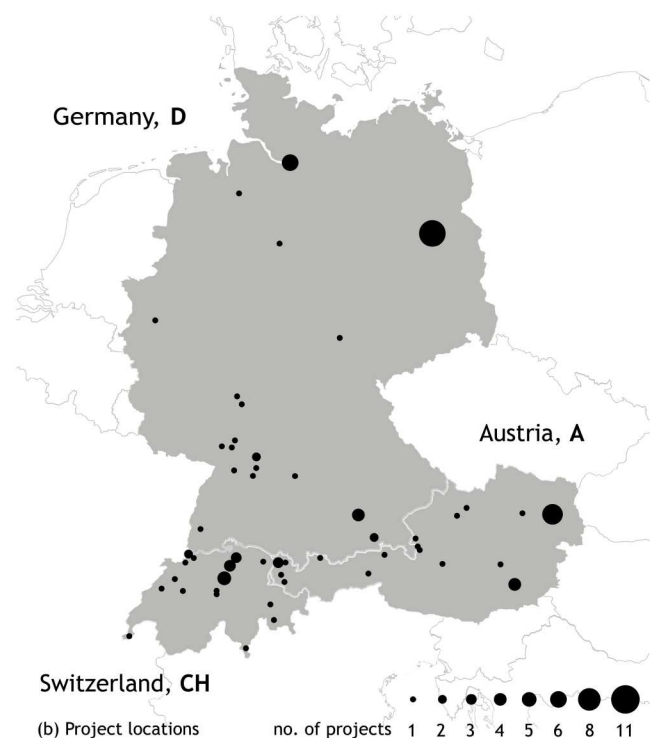


Figure 2. Methods overview.



The interviews were primarily in German over video-conference tools or phone, due to the pandemic situation, and recorded for transcription. Prior to the interviews, interviewees gave written consent to record, store, analyze, and anonymize the interview data. The second author coded the interviews and analyzed them using a grounded theory approach (Charmaz, 2006; Strauss & Corbin, 1990).³ Quotations from German interviews were translated into English for this article.

Additionally, we presented preliminary results to fourteen timber experts at a one-day research workshop in June 2022 (for expert background, see Table 4). Selection criteria included participation in digital timber projects and MSTBs, professional roles, and work experience, aiming for stakeholder plurality. Experts



Finally, collected data were jointly analyzed and manually coded to understand the relationships between qualitative and quantitative datasets (Figure 2). Barriers and potentials were identified, while motivations were based on texts and interviews. The analysis of multi-storey timber projects grouped those based on similar design and stakeholder network patterns. The *architect-engineer-construction company-client* constellations in each project, together with the building design factors, served as an indicator for the identification of the innovation trajectories and their characteristics. The degree of involvement of the stakeholder companies with a timber focus, their role(s) on the project, and their interrelation in the project constellation represented one of the pattern distinctions, as specialized knowledge can be indispensable to innovation, and allowed us to distinguish the innovation trajectories.

Similarly, the level of repetition of elements or their customization, their incorporation into the building design, as well as spatial organization and material usage impacted the grouping and signalled the different innovation trajectories. These indicators, supplemented by re-examining source literature and documentation,

Table 3. List of interviews.

Interview-ID	Actor Group	Type of Firm / Work Focus	Role	Country	Language	Length (min.)	Date
T01	Corporate organization	Timber consultancy (digital fabrication services)	Director	Germany, Switzerland	German	75	May 26, 2020
T02	Scientific organization	Digital timber fabrication	Senior researcher	Switzerland	German	97	Jul 17, 2020
T03	Corporate organization	Structural engineering	Structural engineer (head of department)	Germany	German	66	Aug 4, 2020
T04	Corporate organization	Structural engineering	Structural engineer (parametric design)	Germany	German	32	Aug 10, 2020
T05	Corporate organization	Timber construction / fabricator	Chief Technical Officer	Germany	English	95	Aug 12, 2020
T06	Interest group / lobby	Timber construction	Head of department	Germany	German	68	Sep 17, 2020
T07	Corporate organization	Timber construction / fabricator	Chief Technical Officer	Switzerland	German	97	Sep 28, 2020
T08	Corporate organization	Timber construction / fabricator	R&D Manager (architecture)	Germany	English	55	Nov 17, 2020
T09	Corporate organization	Structural engineering	Structural engineer (parametric design)	Austria, Germany	German	82	Nov 24, 2020
T10	Scientific organization	Timber construction	Senior researcher	Germany	German	86	Mar 22, 2021
T11	Corporate organization; scientific organization	Timber construction / fabricator; digital fabrication	Computational designer, educator	Switzerland	English	72	Feb 23, 2021
T12	Scientific organization	Digital timber fabrication	Researcher	Switzerland	English	56	Nov 17, 2021

served as a basis for determining drivers and barriers within the individual trajectories. Analysis of stakeholder interviews, the workshop discussion, and document analysis supplemented the trajectory characterization and further substantiated drivers and barriers for multi-storey timber construction overall.

Results

We identified three innovation trajectories that are co-developing along each other as well as interdependently: (1) *standard innovation*, (2) *incremental innovation*, and (3) *pioneering innovation* in timber construction. The main characteristics of the *standard innovation* trajectory include the repetition of standardized timber elements or systems, a drive for productivity, and timber as a primary material. The *incremental innovation* trajectory, on the other hand, is characterized by varied combinations of standardized elements and materials

(e.g. steel, concrete, hybrids) and a motivation for design freedom. *Pioneering innovation* adopts digitally enabled customizable elements and novel building systems driven by increased performance with timber specifically.

While several influencing factors overlap between the trajectories, these also exhibit significant differences, as discussed in the following sections (Table 5; representative projects per trajectory in Table 6). The grouping and naming of the trajectories derive from the range of differences and changes in the use of the building components, elements, materials, or fabrication processes of the analyzed MSTBs projects, as well as the differences in the actor-networks involved in them (Table 6) rather than following the typical classification related to innovation types, i.e. sustaining, incremental, disruptive, and radical (Godin, 2017). Social studies of innovation, in general, and of innovation in construction, in particular, emphasize that innovation is a dynamic process 'of transformation, re-use and re-

Table 4. List of workshop participants.

ID	Actor Group	Type of Firm / Work Focus	Role	Location
WS01	NGO	Housing cooperation	Board member	Germany
WS02	Corporate organization	Timber construction / fabricator	R&D manager & structural engineer	Germany
WS03	Corporate organization	Timber construction / fabricator	Carpenter	Germany
WS04	Interest group / lobby	Timber construction	Consultant	Germany
WS05	Finance	State bank	Business Economist (ESG)	Germany
WS06	Corporate organization	Architectural firm	Head of timber architecture department	Germany
WS07	Corporate organization	Architectural firm	Architect	Germany
WS08	Political organization	Timber construction & digital technologies	Policy advisor	Germany
WS09	Scientific organization	Timber construction and architecture	Professor	Germany
WS10	Political organization	Federal state ministry	Coordinator governmental funding programme	Germany
WS11	Corporate organization; professional association	Timber construction / fabricator; carpenter association	Carpenter / Head of local carpenter association	Germany
WS12	Political organization	Federal state ministry	Head of bio-based economy department	Germany
WS13	Political organization	Federal state ministry	Head of forestry and timber construction department	Germany
WS14	Scientific organization	Digital timber fabrication	Professor	Germany

Table 6. Representative project selection by trajectory with actor-network constellation*

Trajectory	Country	Project Name	Architect	Engineer	Timber engineer	General contractor	Timber contractor	Timber supplier	Client	Motivation	Programme	Structural type		Number of stories	Year
												Building system	Materials		
T1	D	Nachverdichtung Speyer	Schöne Architekten, Architekturbüro Schnieder	Ingenieurbüro von Fragstein GmbH	Ingenieurbüro von Fragstein GmbH	Züblin Timber	Züblin Timber	Züblin Timber	public	sustainability	residential	panel	CLT	5	2015
T1	A	Seniorenwohnheim Hallein	SPS architekten	Merz Kley Partner	Kaufmann Bausysteme	Kaufmann Bausysteme	Kaufmann Bausysteme	Mayr-Melnhof Holz	public	speed	retirement home	3D Modules	CLT	5	2013
T1	A	BMW-Hotel Alpenhof (Hotel Ammerwald)	Oskar Leo Kaufmann, Albert Rüt	Mader + Platz	Merz Kley Partner	Kaufmann Bausysteme	Kaufmann Bausysteme	KLH MASSIVHOLZ GMBH	private	sustainability	hotel	3D Modules	CLT	5	2009
T1	CH	Hotel Revier	Carlos Martinez Architekten AG	Plan4 AG	Josef Kolb AG	n/a	Kaufmann Bausysteme	Binderholz	private	technical aspects	hotel	3D Modules	CLT	5	2017
T1	CH	Asylunterkunft Rigot	acau architecture sa	T ingénierie SA, Thomas Jundt Ingénieurs Civils SA	Charpente Concept SA, JPF-DUCRET SA	Hospice général	JPF-DUCRET SA, Dasta Charpentes-bois SA, Casai SA	Burgat Saint Aubin, Corbat, Despond SA Bulle, Zahnd SA Rueyres	public	speed	refugee housing	3D Modules	CLT, GLT	5	2019
T2	D	C13	Kaden-Lager Architekten	Pirmin Jung Ingenieure	Pirmin Jung Ingenieure	oa.sys baut gmbh	oa.sys baut gmbh	Hector Egger Holzbau	private	sustainability	residential	frame & panel	DLT-concrete, steel	7	2014
T2	D	Skaio	Kaden-Lager Architekten	bauart Konstruktions	Ingenieurbüro von Fragstein GmbH	Züblin Timber	Züblin Timber	Züblin Timber	public	sustainability	residential	frame	CLT-steel	10	2019
T2	A	Illwerke Zentrum Montafon	Hermann Kaufmann + Partner ZT GmbH	Merz Kley Partner	Merz Kley Partner	Cree GmbH	Cree GmbH	Mayr-Melnhof Holz	private	technical aspects	office	frame	GLT-concrete	5	2014
T2	A	Aigner-Rollet-Allee	Nussmüller Architekten	ConLignum ZT GmbH, Rosenfelder & Höfler Consulting Engineers, GDP ZT (concrete)	DI Josef Koppelhuber	n/a	Strobl Bau – Holzbau GmbH	Mayr-Melnhof Holz	public	sustainability	residential	panel	CLT; concrete	5	2018
T2	A	HoHo	Rüdiger Lainer + Partner	Woschitz Group	Woschitz Group	Handler	Handler	Hasslacher Norica Timber, Xlam Concrete	private	sustainability	mixed-use	frame	CLT-concrete; concrete	24	2019
T2	CH	Suurstoffi 22	Burkard Meyer Architects	MWV Bauingenieure AG	ERNE AG Holzbau	ERNE AG Holzbau	ERNE AG Holzbau	Pollmeier	private	technical aspects	office	frame	GLT + LVL-concrete; steel	10	2018
T3	D	Cradle	HPP Architekten GmbH	Knippers Helbig, SJB Kempter Fitze AG	DERIX-Group	n/a	Design-to-Production, DERIX-Group	Binderholz	private	technical aspects, sustainability	office	exoskeleton	GLT, CLT	7	2024
T3	A	BOKU	ARGE SWAP Architekten	Bollinger + Grohmann	Bollinger + Grohmann	Lieb Bau Weiz		Stora Enso	public	technical aspects	university	frame	GLT, CLT	5	2020
T3	CH	Tamedia	Shigeru Ban Architects	Creation Holz	Creation Holz	HRS Real Estate	Blumer Lehmann AG	Blumer Lehmann AG	private	technical aspects	office	frame	GLT	7	2013
T3	CH	Fasanenhof	Scherer Architects	Timbatec AG	Timbatec AG	Scherer Architects (construction management)	Timbatec AG	n/a	private	technical aspects	residential	frame	CLT	4	2021

*Project selection is based on four variables: country (a representative project from each of the DACH countries), programme of the buildings, structural type, and different number of stories within the trajectory (if possible) to showcase the variation among the stakeholder-network constellations, motivations, and use of construction materials and elements. Projects with repeated stakeholder collaborations are also included.

Table 5. Overview of identified timber innovation trajectories.

T	1 – Standard Innovation	2 – Incremental Innovation	3 – Pioneering Innovation
N	35	58	6
C	Repetitive standard elements and components Timber projects	Variety of standard elements and materials Timber-based projects	Custom elements or novel building systems Timber projects
A	Fabricators (majority)	Mixed	Experts and ‘innovators’
D		Better building sustainability	
R		Higher efficiency and speed	
I		<i>Technical & material limitations</i>	
V	Costs and <i>economic potential</i>	Greater design freedom (within the system)	Design showcase, detail expression and freedom (outside established systems)
E	Productivity	Use of other materials to increase timber performance	Optimized and increased material performance
R		<i>Regional building and fire code variation</i>	
S			
B		Preplanning requirements	
A		Lack of timber-related knowledge & experience	
R		Influence of other material networks	
R	Design limitations	High product variety & systems (composite, steel, timber)	High risk and investments due to R&D
I	Not fitting all programmes	CO ₂ emission	Permissions
E	Construction limitation	Standards	(non-standard buildings)
R	<i>Regional building code variation</i>		Speed and time
S	<i>Technical & material limitations</i>		<i>Regional building code variation</i>

Overview of identified innovation trajectories (T), number of projects per trajectory (N), their characteristics (C), actor networks (A), and influencing factors: drivers (D) and barriers (B). Drivers and barriers identified in the interviews are *italicized*.

configuration’ that unfolds over time (Irwin, 2023, p. 3) and in dialogue with multiple concurrent and contested building practices, organizational conditions, and actor preferences (Akrich et al., 2002a, 2002b; Callon, 1986; Harty, 2005; Whyte & Hartmann, 2017). Thus, the trajectory labels also reflect timber construction innovation in relation to: (i) established processes in construction with conventional materials, i.e. concrete and steel, (ii) the regenerative material culture focused on responsible material sourcing and circular economies, and (iii) the different views on timbers and motivations for its use as a building material from a design perspective.

Description of innovation trajectories’ characteristics and actor-network constellations

T1: Standard innovation

This trajectory (T1) reflects what stakeholders consider innovative in practice, represented in discussions on prefabrication and increased speed of construction, compared to widespread design and construction processes. Timber in T1 is linked to architectural standardization, limited use of its design potential, and focuses on the efficiency of production, as the projects are mainly defined by the *repetition of standardized elements*, higher levels of prefabrication, and panel and spatial modules’ construction with mass-produced

building components, transported and assembled on-site. As industrial production and prefabrication of timber elements and complete room modules often rely on the delivery of complete building components and units with internal furnishings and fittings, the connections are ‘speed-oriented’ and mainly composed of simple brackets for fast on-site assembly (Figure 4). Besides cores and connections, the projects are *built in timber only*. The dominant system is CLT panels, with only one project with OSB box slabs and two projects constructed with an additional layer of concrete. A primary strategy for customization is to use varying module sizes and change the orientation of elements. Overall, the projects’ massings show rectangular building volumes with a repetitive layout (Figure 5). Accordingly, common building typologies in T1 are programmes such as hotels and student, elderly, or social housing projects, with the tallest MSTBs being seven storeys.

Projects’ clients were evenly split between public and private actors. Surveyed projects show that fabricators and timber suppliers played central roles, often acting as a contractor and an engineer on a project (Figure 6; Table 6). Austrian companies Kaufmann Bausysteme, Mayr-Meinhof, Kulmer Holzbau, and Merz Kley Partner are most frequently listed and often fulfil a contractor and supplier role simultaneously. For example, as can be seen in Figure 6, in



Figure 4. Details in T1: Steel angle connections(left); metal plate connections for prefabricated panels (mid); form-fitted connections between 3D modules (right).

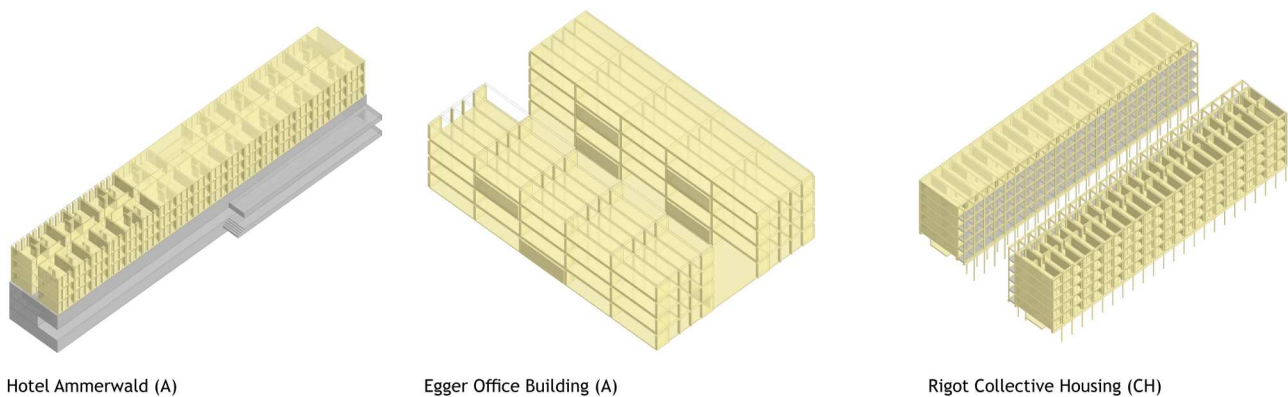


Figure 5. Examples of projects in T1 showcasing high rectilinearity and use of timber (in yellow). The systems cover CLT panel systems (left), box-slab frame structures (mid), and 3D modules with timber foundations (right).

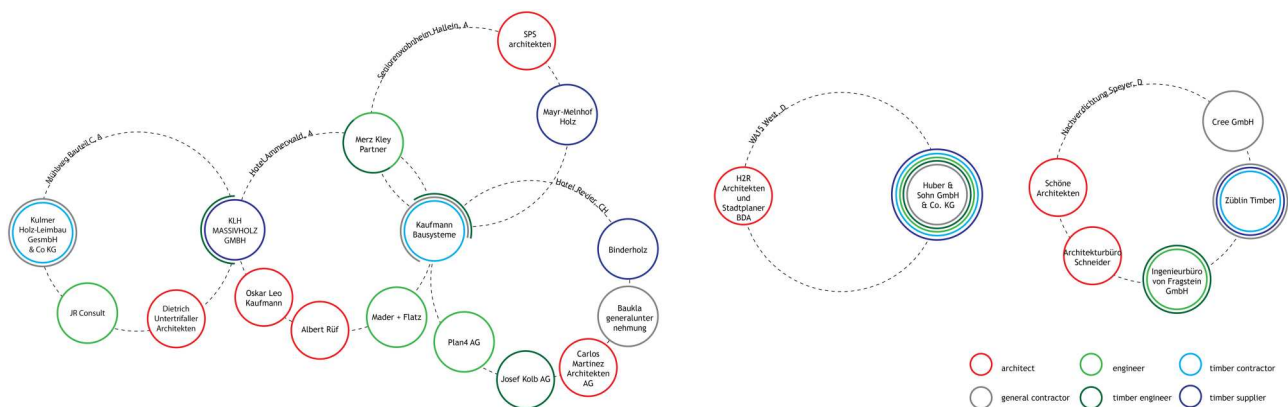


Figure 6. Representative actor-network constellations in T1.

the *Seniorenwohnheim Hallein* project, Kaufmann Bausysteme acts as timber engineer, general contractor, and timber contractor, while in *Hotel Ammerwald* and *Hotel Revier*, they hold fewer roles. The selection of the fabricator company often defines the structural system, as Kaufmann Bausysteme specializes in 3D

prefabricated modules and Kulmer Holzleimbau for 2D CLT panel construction. Project *WA15 West* stands out, as the company Huber & Sohn acts nearly as a full-service general contractor, which takes on both construction and planning, along with only one architecture office.

T2: Incremental innovation

The most prevalent trajectory represents various incremental innovations in timber construction, defined by the use of a *variety of standardized elements and products*. The incremental innovation trajectory (T2) reflects gradual and continuous improvements and most minor changes, where most of the design and fabrication processes align with established practice, meaning that only what is easy to change is executed in timber. As such, projects are often 'hybrid' or *timber-based* and incorporate different materials into the structural system. Hybrid components are used to deal with issues relating to load-bearing, acoustic, and fire performance. Therefore, the focus is less on the benefit of timber's full potential in MSTBs but on supplementing with timber as a material to refine existing building culture. More complex connections with steel and concrete used for load transfer are present (Figure 7), along with different timber-based building systems resulting in a wider range of element combinations⁴ and EWP's⁵ used (see Table 6). Although production speed remains a driver, unlike T1, programmes and designs are more heterogeneous, with heights ranging from five to over twenty storeys. While most projects have rectangular forms, semi-rectangular forms based on grid intersections or the use of concrete and steel for form variation are present, too. Mostly, standard timber elements are used with irregular concrete areas, but few projects showcase irregular forms. Therefore, projects within T2 suggest that *greater design freedom within established systems* is pursued (Figure 8).

Despite slight differences in each country, the actor constellations within T2 show more mixed stakeholder representation with varying levels of experience and knowledge in timber construction, i.e. architects and engineers with first-time timber projects, advanced timber fabricators like Blumer Lehmann, and more traditional carpentry companies. A few recurring stakeholders like Kaden Lager Architects, Pirmin Jung, Woschitz Group, Merz-Kley, or ZÜBLIN Timber, proven experts in timber construction, along with traditional construction companies that have developed timber-concrete-composite (TCC) systems in the recent years, i.e. ERNE Holzbau, have critical roles in several projects and illustrate the high interconnectivity of the actors in cross-project collaborations (Figure 9). Additionally, in several projects in Germany (E3, Prenzlauer Berg, 3XGrün), some of these actors also formed a so-called Baugruppe, meaning a group of builders without developers as the premise for a co-housing development (Salvadori, 2021).

T3: Pioneering innovation

Pioneering innovation in timber construction is the least represented trajectory (T3) in the survey and consists primarily of one-off construction projects. Although the projects are based on CLT or GLT construction, it is defined by more complex timber construction, the use of *custom elements* with greater dimensional variety, the use of more *novel timber-only building systems* and timber connections, as well as the key presence of cutting-edge companies. Its naming reflects the objective to fully realize timber's potential and its focus on timber expression. As such, projects in T3 are driven by *improved timber mono-material performance*, technological advancements, and *detail orientation* and act as showcases for state-of-the-art timber (only) designs and structures with a higher level of design freedom outside of established standardized timber products and systems.

Most projects had private clients. The six projects include bank and office headquarters, residential projects, and a university building. *Tamedia* and *Omega Headquarters* showcase high-accuracy timber frame structures with screw-less connections as innovations in advanced joinery. The *Cradle's* exoskeleton combines facade and structure, showcasing variations of angles and depth along with novel timber connection nodes. *Fasanenhof* and *Unterhub* utilize Timber Structures 3.0 technology (TS3), which enables larger-than-before wooden flat slabs through new edge connections and a newly developed layered timber column head for large spans (Figures 10, 11).

The actor-networks consist of multiple cutting-edge companies, such as timber start-ups, fabricators, and engineers specialized in complex geometries or developing new processes, e.g. Derix Group incorporating disassembly and material take-back. Many of these also developed out of an academic context: Design-to-Production/ETH Zurich (Scheurer, 2012), Knippers Helbig Advanced Engineering/University of Stuttgart (Grewe, 2011), and Bollinger+Grohmann/TU Darmstadt, University of Applied Sciences Vienna and University of Kassel (Schittich & Brensing, 2013). Similarly, the TS3 System used in *Fasanenhof* is the result of over a decade of research and development by TimbatecGroup, Bern University of Applied Sciences, and ETH Zurich (TS3, n.d.). The constellations generally show that novel building methods require an experienced and tested group of stakeholders (Table 6). An example is the repeated collaboration of Shigeru Ban Architects with Blumer Lehmann and their engineering sister company, Creation Holz (Figure 12). A different type of collaboration can also be seen, with Timbatec holding a



Figure 7. Variety of details in T2: Prefabricated wood and concrete elements with steel inlays prior to adding reinforcement, ductwork, and concrete on site (left); steel connection (mid); simple connection for assembly of the CREE ribbed ceiling system (right).

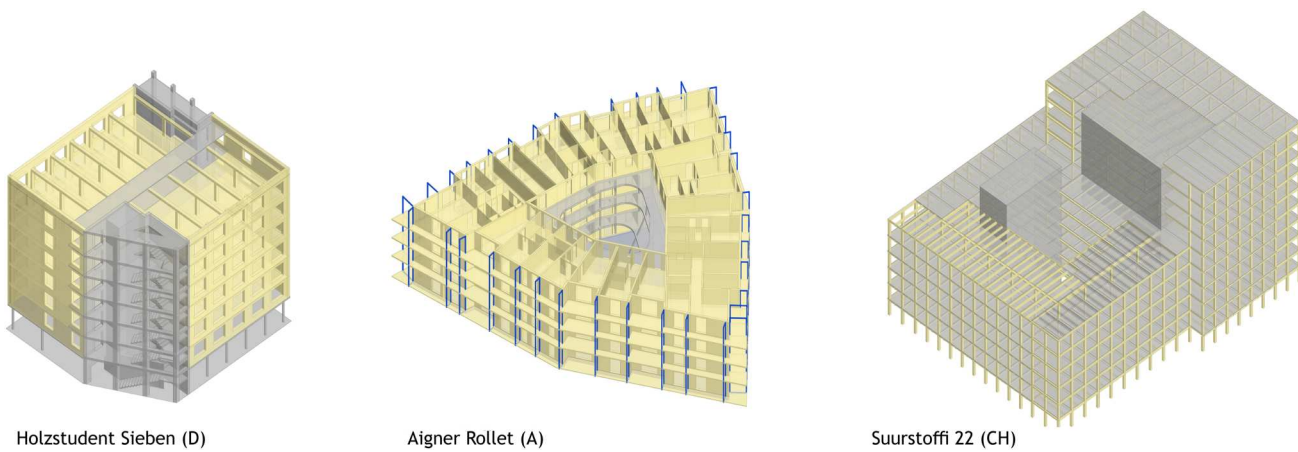


Figure 8. Representative projects in T2: Irregular circulation and atrium areas in concrete (left, mid), hybrid floor slabs on top of a timber frame structure (right). Materials: timber (yellow), concrete (grey), and steel (blue).

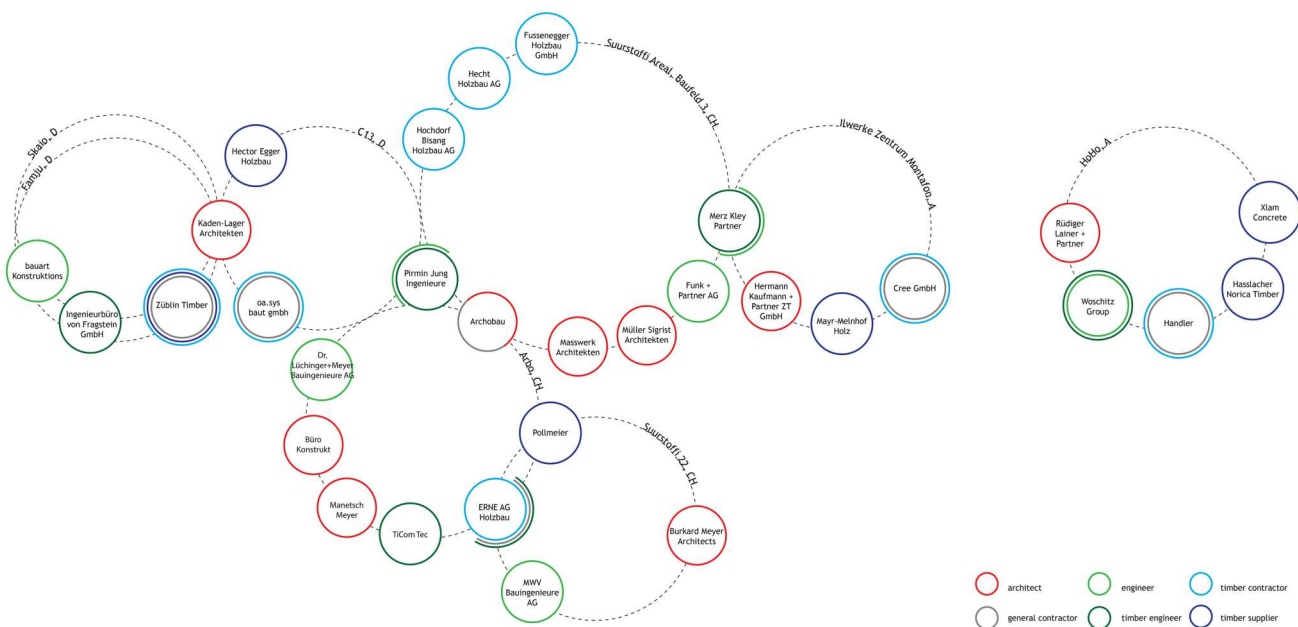


Figure 9. Representative actor-network constellations in T2.



Figure 10. Details in T3: A glueless demountable LVL beech connection (left); a custom CNC oval beechwood pin connection (mid); new glued connections in the TS3 system (right).

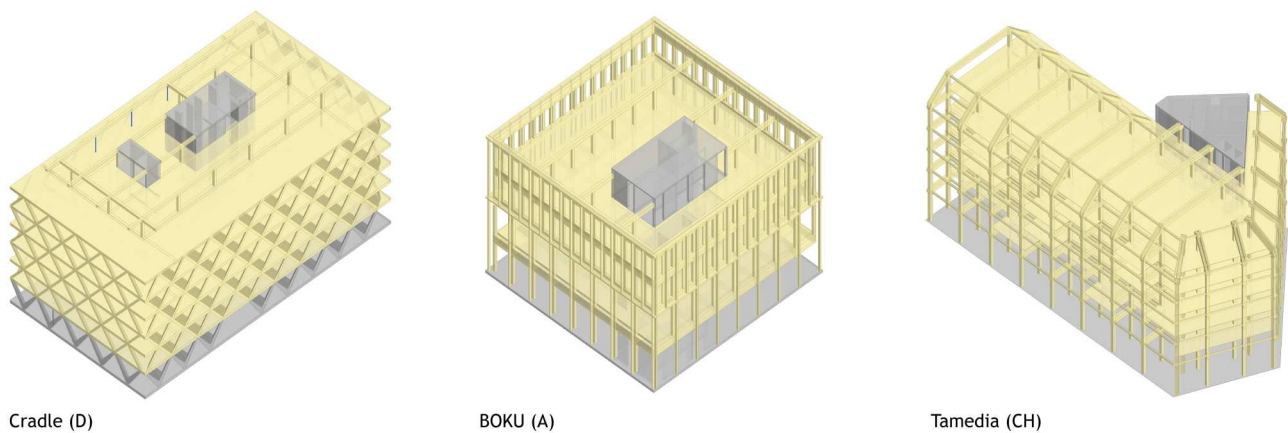


Figure 11. Examples of projects in T3: An expressive timber truss facade (left); a variable structural grid across storeys (mid); a timber frame adapting to the site (right). Materials: concrete (grey), timber (yellow).

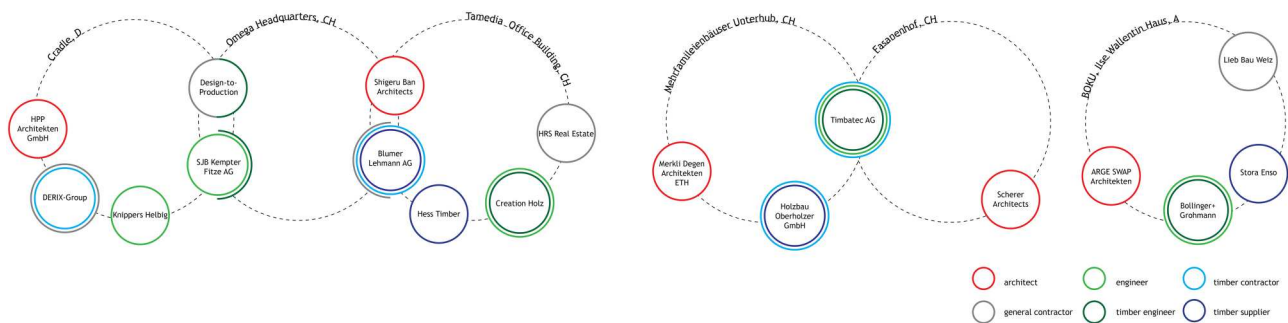


Figure 12. Actor-network constellations in T3.

central role in combining contracting, engineering, and fabrication on two projects due to the novelty of the slab system. Concurrently, more conventional companies also appear in the networks.

Common drivers across innovation trajectories

The prevalent drivers of multi-storey timber construction in DACH across all three trajectories relate to

sustainability, regulation, and economy. As drivers, these aspects are intertwined, which means that the sustainability transition of the construction sector is attached to public expectations as much as to financial incentives and funding programmes. The interviews additionally stress three central driving motivations for multi-storey timber constructions: (1) *higher efficiency and speed of production* ascribed to digital design processes and automation technologies and

related to that, (2) a significant *economic potential* through standardized building components and processes, as well as (3) *better building sustainability* ascribed to the use of local bio-based materials. Within this context, the potential appeal of timber architecture is also related to the fact that ‘*wood is simply an organic building material*’ and ‘*available in countless different varieties*’ (T09, 2020).

Sustainability is a dominant motivation for timber construction among the surveyed projects. In Germany, several projects like 3XGrün (Informationsdienst, n.d.) and Holz 8 (Mayo, 2015) were linked to sustainability policies and joint public-private ventures. While public interest in timber construction is a key driver, interviews reveal that for clients, the main drivers are sustainability certificates, which can improve financialization chances and asset values. In the survey, primarily in T1 and T2, many Swiss projects were built according to the Minergie standards, while German and Austrian ones to QNG, DGNB, or PEFC certification (Tables 2 and 6). However, as a timber engineer noted, this depends on the project owner’s objectives, as those with ‘*high expectations on the level of certification [...] will tend to choose sustainability factors rather than costs*’ (T08, 2020). In many instances, timber construction has become a means to legitimize new construction. With increasing pressure from society to meet sustainability goals and their impact on construction, more clients want timber buildings ‘*no matter the cost*’ to remain ‘*plausible outside*’ (T07, 2020). Furthermore, the growth in regional or national funding programmes and policies has helped balance the still higher costs compared to traditional construction materials and processes, with municipalities and public sector clients benefiting in particular and governmental initiatives such as Holzbau-Offensive BW (D) acting as promoters.

Relaxation of different regulations and building codes, particularly regarding fire protection and additional storeys, has led to an observable increase in MSTBs. Individual pilot and experimental projects, especially taller buildings like LCT I or HoHo, which needed special permissions and testing (Vihemäki et al., 2019; Woschitz, 2019), have provided necessary confirmation and reassurance that multi-storey timber construction is possible and viable, as an interviewee from a timber construction company notes: ‘*We also could [build tall] before. But in people’s minds, society has accepted that a five-storey building in timber also works*’ (T07, 2020).

Several projects also emphasize *speed of construction* as the principal motivation with expectations of eventually lower *costs* as reduced fabrication time

makes timber more competitive with concrete (Abed et al., 2022; Ahn et al., 2022; Bhandari et al., 2023; Smith et al., 2018). Interviews confirm that costs remain the primary factor defining building projects’ design and realization. Thus, production efficiency is perceived to allow building economically, faster, and ‘*realising appealing architecture*’ (T06, 2020) and is mainly attributed to timber prefabrication (Kaufmann et al., 2018). Integrating digital design and automation technologies into streamlined workflows, commonly offered by timber construction companies, promises to bridge material sourcing and resourcing. As one interviewee remarks, the growing presence of digitally-based timber companies like Gropys alongside traditional timber fabricators like Rhomberg Bau influence this trend through a ‘*refreshing approach to [...] the entire chain from forest to the demolition [with] as much digital integration as possible*’ (T09, 2020). Large construction companies acting as general and timber contractors as well as timber suppliers prevail T1 and T2, further playing a key role in achieving the potential of higher production efficiency due to the standardization of building components. At the same time, T1 projects show that streamlining manufacturing and assembly into standard units and dimensions can limit design variation.

Finally, although not primary drivers, stakeholder interviews and the projects’ survey reveal that long-standing local carpentry and timber construction traditions, the interest in supporting local industry, the higher concentration of local actors across the entire timber value chain influence, as well as their early adoption of automation strongly influence present opportunities for MSTBs’ advancement.

Common barriers across innovation trajectories

Our study identified four interrelated main groups of barriers influencing the adoption and diffusion of multi-storey timber construction across the three trajectories: (1) *lack of knowledge* and practical experience in building with timber among different stakeholder groups along with early decision-making (*preplanning requirements*); (2) *regional building code variations* concerning building heights and fire protection; (3) the *material and technological aspects* of MSTBs, such as material performance and local availability of resources; and (4) the *dominance of other material systems and their actor-networks* as well as *established conventions and practices* in the building sector, which situate multi-storey timber construction in it.

Material knowledge and experience inform architectural practice. Projects' analysis shows that concrete and steel are highly present in MSTBs, with terms like 'timber-based' used to describe them (Salvadori, 2021), even in T1 and T3 due to different core or podium materials. Interviews reveal that the 'basic understanding' of design and construction itself is shaped by longitudinal experience with conventional materials; planning 'with the idea of a solid construction [Massivbau] in mind' makes it difficult to convert to timber construction (T10, 2021). Experts and previous research relate that to the challenges of 'not knowing other planning principles of timber construction' (T10, 2021).

Furthermore, as high-rise construction and building stock extensions gain relevance in the DACH region, timber construction has to deal with different issues and aspects than the ones in conventional construction, as there are still 'no [comparable] key figures' for reference (T07, 2020). A problem for architects, as seen by timber interest group representatives, is the large variety of timber products, requirements, and regulations, as well as timber construction being 'very detail enamoured' (T06, 2020). An interviewee notes: 'For every wall, there are twenty different possibilities to construct it' (T01, 2020). Thus, for architects to be 'taken on board', a simplification of building materials, structures, and requirements may be necessary, as shown in the high number of T1 and T2 projects.

Clients also lack know-how and experience in building with timber. Here, timber fabricators play a central role, particularly those providing multiple services ranging from planning and consultancy to fabrication and

assembly, such as in T1. Although timber fabricators in DACH are frequently described as forerunners in adopting advanced technologies and investing in the training of craftspeople, knowledge development requires collaboration and exchange between disciplines and trades: 'As a natural material, wood is so complex. [You] need so much material-specific knowledge about timber constructions and material behaviour' (T02, 2020).

The project planning stages act as another barrier in multi-storey timber construction, particularly in the DACH region, where architects typically take on more tasks beyond design documentation and the stages are subdivided into more groups compared to other countries like the UK or US (AIA, 2023; BDA, 2011; RIBA, 2024). Although each DACH country has defined the stages differently, the model is generalizable (Table 7). The division of planning and implementation, in which the architect, the construction company, and other experts are separate, is less suitable for timber construction due to its complexity. An overwhelming variety of materials, variations in product approval, fire-safety concepts, lack of standard regulations, technical challenges that require co-planning of both structure and other layers, e.g. envelope, as well as the reliance of construction companies on their own systems and details, all makes this a 'multifaceted' process (Huß et al., 2018). An interviewee emphasizes that prefabricated timber construction also requires a reconfiguration of stakeholders' constellations in the design and construction process as defined by regulation, which authorities used to establish planning models are not familiar with (T10, 2021).

Table 7. Project planning stages in DACH region

	Germany (D)	Austria (A)	Switzerland (CH)
Ordinance	HOAI, Honorarordnung für Architekten und Ingenieure (Schedule of Services and Fees for Architects and Engineers)	LM.VM, Leistungs – und Vergütungsmodellen	SIA 112 Modell Bauplanung, includes SIA 102 Ordnung for Architects & SIA 103 for Engineers among others
Strategic planning	LP1 Basic evaluation	LPH1 Basic analysis	Strategic planning 11. Definition of needs, solution strategies
Preliminary studies / project preparation	LP2 Preliminary planning and estimate	LPH2 Project preparation	Preliminary studies 21. Project Definition 22. Selection procedures
Project planning concept, schematic, and detailed design	LP3 Design planning including cost calculation LP4 Building permission application LP5 Detailed design LP6 Preparation for contract award and tender	LPH3 Design Planning LPH4 Submission planning LPH5 Submission planning	Project 31. Preliminary project 32. Construction project 33. Approval i.e., permit-obtaining procedure/submitted
Tender	LP7 Tender and cost estimate	LPH6 Tenders	Tender 41. Tender
Construction handover	LP8 Project supervision LP9 Project control and documentation	LPH7 Accompanying construction work LPH8 Local construction supervision and documentation LPH9 Property management	Realization 51. Execution 53. Commissioning Management 61. Operation 62. Conservation
In use	n/a		

Despite regulation improvements, the *regional variation of building code* is considered a barrier among many stakeholders. In all three countries, fire resistance and the use of non-combustible materials in high-rise buildings are defined differently, often regionally-specific down to federal state, canton, and even municipality level (see Table 1). In Germany, apart from the Muster-Holzbaurichtlinie (MHolzBauRL) introduced in June 2021, the building code for MSTBs varies between the federal states. As noted in the interviews, the absence of comparable regulation complicates planning, discouraging risk-averse stakeholders from considering MSTB concepts. An example is proposing different design concepts for fire exit strategies for taller buildings, mostly in T2, which, according to a timber structural engineer, takes favourable authorities and ‘a certain kind of daring’ (T03, 2020).

Availability and access to locally situated fabricators present another barrier. While the DACH region has many small and medium-sized carpentries and timber fabricators focused on covering the single-family house market (Kind et al., 2022), those capable of meeting the technical and constructive requirements for MSTBs are still few and ‘not yet ready’ (T03, 2020). The number of fabricators ‘who can also carry out projects on this scale’ is comparatively low, even in the timber-strong areas of DACH (i.e. Bavaria, Baden-Württemberg, Vorarlberg), while companies working at full capacities lack the incentive to change their direction towards multi-storey construction (T06, 2020; also, Kind et al., 2022). Additionally, a shortage of skilled staff, related to higher costs of carpenters due to their vocational training, and high investment costs of automation and digitalization for prefabrication hinder the capacities of many companies. Experts, therefore, see a need for transforming the entire design and construction process to realize MSTBs’ potential.

Finally, the use of other materials as solutions to fire, vibration, or sound insulation suggests that beyond material performance limitations and regulations, the pre-eminence of mineral-based materials and their social networks may impact MSTB developments. Several interviewees indicated that existing material lobbies and networks continue to hinder developments. One expert remarks that other materials ‘are lobbying very hard’, and compared to their established structures, timber lobbying ‘has only really picked up in the last ten years’ (T06, 2020). Moreover, established actor-networks on a municipality level and their lack of timber knowledge may prevent public clients from choosing timber as a building material (T06, 2020). As our results show, the barriers behind MSTBs’ development and

how that reflects decisions about alternative building systems and methods are strongly intertwined, emphasizing that technical innovation alone, without consideration of the various social, political, and economic contexts, cannot bring about the paradigm shift in this sector.

Discussion: converging directions of development

Based on the results, we can observe that the identified drivers and barriers affect many socio-technical aspects of multi-storey timber construction. Despite the commonalities between influencing factors across the trajectories, there are also juxtapositions and nuances in how certain influencing factors shape those (see Table 5). These differences may explain why the incremental innovation trajectory (T2) is the most widespread in the DACH region.

Although *sustainability* is a strong driver for MSTBs overall, T2 has a significant trade-off effect due to the use of structural concrete and steel compared to other trajectories. As emissions increasingly define regulations or carbon taxation, timber alone and its role as carbon storage may not suffice to offset emissions without more limited use of other materials or their reuse. Similarly, while the standard innovation trajectory (T1) is driven by the expectations of automation and digitalization bringing maximum *efficiency* at a low cost, T2 is propelled by efficiency using different materials to increase the performance of timber construction. In contrast, the pioneering innovation trajectory (T3) rests on the expectation of digital technologies opening up new technical possibilities through customized and resource-efficient *timber design*. Concurrently, it demands high costs and investment and takes longer to develop and apply new systems in practice. Therefore, despite its potential to reduce environmental impacts and store CO₂, its developments are less widespread.

Our results further suggest that even if research on digital technologies in timber construction demonstrates that advancements enable innovative designs and material reduction, actual implementation in the region predominantly applies ‘digital-timber’ innovation in MSTBs for their cost and time-saving potential. This likely addresses stakeholder expectations for results similar to those achieved with industrialized timber construction in the Nordic countries (Brege et al., 2014; Lindgren & Emmitt, 2017; Mahapatra & Gustavsson, 2008). The identified trajectories also show links to previous research from industrialized timber housing which identified three strategic company orientations

with varying degrees of product customization within predefined limits (Lessing, 2015), where T1 corresponds to product-based construction concepts with closed and controlled production systems, T3 resembles some of the project-unique design concepts, and T2 combines both approaches in timber and concrete construction. However, these industrialized construction concepts still have limited applicability to the identified innovation trajectories in the DACH region due to the formal planning phases and bidding requirements aligned with typical architect-engineer-construction company constellations, compared to commissioning an all-in-one-construction company. The sector and timber construction in the region have so far only incrementally adopted new technologies and innovation, showing little signs of 'disruptive modes' in innovation, such as the ones reflected in T3 projects.

That said, while digitization and automation have been relatively well integrated into timber production and construction chains across all three trajectories, early decision-making related to timber effectively conflicts with the promise of digital technologies to allow later design changes as errors in planning and assembly on site leave less room for adjustments in the context of prefabrication with high fabrication accuracy. This requires bringing planning forward with digital processes and early cooperation of other participants, meaning subsequent changes result in higher implementation costs. Early decision-making in the design process suits collaborative digital planning or BIM methods. However, these are not yet widely embraced by local stakeholders (Boeva et al., 2024), and according to the German project planning stages model, coordination-heavy digital and 3D planning rarely starts before the end of schematic design or design development.

This becomes visible in how the different trajectories reflect on the project planning stages. Within the T1, preplanning barriers are addressed by manufacturers taking on a general contracting approach. In T3, developments of new systems mean a change in the conventional planning process, which separates planning and implementation, similar to one-time permissions for projects above height restrictions. T2 tends to align more closely with German and Austrian planning phases (see Table 7), likely due to the continued use of concrete and steel, as a more integral planning model is necessary for multi-storey timber construction, which may further explain its wider adoption. Simultaneously, this increases the construction complexity due to slower speed, organization, and costs, but also a separation of trades with prefabricated concrete and steel components typically produced independently of

timber structures and carried out by different actors. Considering the need to change the planning process and align the fee model with that, the increasing use of hybrid timber-concrete elements across projects suggests a potential shift towards standardization and convergence of the standard (T1) and incremental (T2) innovation trajectories. This potential development is similarly suggested by the government-commissioned report on the prospect of timber construction for Germany's urban built environment (Kind et al., 2022). Some projects already illustrate a potential shift and overlap between T1 and T2, such as the insertion of standardized 3D timber modules into a freeform concrete skeleton (*Kiubo*) or construction with prefabricated TCC panels (*LCT I* and *Illwerke*: CREE; *HoHo*: X-Lam concrete), showing that modular hybrid elements are used to construct T1-like building typologies. However, such development may curb the high potential of timber construction and MTSBs for more climate-neutral built environments and a regenerative material culture.

Additionally, as our study shows, T2 is less actor-network-specific and opens the potential for the participation of various actors largely without timber experience. Whereas other trajectories depend on the knowledge and support of fabricators (T1) and innovator groups (T3), T2 is marked by a lack of permanent actors, often exhibiting loose coupling (Dubois & Gadde, 2002), where the same project is rarely repeated or involvement of similar actors in different projects is infrequent, suggesting meaningful knowledge transfer and potentially hindering innovation (Mahapatra & Gustavsson, 2008; Muldoon-Smith et al., 2021). Moreover, as most architects are still more familiar with concrete or masonry structures, T2 facilitates a more familiar planning and design approach for those starting with timber, as academic education on timber in DACH is still limited but increasing. Strategic hires and curriculum reforms in architecture and engineering, funded mainly by local governmental timber programmes such as *Holzbau-Offensive BW*, will likely advance the knowledge and skills of future professionals.

On the other hand, timber lobby, interest organizations, and professional associations pro-actively offer knowledge exchange events, e.g. on building code or showcase projects, and maintain online knowledge platforms for current practitioners⁶, indicating a prevalence of information or voluntary types of 'policy instruments' in the DACH region (Wiegand & Ramage, 2022). However, this more informal approach may not guarantee knowledge advancement, as many stakeholders lacking timber experience might be unaware of these educational offers. Moreover, our document

analysis suggests that key actors and actor-networks in T1 and T3 are involved in knowledge demonstration and distribution, with an observable increase in topics related to timber hybrids and, thus, the incremental innovation trajectory (T2). Since many practitioners have considerable education and experience with other materials, providing solutions and connections to those allows for considering timber in the design and construction of MSTBs.

An example of making timber ‘easier’ to design with appears even among the more timber-pioneering developments, such as the TS3 system, which appropriately promotes planning and thinking ‘in reinforced concrete, but build[ing] in wood’ (Meier, 2021; TS3, 2024). This recalls prior critique by Fleming et al. that many multi-storey timber ‘buildings are conceived of as tower blocks using concrete slabs but building using CLT panels’ (2021, p. 22). In addition, the projects built with the TS3 system do not architecturally match other pioneering projects in T3. This indicates that over time, the application of this system presents itself as suited for both T1 and T2 depending on project goals and actor-network constellations, which means either taking a more centralized role by this company or offering products to others to achieve greater variety and design freedom with timber.

However, it is important to note that the trajectories may manifest differently in other building cultures. Other studies show that there are differences in the types of MSTBs constructed internationally, even among the regions with a strong tradition in timber construction (Salvadori, 2021). In comparison to the DACH region, the Nordic countries have higher rates of all timber panel construction (Norway, Sweden) and 3D module construction (Finland); similar trends are visible also in the UK with higher rates of CLT panel construction, suggesting prevalence of T1 and few projects in T2. On the other hand, MSTB construction in the USA most commonly features timber-steel frame structures and different EWP usage such as nail-laminated timber, NLT (*ibid.*). This suggests a completely different manifestation of T2 than in DACH. Further analyses on drivers and barriers are difficult without a thorough examination of each of those contexts.

Given the study’s qualitative research design and theoretical sampling, it allows only for limited generalizability of the results and drawing conclusions applicable to other geographic areas. Instead, it emphasizes the significance of more situated perspectives on the heterogeneous dimensions of construction innovation, as highlighted by previous studies. In this paper, we focused on the design and socio-technical factors directly influencing MSTBs as timber innovation, i.e. structural and

material variety, spatial possibility, knowledge, social networks, regulation, public interests, and sustainability transition. However, a wide range of external factors such as economic ones (e.g. the 2008 finance crisis), climate change-related ones (e.g. the surge of bark beetle populations, natural disasters), or exogenous shocks (e.g. Covid-19 pandemic, armed conflicts) create market fluctuations and affect material supply or prices, too, which were noted in experts’ comments as decisive for clients (also, Barsauskas et al., 2011; Boisvert-Marsh et al., 2014; Hlaváčková et al., 2024; Wassermann, 2024). These are likely to have a long-term impact on present and future MSTB developments regarding material choices and, thus, architectural design and sustainability.

Although our interviews predate some external factors’ appearances, the experts in the workshop in June 2022 reflected on them, e.g. the timber price increase due to pandemic-provoked demand. Nevertheless, there has been no significant change in MSTB construction trends within the DACH region. This can be seen in projects built up to 2024 from the survey and is supported by other research showing the increase in timber panel projects in Germany due to increased construction in residential buildings as the only trend shift (Salvadori, 2023). Exogenous effects on timber prices in the region have also partially led the industry back to integrating more concrete and even entirely replacing timber with it (Holzkurrier, 2023). This shows that any changes in MSTB trends and trajectories do not occur as a part of an accelerated process but relate to locally specific socio-cultural and organizational aspects. Furthermore, the prevalence of the identified innovation trajectories does not fully reflect all developments in timber construction, as MSTBs represent one segment and come with a specific set of challenges. Therefore, it is crucial to examine upcoming projects, the evolution of EWPs’ implementation, as well as their availability and maturity in different regional markets. Moreover, outside our disciplinary expertises, more research and material on economic and business models, cost-benefit analysis, and longitudinal studies of stakeholder innovation adoption, such as fabrication companies’ investments in product platforms and production systems, and climate change adaptation are needed to provide more practical insights for industry and policymakers.

Conclusion

A joint architectural and social science perspective on the development of multi-storey timber buildings (MSTBs) is rarely discussed in the literature, as most studies focus only on technical or on economic perspectives. This study connects the analysis of MSTB designs

on similar design, construction methods, and the related actor-networks in the DACH region to stakeholder interviews to identify three concurrently developing innovation trajectories – (1) *standard*, (2) *incremental*, and (3) *pioneering* timber innovation – as well as the influencing factors behind them. The study highlights that while all trajectories embrace the material and environmental qualities of MSTBs, driven by sustainability, economic potential, higher efficiency, and speed through prefabrication, the interplay of different factors, stakeholder motivations, and their sectoral contextualization lead to varying and partially contradicting innovation potentials. Specifically, lack of knowledge, building codes, material and technological properties, and conventions of practice create limitations leading to significant differences between the trajectories.

The results show that the *incremental innovation* trajectory, despite the complexities of construction with a variety of materials and elements, is the most dispersed in the DACH region, likely due to building code restrictions, limited design performance with timber systems, higher degree of alignment with established project planning phases, and lack of permanent actor-networks. In contrast, the *standard* and *pioneering innovation* trajectories are much more actor-network-specific and try to maximize wood usage in the projects. While productivity, higher efficiency, and speed drive *standard* timber building typologies, and their extension is underway, the *pioneering innovation* trajectory of timber construction is shaped by technological developments and the potential of extending the material performance and design typologies, mostly through one-off building systems that remain on the margin. Therefore, despite the description of DACH fabricators as the forerunners in adopting digital and automation technologies, the actual implementation predominantly applies digital-timber innovation in MSTBs for efficiency reasons.

Recent developments suggest that incremental innovation in timber construction is the strongest contender for out-of-niche growth, allowing diverse stakeholder involvement, higher local project interactions, and increasing interest of established actors to enter the timber and, therefore, the sustainable construction market due to the use of hybrid components and incorporation of conventional materials. Additionally, a convergence of the *standard* and *incremental innovation* trajectories rather than ‘disruptive’ innovations in the future is likely, as even with various levels of prefabrication, timber construction offers an overwhelming variety of mass timber products, systems, and connections for those without expertise, while concrete is increasingly incorporated. Therefore, their conjunction may lead to a

reduction and further standardization of engineered wood products to simplify design and construction. Global studies have confirmed that MSTBs are still niche and a ‘complex and heterogeneous phenomenon’ with timber engineers and fabricators, sometimes suppliers, having the main impact in many countries (Salvadori, 2021). It remains unclear if MSTBs globally will have similar practices with large companies producing standardized buildings or if regional differences will be promoted to meet local material availability through tailored products. However standardized systems might make MSTBs more common overall internationally. It remains to be seen whether future developments will prioritize the production of easy-to-use and easy-to-produce timber or timber hybrid products to counter knowledge gaps and material lobbies or optimize wood resources through innovative digital technologies to reduce material use and overcome limitations in timber construction. For greater adoption of the more ambitious ‘fully timber’ trajectories of MSTBs and new technologies and methods, established design and construction processes, as well as organizational structures, would need to be adapted.

Notes

1. A three-layer ‘Dreischichtplatte’ panel was already in production in the 1950s (Doka, A). In the 1990s, parallel developments of ‘BlockHolz’ (Pius Schuler AG, CH), ‘Dickholz’ (Merk-Holzbau + Karl Moser, D), and ‘BRESTA-H’ (Gerhard Shickofer + KLH, Stigl and Santner, A) were pursued. KLH started production of CLT panels in 1999, later expanding internationally (Falk, 2005; Fleming, 2021; Salvadori, 2021).
2. Construction of several projects with the addition of performance-based code acted as catalysts for MSTBs: Vienna’s first mass-timber project, *Frauengasse I&II* (4-storeys, 2001), followed by *Spöttlgasse* (5-storeys, 2004), and the first timber-hybrid *LCT I* (8-storeys, 2015) (Kaufmann et al., 2018; Salvadori, 2021; Vihe-mäki et al., 2019).
3. In grounded theory, theories are set into the qualitative data themselves. This means that typically research design follows an ongoing, open process of parallel data collection, analysis, and comparison, as well as sampling aimed toward saturation and theory construction. In our case, this meant successive sampling of interviewee partners following analysis of prior interviews and documents. Review of relevant literature begins after initial analyses of data.
4. Combinations are timber slabs on top of concrete elements (HoHo), steel beams integrated into timber slabs (C13, E3, Skaio, Carl), or timber-concrete composite slab elements particularly present in Swiss projects (Suurstoffi S22, Arbo, Hufgasse, Giesserei, Siloah).
5. EWPs in T2 range from CLT, GLT, LVL (laminated veneer lumber), DLT, up to their related hybrids.

6. Examples include, e.g., Austrian platforms *meta_wissen_holzbau* and *Holzkurrier*, German *Ingenieurholzbau*, or the EU-wide *dataholz.eu*.

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Data availability statement

The project overview data are openly available in DaRUS, the data repository of the University of Stuttgart, at <https://doi.org/10.18419/darus-4442>. The interview and workshop data cannot be made publicly available due to them containing information that could compromise research participants' privacy and consent.

Ethics approval

This research followed the guidelines of the University of Stuttgart and did not require ethics approval. The participants gave written consent to record, store, analyse, and anonymise the interview data prior to the interviews. Workshop participants also provided written consent at the beginning of the workshop.

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