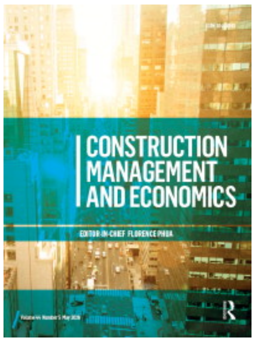

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Transition to timber construction: project level socio-technical processes interpreted through a TIS framework perspective

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Transition to timber construction: project level socio-technical processes interpreted through a TIS framework perspective

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ABSTRACT
In recent years, the use of timber as a sustainable construction material has gained increasing attention driven by environmental policy incentives and growing demand for low-carbon alternatives. The idea of separate approaches to the social and technical systems upon transitioning towards timber could no longer suffice for the complex construction sector. We therefore investigate, (1) what are the socio-technical dynamics driving the transition to timber building projects? and (2) how can the transition to timber be facilitated within the complex and multifaceted residential construction industry from a Technological Innovation System (TIS) framework perspective? The socio-technical dynamics identified following the analysis of 17 semi-structured interviews in the Netherlands are leadership, standardization, product-based construction, stakeholder alignment, and business case viability. Theoretically, we argue that the timber transition requires a comprehensive approach across production systems and service delivery. Practically, this research identifies enabling processes that can support learning and legitimacy in timber construction projects.

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Introduction

The increasing urgency of environmental concerns and evolving regulations necessitate innovative and competitive solutions for a sustainable transition in the construction industry. As one of the largest contributors to the global carbon footprint, the construction sector accounts for 38% of global CO_2 emissions, with 10% attributed solely to construction materials and therefore reducing these emissions is critical to mitigating climate change (Huang *et al.* 2018). In addition, the residential construction industry is currently facing a growing housing shortage while simultaneously working to reduce its CO_2 emissions necessitating sustainable construction techniques that enable the rapid development of denser urban areas (Changali *et al.* 2015). The industry's productivity has stagnated due to low levels of digitization, a shortage of skilled labour, and slow construction times, which further complicate emission reduction efforts (Barbosa *et al.* 2017).

Timber construction, particularly due to its suitability for high levels of prefabrication, offers a viable solution to reducing the environmental footprint and improving the efficiency of the residential construction sector. Its lightweight nature enables faster construction times and reduced labour intensity (Hough 2019). Additionally, timber is a renewable material with carbon capture and storage capabilities, while also demonstrating structural performance comparable to traditional materials such as steel and concrete (Svatoš-Ražnjević *et al.* 2022). Despite its advantages, timber remains underutilized in the construction industry, where concrete and steel continue to dominate new building projects. For example, timber-based construction holds only a 3% market share in the Netherlands (Fraanje 2023). Addressing this need, this study focuses on the Dutch residential construction sector where timber adoption is still in its early stages, with industry stakeholders gradually exploring its implementation driven by national climate commitments.

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Timber adoption requires a significant behavioural shift and steep learning curves for industry actors, which has limited its widespread implementation (Geraedts *et al*. 2014). A fundamental shift in building practices as the routines, norms, and habitual ways of doing among actors (Shove *et al*. 2012), necessitates a socio-technical perspective (Tykkä *et al*. 2010). Afterall, a transition in the construction sector is influenced by a complex interplay of technological, economic, social, cultural, institutional, and political factors (Toivonen *et al*. 2021). Therefore, this study aims to explore how socio-technical dynamics and systemic conditions contribute to the transition to timber construction in the Netherlands.

While socio-technical transitions have been studied in earlier works (Rohracher 2001, Geels 2004), there remains a lack of clarity on how these socio-technical dynamics manifest at the project level within the context of timber construction. We employ the Technological Innovation System (TIS) framework as it provides an analytical lens for systematically examining the socio-technical conditions (Ortt and Kamp 2022) that shape timber adoption. Prior studies in construction demonstrate that TIS is useful for examining material transitions (Wesseling and Van der Vooren 2017, Coenen *et al*. 2023), however, timber construction presents distinct socio-technical characteristics, such as fragmented project delivery, strong path dependencies, and early-stage niche development, that have not yet been systematically examined through a TIS lens. Thus, this research is guided by two key questions: (1) What are the socio-technical dynamics driving the transition to timber building projects? and (2) How do project-level socio-technical dynamics contribute to, and constrain, the facilitation of timber construction within the residential construction industry when interpreted through a TIS framework?

To address key questions surrounding the dynamics of timber construction in the Netherlands, we first review literature on socio-technical transition dynamics relevant to this field, highlighting notable gaps in existing research. Anchoring our qualitative study within the Technological Innovation Systems (TIS) framework, we draw on 17 semi-structured interviews with diverse actors involved in residential timber construction in the Netherlands. Through this approach, we identify five recurring socio-technical dynamics such as leadership, standardization, product-based construction, stakeholder alignment, and business case viability. In doing so, this study contributes to a more contextualized understanding of how innovation unfolds in timber construction and offers both theoretical and practical insights for accelerating sustainable transitions in construction. We conclude with a summary of our contributions, discuss limitations, and outline directions for future research.

Literature review

This section explores the literature on timber construction as a socio-technical transition and the relevance of the Technological Innovation System (TIS) framework in analysing the integration of timber construction into mainstream building practices.

Timber construction as a socio-technical transition

Transition is a long-term, multi-dimensional reconfiguration of technologies, actor networks, practices, and institutions (Geels 2004). Timber adoption can be treated as both innovation adoption, i.e. the uptake of a new material, and broader socio-technical transition, i.e. construction sector incrementally shifting away from cement- and steel-based logics. It occurs within a sector still structurally and institutionally optimized for concrete and steel. This means that the emerging “timber transition” interacts with, and is constrained by, the dominant cement-based regulations, design norms, contracting models, supply chains, and risk perceptions. Understanding the transition therefore requires examining how timber actors operate within this incumbent regime rather than replacing it, which is characteristic of early-stage niche development.

While transition studies in general have explored socio-technical change, the construction industry presents distinct characteristics that complicate innovation adoption. These include its fragmented supply chains, strong path dependencies, risk-averse culture, and regulatory complexity (Slaughter 1998, Uusitalo *et al*. 2024). Unlike more centralized sectors, construction projects are temporary coalitions involving diverse stakeholders, each with unique interests and incentives (Winch 1998). Specifically, the features of the construction sector such as project-based delivery models, stakeholder fragmentation, and regulatory rigidity hinder systemic alignment and slow the uptake of novel technologies like timber (Mahapatra and Gustavsson 2008). Thus, transitions in construction cannot be viewed as linear shifts but as multi-scalar, adaptive processes embedded in institutional routines, actor networks, and material practices.

The transition to timber construction signifies a systemic shift from conventional, resource-intensive materials and construction methods toward more sustainable, circular, and prefabrication-based timber solutions, reflecting changes in technology, practices, and institutional frameworks rather than a simple material substitution. It involves a diverse range of stakeholders, including timber producers/suppliers, lead clients, the government, architects, contractors, knowledge providers such as research institutions, and others such as insurers, consultants, and banks (Mahapatra and Gustavsson 2008). For it to succeed, entrepreneurs in the sector must take the initiative in establishing new networks, staying ahead of the competition, actively developing technologies, and generating demand by informing stakeholders (Woolthuis *et al*. 2010). Timber producers and contractors seek to create demand by challenging traditional construction processes through pilot projects that showcase the potential of timber (Moore and Doyon 2023). However, they face challenges due to limited participation from two key actors: the government, which demands high quality to validate new timber construction techniques, and lead clients, who are hesitant due to concerns about higher costs (of construction, failure, and maintenance), uncertainty regarding long-term performance and durability, and a lack of expertise and skilled labour in the supply chain (Jones *et al*. 2016).

In the residential construction sector, timber building practices are increasingly shaped by standardized conceptual building and industrialization (Lessing *et al*. 2015). These approaches facilitate the market adoption of timber by integrating socio-technical dynamics that support the transition. An integrated design approach is essential for adoption at a larger scale (Wagner *et al*. 2020). However, certain properties of timber, such as its neutral character as a natural material and its linear elastic behaviour under typical conditions, can present challenges when translating designs into production, which may result in errors, redesigns, and potential increases in cost and project duration (Santana-Sosa and Kovacic 2022). Execution plans between planners and timber contractors often suffer from incomplete or inaccurate details due to a lack of knowledge about prefabricated timber construction, requiring ongoing revisions, and adjustments (Brege *et al*. 2014).

The redesign phase, occurring between design and production, often faces challenges because company-specific solutions do not easily align with the systems, platforms, and supply chains of the involved entities, leading to coordination difficulties and potential inefficiencies (Fixson and Park 2008). This complex, multidisciplinary process can lead to substantial delays, cost overruns, and dissatisfaction among value chain actors if not carefully managed. Ribeirinho *et al*. (2020) suggest three strategies to integrate timber expertise early in the design phase: hiring an independent timber specialist, engaging an experienced design team, or involving the timber construction company as an advisor or contractual partner. These strategies highlight the systemic changes needed to move beyond conventional construction practices by embedding timber expertise early in design, which transforms actor roles, collaboration patterns, and knowledge flows. Given the risks and uncertainties associated with innovation, timber construction stakeholders aim to mitigate these challenges by information-sharing and absorbing additional project costs (Toppinen *et al*. 2018). This process of information-sharing plays a key role in reducing risk and uncertainty, particularly in an industry lacking standardization such as the construction industry (Ozorhon *et al*. 2014). Thus, achieving a low-carbon housing future requires more than technical solutions and it necessitates fundamental structural changes in housing provision and usage (Doyon and Moore 2019, Raven *et al*. 2021).

The transition to innovative timber practices, framed within the landscape of transition model (Moore 2012), is occurring within specific niches. Niches are protected spaces where radical innovations can mature, relatively shielded from prevailing market selection pressures (Schot and Geels 2007). According to Moore and Doyon (2023), timber construction has not yet led to a systemic industry-wide transformation, though experimentation and niche-level development have been substantial. In the Netherlands, increasing regulatory pressure is beginning to challenge conventional construction practices, signalling that timber construction may be approaching an early acceleration phase in which niche experimentation intensifies, without yet resulting in regime-level stabilisation. As niche players start to disrupt entrenched practices, there is a need to understand the enabling processes and conditions for transitioning timber into mainstream residential construction. Here, socio-technical perspectives such as the Technological Innovation System (TIS) framework can be helpful.

Technological innovation Systems (TIS) framework

Research on the social aspects of technology has often been overlooked, with greater emphasis placed on the "content" of technology rather than its broader societal impact. However, technological progress is not driven solely by inherent logic; it is influenced by organizational, political, economic, and technological factors, as well as actor strategies (Murtagh *et al*. 2020). A socio-technical perspective enables the identification of dynamics that add value to the existing system (Geels 2004) and such an approach can facilitate the transition to timber construction by improving political engagement, mapping actor relationships, and enhancing collaboration among stakeholders. Understanding these dynamics can strengthen links between designers and users while supporting the development of integrated socio-technical frameworks (Rohracher 2001). Additionally, examining stakeholder strategies and perspectives can contribute to a more transparent dialogue on sustainability in timber buildings (Ninan *et al*. 2022).

While several socio-technical perspectives and broader transition theories, offer valuable insights into innovation within the construction sector, this study adopts the Technological Innovation Systems (TIS) framework to analyse timber construction transitions. TIS provides a structured lens to examine how emerging technologies develop, diffuse, and become institutionalized within a socio-technical context (Bergek *et al*. 2008, Hekkert and Negro 2009). It focuses on the dynamic interactions between actors, networks, institutions, and technologies, and emphasizes key system functions such as knowledge development, market formation, and institutional alignment, that enable or constrain technological transitions. Thus, compared to other transition frameworks like the Multi-Level Perspective (MLP) or Strategic Niche Management (SNM), TIS offers a more actionable and functionally oriented approach, making it particularly suitable for understanding how the complex organizational, market, and regulatory dynamics shape timber adoption within the established construction industry (Ortt and Kamp 2022).

The Technological Innovation System (TIS) framework is defined as a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology (Carlsson and Stankiewicz 1991). Building on this foundation, Bergek *et al*. (2008) propose a detailed scheme of analysis that includes both structural elements and functional processes across actors, networks, institutions, and technologies, that determine system performance. These seven key system functions include: (1) entrepreneurial experimentation as the testing, adapting, and demonstrating new technologies and applications, (2) knowledge development as the learning by doing, using, and interacting, including R&D and experiential learning, (3) knowledge diffusion through networks as the exchange of information and learning across actors and institutions, (4) guidance of the search as the visions, expectations, and policy targets that shape directionality, (5) market formation as the development of demand, standards, and user acceptance, (6) resource mobilization as the allocation of financial, human, and physical capital to support development, and (7) legitimation as the social acceptance and political support that stabilize expectations. Each function is interdependent and subject to feedback dynamics (Hekkert and Negro 2009). For example, entrepreneurial experimentation may generate new knowledge, which diffuses through networks and shapes collective expectations and at the same time, legitimation can help attract resources and strengthen market formation. System performance is assessed based on the presence, strength, and alignment of these functions (Bergek *et al*. 2015). However, Weckowska *et al*. (2025) show in their systematic review of 138 studies that, TIS is criticized for its insufficient attention to macro-level structures, under-specification of agency, and focusing too heavily on enabling conditions, while underemphasizing power dynamics and structural barriers. Furthermore, existing TIS formulations often lack explicit mechanisms to capture temporal dynamics of standardization processes and the interplay between product-, process-, and project-based innovations. The construction sector provides a rich context to address these gaps in TIS and study structural barriers with its unique project-based, highly regulated setting, temporary coalitions and slow-moving institutional change.

While the TIS framework has been extensively applied to manufacturing and energy sectors (e.g. Markard and Truffer 2008), its application to the construction industry, and specifically to timber construction, remains limited. This research addresses this gap by applying the TIS framework to the specific context of timber construction helping us understand the socio-technical dynamics at play in the transition towards timber. We thereby aim to advance theoretical understanding of socio-technical transitions within the built environment for providing actionable insights for industry stakeholders.

Research setting and method

This study investigates the incentives, challenges, and drivers influencing the transition to timber construction through a qualitative research study. Qualitative research methods are effective in providing deep, contextualized insights, enabling a thorough exploration of complex phenomena in specific settings (Lundin and Steinthórsson 2003). The Netherlands was chosen as the study area due to three reasons. First, its increasing emphasis on sustainable building practices, growing policy support for sustainable construction, and the presence of innovative timber construction projects (Walker *et al.* 2021). The setting has significant government interest through ambitious initiatives such as the Circular Construction Economy mission targeting full circularity by 2050. Second, despite this momentum, significant barriers remain, including regulatory uncertainties, market hesitancy, high levels of institutional fragmentation, and pressure to innovate in both new build and infrastructure rehabilitation. Finally, the sector is marked by a complex project-based organization, diverse actor networks, and a tradition of consensus-based policy development offering a setting different from other countries such as Sweden or Finland where TIS has been applied, with a more centralized and regulatory frameworks. Studying the Netherlands context provides insights into how timber construction is evolving in a highly regulated and innovation-driven environment, making it a valuable context for understanding broader industry transitions.

While TIS framework is typically applied at a system-level, recent studies show that system functions also manifest through the practices, constraints, and coordination challenges experienced by actors in concrete projects (Sovacool 2021). Semi-structured interviews were conducted with key stakeholders in the Netherlands timber construction projects. Respondents were selected using purposive and snowball sampling to ensure representation from various actors involved in the transition, including architects, engineers, contractors, developers, policy advisors, etc. While certain stakeholder categories such as Ministry officials, standardization bodies, financers, architects, and real estate investors were not directly interviewed due to access constraints, we sought to address these gaps by including interviewees from organizations engaged in regular dialogue with these groups such as municipalities, contractors, clients, and housing corporations. Interview questions were designed to explore key aspects of timber construction, such as regulatory challenges affecting timber construction, how investors and developers perceive the timber buildings compared to traditional materials, technical barriers in scaling timber construction, the role of different stakeholders in facilitating or hindering timber adoption, etc. The semi-structured format allowed for flexibility, enabling respondents to elaborate on key themes while ensuring consistency across interviews (Aberbach and Rockman 2002). The interview protocol used in this study is shown in Appendix A. All interviews were audio-recorded with participant consent and transcribed for analysis.

A total of 17 interviews were conducted and even though it may be considered modest for a sectoral-level study, it aligns with comparable qualitative studies of achieving theoretical saturation (Guest *et al.* 2006, Boddy 2016), where the aim is to gain depth of understanding rather than statistical representativeness. Saturation was assessed through ongoing data analysis, where patterns and themes became consistently reinforced rather than yielding novel perspectives. This ensured that the findings captured the most critical enablers and barriers without unnecessary redundancy. Interviews lasted approximately 60 minutes, with some extending to 105 minutes, depending on the depth of discussion. Interviews were conducted in-person and via video conferencing, depending on respondent availability. The details of the interviews conducted are summarized in Table 1.

Along with interviews, we have also analysed publicly available policy reports such as Manifesto Circular Construction Economy 2050, Guidance on the EU Timber Regulation, Houtbouw (timber construction) Pact MRA 2025–2030, Houtbouwmythes (timber construction myths), CircuLaw impact reports, etc., to strengthen the system-level interpretation of the project-level findings.

To analyse the interview data, we employed a structured qualitative coding approach informed by TIS functions (Bergek *et al.* 2008), using them as

Table 1. Interviews regarding timber transition in the Netherlands.

	Organization (Designation)	Duration
1	Contractor (Commercial Manager)	54 m
2	Housing Corporation (Sustainability Manager)	60 m
3	Representative Municipality (Project Lead)	80 m
4	Contractor (Project Manager)	64 m
5	Contractor (Commercial Manager)	56 m
6	Contractor (Director Region South)	55 m
7	Representative Housing Corporation (Project Manager)	61 m
8	Contractor (Project Manager)	59 m
9	Lead Client (Project Developer)	57 m
10	Municipality Network MRA (Project Lead)	58 m
11	Timber Transition Maker (Director)	68 m
12	Timber Network (Director)	52 m
13	Contractor (Head of Industrialization)	42 m
14	Advice & Engineering (Manager Design)	105 m
15	Advice & Engineering (Commercial Manager Midrise)	65 m
16	Contractor (Sponsor timber projects)	55 m
17	Contractor (Director Production & Assembly)	72 m

interpretive lenses. The coding process combined both deductive and inductive strategies. First, we developed a deductive coding scheme based on the seven core TIS functions such as entrepreneurial experimentation, knowledge development, network formation, guidance of the search, market formation, resource mobilization, and legitimation. These functions were operationalized into first-order codes, which we used as analytical lenses to identify segments of text that corresponded to established theoretical constructs. Simultaneously, inductive coding was used to capture novel or context-specific themes that emerged from the interviews but were not explicitly covered by the TIS framework such as practices unique to Dutch project delivery models or actor coordination in timber pilot projects. As coding progressed, new inductive codes were refined and occasionally clustered under broader TIS-related categories when conceptual alignment became apparent. Through iterative coding cycles, we employed constant comparison to examine relationships between codes, identify recurring patterns across interviews, and synthesize higher-order themes. Memos were written throughout to document emerging insights, connections between actors and processes, and interactions between socio-technical factors. This grounded, theory-informed approach allowed us to develop an empirically supported analytical model that maps how TIS functions manifest in the context of Dutch timber construction. In doing so, we were able to systematically link interview data to the TIS framework, while remaining open to contextual nuances that extend or adapt the original theoretical structure.

Findings

This section presents the main empirical observations from semi-structured interviews on timber construction in the Netherlands, structured around three thematic domains: organizational shifts shaping timber innovation within individual projects, actor interactions and project coordination, and the financial and institutional constraints that shape feasibility.

Organizational shifts driving timber adoption

The transition to timber construction in the Netherlands is primarily propelled by top-down strategic decisions from within construction firms. These are often spearheaded by leaders who possess a strong conviction in the potential of timber and act as internal champions for change. One of such champions, a commercial manager of a timber project from the contractor side described how securing an initial timber contract acted as a catalyst for future opportunities, as below,

> For this timber project, we secured a win, and that truly acted as a catalyst for further opportunities. As a result, I noticed that our involvement in inquiries increased significantly. Suddenly, instead of being placed on a long list of potential sustainable projects, we were directly shortlisted for other inquiries. (Contractor, Interview #5)

A project developer from a client organization highlighted that they have to maintain continuity in conventional building methods to ensure business sustainability. Moreover, the lack of robust assessment frameworks for timber contributes to uncertainty during design and planning. This is compounded by the burden of documentation, especially when proving compliance with fire, acoustic, and structural standards, further slowing adoption.

Standardization plays a central role in the scalability of timber construction. A respondent from the contractor side claimed that shifting to timber construction inevitably requires embracing industrialization, standardization, and modularity to achieve cost and time efficiencies. The respondent highlighted the importance of an industrialization team which is a dedicated group within construction firm responsible for scaling and systematizing prefabrication and product-based approaches, in contrast to traditional project-based teams. Yet, a common practice has been to convert concrete designs into timber without sufficient adaptation, often leading to technical and financial risks. Treating timber as a substitution material rather than leveraging its unique attributes compromises feasibility.

Internally, construction firms must undergo organizational restructuring to accommodate a product-based logic. This involves redefining roles, transferring tasks between departments, and forming dedicated timber units capable of overseeing prefabrication and quality control. Early timber projects serve as valuable references, with project teams increasingly drawing on cross-project learning to refine future practices. A contractor highlighted the significance of learning from past projects:

> Looking forward, it is vital to learn from these experiences. If faced with another timber construction request, we might have to reconsider the project's approach unless we can apply lessons learned. (Contractor, Interview #16)

The move from bespoke, project-based methods toward a conceptual design strategy enables repeatability and cost predictability through standard building systems. Central to this transformation is a clear allocation of responsibilities, particularly around product ownership and inter-departmental communication. Thus, strategic decision-making, leadership commitment, internal restructuring such as forming industrialization teams, and shifts from project- to product-based models play a role in how organizations adapt to enable timber construction.

Actor interactions and project coordination

Success in timber construction hinges on stakeholder alignment, both internal and external, as they share a belief in the potential of timber as a construction material. Yet scepticism remains, especially regarding long-term performance and financial risk. Collaborative approaches, such as Bouwteam contracting, where client and contractor work together from an early project stage to jointly develop the design, technical specifications, and cost estimation, helps mitigate risks and fosters learning. Relationships with external experts, especially manufacturers, are key to building technical capacity. Contractors benefit from long-term collaborations with timber suppliers, policymakers, and industry experts, allowing them to lobby for regulatory changes and develop robust compliance frameworks. A regional director emphasized the importance of partnerships in pioneering timber construction:

> We knew that we had to pioneer by completing the first large-scale timber project including a neighbourhood, and as shared through lessons learned in practice, it is important to bridge the barriers of partnering up with manufacturers as big as us. (Director, Interview #6)

At the same time, alignment with client needs in tenders must be prioritized to avoid downstream design revisions. Teams also face the challenge of maintaining consistent sustainability goals throughout execution, requiring frequent communication and value alignment with clients and subcontractors. A recurring issue is the misalignment between the tender phase and execution, especially when the technical feasibility of timber designs is underdeveloped during bidding. The fragmented industry efforts limit knowledge-sharing, as highlighted by the director of a timber transition maker:

> Many builders are still developing their systems independently, without fully recognizing that they are part of a larger transition. Greater collaboration and a shared commitment to the broader goals are needed. This is evident in many areas, such as the introduction of digital techniques and parametric modelling, which are costly but necessary. (Timber transition maker, Interview #11)

Traditional building design approaches are not easily adaptable to timber. Many project leads, who were accustomed to concrete and brick construction, initially treated timber as a substitution material, rather than redesigning projects to optimize its strengths. This led to misalignment between design requirements and financial projections, causing cost overruns and jeopardizing project feasibility. Thus, stakeholder engagement, tender processes, collaborative models such as Bouwteam, and external partnerships highlights the importance of relationships and coordination in timber construction.

Financial and institutional constraints

The availability of funding for R&D, especially during early design stages is a critical enabler for transition to timber construction. One key financial strategy is incorporating the residual value of timber buildings into project business cases, making timber more attractive to clients. A commercial manager described a case where the client provided financial assistance to sustain the timber project:

> When the timber project led to a negative business case, the client offered financial support to cover part of the research costs and additional time to help the team become familiar with designing using timber. (Commercial manager, Interview #5)

By absorbing early-stage risks, clients can accelerate industry-wide timber adoption and increase financial feasibility for construction firms. In contrast, projects that fail to secure a viable business case, whether due to underestimated risks or changing market conditions, may be halted altogether. One of the key risks lies in translating financial models from concrete to timber, which often leads to flawed assumptions about costs, margins, and durability. Support from academic institutions and design researchers provide crucial guidance, helping project teams make more informed choices about materials and system configurations.

Ultimately, timber requires a new business logic. Firms must incorporate long-term factors such as residual value, carbon savings, and circularity into their value propositions. In cases where timber projects become financially unviable, contractors may consider alternative materials, as described by a project developer:

> We won the tender based on timber and sustainability, so stepping away from bio-based materials is utmost challenging and can knock us out of the project. However, we are exploring the possibility of constructing some homes with sand-lime brick, especially the more expensive ones, as it offers more design insurability than timber. (Project Developer, Interview #9)

This highlights the practical trade-offs between sustainability commitments and business feasibility, requiring adaptive decision-making during project execution. For timber to be scalable, construction firms may need to adapt their existing business models, risk management strategies, and financial assessment frameworks to better reflect the unique characteristics of timber construction. At the same time, construction firms struggle to scale timber projects at a pace that balances risk and opportunity. A measured, portfolio-based approach is often used to reduce exposure. The failure of complex initial projects can significantly hinder organizational confidence and market positioning. As a project manager noted:

> It is not favourable to undertake an overly complex timber construction project as the very first pilot project, as this increases failure costs throughout the design process and challenges the viable business case. (Project Manager, Interview #4)

Finally, design cost overruns, especially during early pilot projects, often occur due to the unfamiliarity of teams with timber-specific detailing and lack of tolerance in prefabricated systems. Supporting this transition demands not only financial flexibility but also systemic learning, ongoing intra-firm and inter-firm knowledge exchange, and robust collaboration with regulators and supply chain partners. Thus, economic feasibility of timber construction is possible through managing financial risks, regulatory barriers, business case fragility, and early-stage funding challenges.

The empirical observations discussed in this section are summarized in Table 2 for quick reference.

Overall, the findings show that timber construction projects act as recurring sites of knowledge development and entrepreneurial experimentation, while difficulties related to legitimation and resource mobilisation continue to constrain broader uptake. Although these dynamics are observed at the project level, their repetition across cases suggests shared challenges faced by timber construction actors, which are discussed in the following section as implications for the further development of timber construction beyond individual projects.

Discussion

This section discusses the findings from the Netherlands context through the lens of the Technological Innovation Systems (TIS) framework anchoring the observed project-level socio-technical dynamics of leadership, standardization, product-based construction, stakeholder alignment, and business case viability, to the TIS functions.

Socio-technical dynamics in the shift towards timber building projects

Leadership

Building on the finding that timber construction projects rely heavily on proactive and risk-tolerant actors, leadership emerges as a central socio-technical dynamic shaping the direction of timber adoption. In TIS terms, leadership primarily contributes to the guidance of the search function by articulating visions, setting strategic priorities, and signalling commitment to timber construction (Bergek *et al*. 2008). Pioneering clients, developers, and contractors initiate pilot projects, absorb early-stage risks, and actively demonstrate the feasibility of timber solutions, thereby shaping expectations within and beyond individual projects. These observations align with prior work highlighting the role of building entrepreneurs in emerging construction niches, who actively create demand and develop technologies ahead of broader market readiness (Woolthuis *et al*., 2010). Leadership also supports entrepreneurial experimentation, as actors test and adapt timber technologies through concrete applications, learning from both successes and failures. In line with Clegg and Ninan (2023), leadership is not concentrated in a single organisational role but distributed across project networks, reflecting Mintzberg; (1979) notion of decentralised decision-making authority. At the same time, leadership contributes to legitimation by enhancing the credibility of timber construction among regulators, financiers, and supply-chain partners. High-profile projects and committed public clients help stabilise expectations and reduce perceived risks. However, the findings suggest that leadership remains largely project-specific and dependent on individual champions. From a system perspective, this fragmentation limits the institutionalisation of guidance mechanisms, reinforcing reliance on ad hoc initiatives rather than coordinated system-level direction.

Standardization

The findings show that standardisation plays a dual and somewhat paradoxical role in timber construction. On the one hand, standardisation, particularly through prefabrication and industrialised production, enhances efficiency, reduces construction time, and improves

Table 2. Summary of empirical observations.

	Empirical observations	Socio-technical dynamics	TIS function
Organizational shifts driving timber adoption			
1	Putting forward driven leaders that truly believe in the transition and the future of timber construction. (Interview #3)	Leadership	Guidance of the search; Legitimation
2	Spin-off strategic decision undertaking timber project serving as a catalyst for future opportunities and building legitimacy (Interview#5)	Leadership	Guidance of the search; Legitimation
3	Continuity of an organization, where the traditional way of building still must remain a part (Interview #9)	Leadership	Guidance of the search; Legitimation
4	Lack of robust frameworks for timber project assessment (Interview #14)	Standardization	Market formation; Legitimation
5	The need to provide extensive documentation and evidence of compliance with local regulations on timber performance and quality (Interview #11)	Standardization	Market formation; Legitimation
6	Shift towards timber inherently leads to incorporating both standardization and industrialization (Interview #13)	Standardization	Market formation; Legitimation
7	Converting design from concrete into wood while adhering to traditional design choices (Interview #14)	Standardization	Market formation; Legitimation
8	Coordinating new processes of internal network formation and task transfers (Interview #10)	Product-based construction	Entrepreneurial experimentation; Knowledge development
9	Securing cross-references and knowledge transfer from the first timber construction projects (Interview #16)	Product-based construction	Entrepreneurial experimentation; Knowledge development
10	Shift construction techniques from project-based approach to conceptual (timber) design approach (Interview #12)	Product-based construction	Entrepreneurial experimentation; Knowledge development
11	Clear allocation of shifts in responsibilities as product owner and communication channels in new process (Interview #5)	Product-based construction	Entrepreneurial experimentation; Knowledge development
Actor interactions and project coordination			
12	Perception, acceptance & true belief in timber buildings by stakeholders, internal colleagues as well as external clients & resident users (support base) (Interview #3)	Stakeholder alignment	Legitimation; Knowledge diffusion through networks
13	Involve client in innovative timber designs preferably in a "Bouwteam" for demarcating liability (Interview #14)	Stakeholder alignment	Legitimation; Knowledge diffusion through networks
14	Network formation with knowledgeable external partners and building strong relationships (Interview #6)	Stakeholder alignment	Legitimation; Knowledge diffusion through networks
15	Identification and incorporating of knock-out criteria in tender during an innovation trajectory - e.g. fully understanding the client's needs and wishes (Interview #9)	Stakeholder alignment	Legitimation; Knowledge diffusion through networks
16	Alignment of shared ambitions on sustainability and conveying project goals throughout the construction phase (Interview #11)	Stakeholder alignment	Legitimation; Knowledge diffusion through networks
17	Misalignment between the tender bid and design phase for execution on timber projects (Interview #15)	Stakeholder alignment	Legitimation; Knowledge diffusion through networks
Financial and institutional constraints			
18	Availability of funding by the client for research and piloting in innovative timber construction projects (Interview #5)	Business case viability	Resource mobilisation, Market formation
19	Termination of project due to unfeasible business case presented by the contractor (Interview #10)	Business case viability	Resource mobilisation, Market formation
20	Assumptions and uncertainties in financial matrix converted from concrete to wood (Interview #9)	Business case viability	Resource mobilisation, Market formation
21	Support of (academic) research in making design choices on new timber construction techniques (Interview #10)	Business case viability	Resource mobilisation, Market formation
22	Incorporation of a new perspective on the respective timber business case (Interview #9)	Business case viability	Resource mobilisation, Market formation
23	Finding the sweet spot between the pace of upscaling timber projects and reinventing the timber wheel (Interview #12)	Business case viability	Resource mobilisation, Market formation
24	Increase failure costs due to undertaking an overly complex timber construction project for an initial pilot (Interview #4)	Business case viability	Resource mobilisation, Market formation
25	Limitations on design alterations when cost overruns in the design phase occur due to project's innovative nature and unfamiliar construction techniques (Interview #6)	Business case viability	Resource mobilisation, Market formation

cost predictability, supporting timber's viability as an alternative to conventional materials. This echoes prior research emphasising the importance of standardised production processes for improving predictability in construction (Ribeirinho *et al*. 2020). On the other hand, the findings indicate that standardisation efforts in timber construction remain largely actor-led and project-specific, rather than sector-wide. Interpreted through a TIS lens, this reflects an early and incomplete phase of market formation, where standards, rules, and user expectations are still emerging and have not yet stabilised (Bergek *et al*. 2008). Within the TIS literature, such standards can be understood as innovation-specific institutions constituting formal and informal rules aligned with an emerging technology rather than with incumbent regimes. While standardisation contributes to legitimacy by stabilising expectations and coordinating actor behaviour (Grillo *et al*. 2024), its timing and scope remain critical. Early standardisation risks locking in suboptimal configurations, whereas delayed standardisation prolongs uncertainty and hinders diffusion (Toh and Pyun 2024). The prevalence of project-specific standards observed in this study suggests a formative phase in which projects function as testing grounds for institutional arrangements, but limited diffusion constrains broader market expansion and systemic legitimacy.

Product-based construction

The shift towards product-based construction observed in the findings reflects attempts to move beyond traditional project-based delivery models. Interpreted through the TIS framework, this dynamic can be understood as a form of entrepreneurial experimentation, where firms explore prefabricated systems, modular components, and repeatable design solutions to improve efficiency and reduce uncertainty (Bergek *et al*. 2008). These experiments are closely linked to knowledge development, as learning occurs through design iterations, construction experience, and feedback among project partners. The importance of managing the pace of scaling is evident, as overly complex early projects can undermine business cases and threaten organisational commitment. This aligns with Gosselin *et al*. (2018), who characterise timber innovation as an early-stage process marked by heightened risks and uncertainties. While the findings indicate movement toward product-based approaches, recent work suggests that timber diffusion may also require broader transformation of construction processes and workflows, rather than a simple shift from projects to products (Sheikhkhoshkar *et al*. 2024). From a system perspective, the persistence of project-embedded learning suggests limitations in knowledge diffusion through networks, as insights gained from experimentation are not consistently codified or shared across organisations and projects.

Stakeholder alignment

Stakeholder alignment emerged as a critical socio-technical dynamic across the cases, reflecting the need to coordinate among clients, contractors, designers, suppliers, regulators, and insurers. From a TIS perspective, stakeholder alignment primarily contributes to legitimation, as shared understandings regarding timber's performance, durability, and regulatory compliance help build social acceptance and political support (Bergek *et al*. 2008). Collaborative contracting arrangements, such as Bouwteam agreements, facilitate early knowledge sharing and risk mitigation, supporting both legitimation and knowledge diffusion through networks. These findings are consistent with prior research highlighting the importance of coordination between design and production in prefabricated construction (Santana-Sosa and Kovacic 2022, Jones *et al*. 2022). Early design freezes, while challenging, are necessary to avoid delays and cost overruns in timber projects. However, the findings also show that alignment is often achieved through intensive, project-specific coordination rather than through stabilised sectoral arrangements. Network formation with timber suppliers and external experts helps navigate regulatory hurdles (Ortt and Kamp 2022), but the continued reliance on bespoke coordination limits cumulative system-level learning and reinforces the project-based nature of timber innovation.

Business case viability

Business case viability remains a central concern shaping timber adoption. The findings highlight challenges related to upfront costs, perceived risks, and uncertainty regarding residual value. From a TIS perspective, these challenges reflect constraints in resource mobilisation, encompassing financial capital, specialised expertise, and organisational capabilities (Bergek *et al*. 2008). Clients who subsidise pilot projects or support early-stage research act as niche enablers, temporarily alleviating resource constraints and supporting market formation by creating protected spaces for experimentation. These observations resonate with Ribeirinho *et al*. (2020), who emphasise the importance of integrated design approaches to reduce misalignments between design and production, particularly when transitioning from concrete-based designs to timber.

Collaboration among timber producers, contractors, and emerging distribution channels helps address conservative industry practices (Woolthuis *et al.* 2010), while external research partnerships support organisational learning (Lessing *et al.* 2015). Nevertheless, the recurring nature of business case challenges across projects suggests that resource mobilisation problems are systemic rather than incidental, despite being experienced at the project level.

Implications

This study contributes to the literature on technological innovation systems (TIS) by illustrating how project-based empirical material can be meaningfully interpreted using TIS functions without claiming comprehensive system-level assessment. By anchoring recurring project-level socio-technical dynamics, such as leadership, standardization, product-based construction, stakeholder alignment, and business case viability, to specific TIS functions, the study demonstrates how project settings can serve as analytical entry points for understanding emerging innovation pathways in highly fragmented and project-oriented sectors such as construction. The findings also refine existing TIS debates by highlighting the uneven development of system functions in timber construction. While entrepreneurial experimentation and knowledge development are relatively strong due to the prevalence of pilot projects and learning-by-doing, functions related to market formation and legitimation remain fragile. This imbalance suggests that the presence of repeated experiments alone is insufficient to trigger broader system stabilisation, supporting prior arguments that innovation system development is non-linear and functionally asymmetric (Bergek *et al.* 2008). Moreover, the study contributes to discussions at the intersection of TIS and construction innovation by clarifying the role of innovation-specific institutions in project-based industries. The findings show that standardisation and regulatory practices in timber construction remain largely project-specific, indicating that innovation-specific institutions are still emergent rather than stabilised. This nuance extends existing work on socio-technical change in construction (Winch 1998, Rohracher 2001) by showing how institutional experimentation can remain embedded in projects, thereby limiting cumulative system-level learning and diffusion. Importantly, the findings caution against interpreting increased timber use as evidence of a full sectoral transition. Instead, the observed dynamics point to an incremental and contested system development process, aligning with transition scholarship that emphasises the coexistence of niche experimentation and regime stability rather than abrupt substitution (Smith *et al.* 2005, Loorbach *et al.* 2010).

For construction firms, developers, and clients, the findings underline the importance of recognising timber projects not only as delivery challenges but also as strategic learning opportunities. Leadership by pioneering clients and contractors plays a critical role in guiding experimentation and legitimising timber solutions. However, reliance on individual champions also introduces vulnerability; organisations should therefore invest in internal structures that institutionalise learning from timber projects, such as codified design guidelines, repeatable component libraries, and cross-project knowledge-sharing routines. The findings further suggest that efforts to improve business case viability should go beyond cost optimisation within individual projects. Firms can strengthen resource mobilisation by developing long-term partnerships with timber suppliers, insurers, and design specialists, thereby reducing uncertainty and transaction costs across projects. Moving towards product-based or process-oriented construction models may help stabilise workflows and improve predictability, but such shifts require careful pacing to avoid overexposure to technical and financial risk in early-stage projects (Gosselin *et al.* 2018). Stakeholder alignment emerges as a persistent challenge, particularly due to the need for early design decisions and regulatory approval in timber projects. Practitioners may benefit from collaborative contracting models, such as Bouwteam arrangements, that enable earlier coordination and shared risk management (Santana-Sosa and Kovacic 2022). Explicitly addressing misalignments between design and execution phases can help avoid cost overruns and reinforce confidence in timber-based solutions.

From a policy perspective, the findings suggest that supporting timber construction requires more than funding additional pilot projects. While pilots are effective in stimulating entrepreneurial experimentation and knowledge development, their systemic impact depends on mechanisms that enable learning to travel beyond individual projects. Public procurement can play a key role in this regard by acting as a source of legitimation and demand creation, particularly when public clients articulate clear performance expectations and sustainability goals. Targeted procurement strategies can help stabilise market expectations and reduce perceived risks for private actors, thereby strengthening market formation. In addition, policymakers and regulatory bodies can accelerate system development by supporting the creation and diffusion of innovation-specific institutions, such as harmonised standards, certification schemes, and approval procedures tailored to timber construction. Reducing regulatory ambiguity can lower entry barriers and support resource mobilisation across the supply chain. Finally, the findings highlight the importance of coherent policy narratives around timber construction. Conflicting policy logics, such as tensions between ecological modernisation goals and cost-efficiency imperatives, can weaken legitimation and slow adoption (Toivonen *et al*. 2021). Aligning environmental, industrial, and construction policies may therefore be crucial for enabling timber construction to move beyond isolated projects toward more stable and scalable application.

Conclusion

This study set out to examine how timber construction projects in the Netherlands are shaped by socio-technical dynamics and to explore what these dynamics imply for the broader development of timber construction when interpreted through a Technological Innovation Systems (TIS) lens. We focused on project-level empirical material and used selected TIS functions as analytical lenses to interpret recurring patterns observed across projects. The findings show that timber construction projects are characterised by a combination of leadership, project-specific standardisation efforts, experimentation with product-based construction approaches, intensive stakeholder alignment, and ongoing challenges related to business case viability. Interpreted through the TIS framework, these dynamics primarily contribute to entrepreneurial experimentation and knowledge development, while functions such as market formation, resource mobilisation, and legitimation remain fragile and unevenly developed. This imbalance helps explain why timber construction can succeed in individual projects yet struggles to stabilise as a routine and scalable practice across the sector. Importantly, the analysis highlights the central role of projects as sites of learning, experimentation, and temporary legitimation in a highly fragmented and project-oriented industry. At the same time, the persistence of bespoke solutions, project-specific standards, and reliance on individual champions suggests that learning and legitimacy often remain locally embedded rather than diffused and institutionalised. From a system perspective, this limits cumulative development of innovation-specific institutions and constrains the translation of project-level successes into broader system stability.

From a theoretical perspective, the contribution lies in offering a conceptual and analytical clarification of how TIS functions can be applied to interpret project-based socio-technical dynamics in construction. The study demonstrates how project-level patterns can be meaningfully linked to system functions without over-claiming system-level empirical evidence, and it highlights the limits of project-based experimentation for stabilising functions such as market formation and legitimation. In doing so, it helps clarify boundary conditions for applying TIS thinking in industries characterised by temporary organisations, bespoke production, and fragmented governance. Practically, the findings suggest that continued reliance on isolated pilot projects and individual champions is unlikely to be sufficient for mainstreaming timber construction. While such projects are valuable for experimentation and learning, greater attention is needed to mechanisms that enable knowledge diffusion, institutional stabilisation, and resource mobilisation beyond individual projects. For policymakers, this implies that supporting timber construction requires not only funding additional pilots, but also fostering coherent regulatory frameworks, harmonised standards, and procurement strategies that strengthen legitimacy and reduce uncertainty across the sector.

While this study offers valuable insights, it has several limitations. First, our study primarily focused on actors directly involved in timber construction projects, such as contractors, clients, and project managers. As such, perspectives from other key system actors such as national policymakers, regulatory bodies, financial institutions, and insurers were not explicitly included. Given that these actors often shape enabling conditions for systemic change, future research could more explicitly engage with their roles. Second, while we reference institutional conditions conceptually, we do not deeply explore broader policy frameworks or long-term institutional change. A more integrated treatment of these dimensions would enrich the analysis of how timber construction can be more scalable. Third, the findings are based on timber adoption during the early stages of the project lifecycle, specifically the tender phase. Further research should explore the application of socio-technical dynamics and enabling processes in later phases of the project lifecycle, such as construction, operation, and assembly. Additionally, while this study focused on identifying shared socio-technical dynamics and enabling processes across the timber construction ecosystem, future research could explore how these dynamics vary between different actor groups to provide a more differentiated understanding of their roles and perspectives. Future research should consider comparative studies across different countries to assess the transferability of our findings to other regions with varying regulatory environments. For example, Scandinavian countries, with their extensive prefabrication expertise and lenient building codes (Mahapatra and Gustavsson 2008), and Canada, where carbon sequestration policies incentivize timber projects, offer valuable insights for the global timber transition. Studying these localized enablers could provide a more nuanced understanding of how timber adoption evolves in different contexts. Several well-documented barriers to timber innovation, such as underdeveloped timber supply chains and the influence of incumbent cement and steel industries, do not feature prominently in the empirical findings. This absence does not imply that such barriers are unimportant. Rather, it reflects the project-level focus of the study and the perspectives of the actors interviewed, who were primarily engaged in the execution and coordination of specific timber projects. These regime-level dynamics remain critical topics for future research that explicitly targets sectoral structures, power relations, and material supply chains.

Author contributions

CRediT: **Melissa Law**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft; **Johan Ninan**: Methodology, Supervision, Writing – original draft, Writing – review & editing; **Hans Wamelink**: Supervision, Writing – review & editing; **Pierre Jennen**: Supervision, Writing – review & editing; **Lennert Meulstee**: Methodology, Supervision, Writing – review & editing; **Imke van den Boom**: Supervision, Writing – review & editing.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix

Appendix A. Semi-structured interview protocol

Thank you for taking the time for this conversation. In this interview, I would like to gain more insight into the key socio-technical dynamics in the transition to timber construction and your experiences in this regard. This interview is planned as an open conversation in a semi-structured format.

1. Can you briefly explain your experience and involvement in the construction sector, specifically on timber construction?
2. Can you describe a situation in which you made decisions focused on timber construction? Were there any choices that needed to be reassessed because timber construction was still unfamiliar?
3. What challenges did you encounter in the process of thinking about timber?
4. How would you assess the performance and quality of the timber construction? Are there any specific quality standards or performance indicators that you applied?
5. How does the price of timber construction compare to traditional construction methods? What are the main cost factors in timber construction for this project? Are there any financial advantages or disadvantages that you observed?
6. Can you describe the timber construction production process?
7. What supplementary products and services are crucial for the success of timber construction? Can you give examples of how these products and services have been integrated?
8. Are there specific partnerships or suppliers that play a significant role in timber construction? Can you give examples of how networking impacted timber construction? Which parties do you think are essential for the successful implementation of timber construction?
9. Which institutional dynamics influence timber construction? Are there specific regulations or institutions that have had a major impact on the project?
10. In your opinion, is timber construction currently still a niche product in the market? How do you see the future of timber construction in the coming years or decade? What do you think are the most important factors that will determine the pace and scale of adoption of timber construction in the coming years?

Thank you for your time. I really appreciate the experiences and ideas you have shared. Can you please let me know if there anything else you want to add. Thanks again!