Testing Ecosystem and Collaborative Circular Business Model Frameworks for Hemp-Based CNC-Knitted Construction at Low Technology Readiness Levels

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This paper explores how ecosystem mapping and circular business modeling tools can support early-stage development of hemp-based CNC-knitted construction systems—a low technology readiness level (TRL), bio-based innovation with potential for circular building applications. The study identifies key structural challenges such as fragmented value chains, limited processing infrastructure, and regulatory gaps and highlights the role of digital fabrication, decentralized production, and intermediary actors in enabling more resilient, place-based circular systems.

This research is highly relevant to **Drastic**'s objectives and its **Nordic Demonstrator**, which focuses on the use of reclaimed timber for innovative structural and load-bearing applications in temporary commercial buildings. By addressing both technical and socio-economic barriers, the paper contributes to broader efforts in scaling circular bio-based solutions in the built environment. Additionally, the insights from this paper build on technologies and practices developed in the Drastic project, applied to lower TRL prototypes in the RAW project in order to evaluate how ecosystem and business modelling tools can be adapted to early-stage contexts.

The connection to Drastic is strengthened by the involvement of project parnter **Omtre** who contributed both to this research and who also co-lead Drastic's Nordic Demonstrator, and **Maastricht University** who lead the ecosystem creation and exploitation.

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ABSTRACT

This short paper explores how ecosystem mapping and circular business modeling tools can support early-stage development of hemp-based CNC-knitted construction systems—a low-TRL, bio-based innovation with potential for circular building applications. Focusing on the European Alpine region, the study identifies key structural challenges such as fragmented value chains, limited processing infrastructure, and regulatory gaps. Through stakeholder workshops and speculative modeling, the research highlights the role of digital fabrication, decentralized production, and intermediary actors in enabling more resilient, place-based circular systems. By addressing both technical and socio-economic barriers, the paper contributes to broader efforts in scaling circular bio-based solutions in the built environment.

INTRODUCTION

The built environment remains one of the most materially and energy-intensive sectors in Europe, driving urgent innovation agendas around biobased materials and circular construction systems. The hemp industry is increasingly positioned as a symbolic and material driver of the European Green Transition, due to its regenerative properties and cross-sectoral versatility. Hemp cultivation offers significant ecological co-benefits, including soil regeneration, carbon sequestration, and low input requirements, making it attractive for circular bioeconomies (Crini et al., 2020; The Hempclub Project, 2023). Its utility spans from high-value fibers for composites and textiles to lower-grade applications such as insulation and biomass-based panels, enabling cascading value chains and the profitability of the production (Alex et al., 2015).

While hemp holds strong potential as a circular material, realizing these benefits depends not only on its biological properties, but also on the design of products, business models, and ecosystem governance structures (Bocken et al., 2016). Circularity is not inherent to any material; it must be actively enabled through systemic strategies such as design for disassembly, take-back schemes, and reuse-oriented fabrication (Pomponi & Moncaster, 2016). The circular economy (CE) is increasingly understood as a systemic, multi-actor, and multi-scalar transition that depends on coordinated interactions across diverse stakeholders and stages of material use (Konietzko et al., 2020). In the construction sector, implementing CE principles requires collaboration across the entire building lifecycle—from design and fabrication to operation, reuse, and deconstruction. These transitions introduce new actors

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and practices, reshaping socio-technical ecosystems and demanding new forms of cooperation to embed circularity meaningfully and durably (Evertsen & Knotten, 2024).

This short paper contributes to the development of circular business models and collaborative ecosystem thinking by exploring how early-stage actors can align material innovations—like Computer Numerical Control (CNC)-knitted hemp—with circular principles through participatory mapping and speculative prototyping.

In order to understand how to foster these cascading value chains illustrating hemp's potential to support circular construction systems, the weaknesses and challenges have to be understood - from a multiscalar perspective. Persistent weaknesses and challenges include the lack of agronomic expertise to cope with the inconsistent material quality, lack of processing infrastructure, and unresolved regulatory constraints (Nath, 2023; Sadrmanesh & Chen, 2019). The dynamics of hemp innovation are also deeply geographically uneven, shaped by historical, institutional, and infrastructural differences across regions.

Drawing from economic geography frameworks for circular economy and Technological Innovation Systems (TIS) theory adapted for ecosystem mapping of circularity transitions of the built environment (Vasseur & Lou Kings, 2025), it becomes clear that regions such as France, Belgium, and East Germany benefit from retained expertise and institutional coordination, while Southern Alpine and Italian regions face innovation inertia due to fragmented networks and missing intermediaries (personal communication with experts, 2025). Understanding hemp not simply as a crop, but as a systemic socio-technical assemblage (Wuyts 2025), is crucial for designing effective support mechanisms that are regionally adapted and capable of scaling ecological, social, ethical and economic impact.

The EU-funded RAW project, which investigates the use of computational technologies for Resource AWare architecture, researchers are actively engaging with the natural material variability and supply inconsistencies inherent to bio-based materials like hemp with the aim to integrate these into the material streams, performance demands and scales of the building industry. Noteworthy, inconsistencies of supply cannot be dealt with by computation, but rather by establishing the necessary conditions to support a value chain. Hence, the wider consortium works with actors in the supply chain and socio-technical scientists to identify the reasons for supply inconsistencies and highlight potential avenues for their mitigation.

Within the project`s fiber track, CNC-knitting technology is explored for architectural application- next to coreless fiber winding (outside this short paper's scope).

CNC-knitting offers a great potential for architectural construction and scaling up, despite its common use in the garment sector. An additive manufacturing and programmability of CNC-knit permits the creation of architectural textiles with seamlessly graded properties and waste-free in fabrication. The computational design strategies allow for natural material specific allocation strategies, where the uneven yarn qualities and strength can be steered for better structural performance of the constructed textile element. See Tamke et al. (2020) for a wider discussion. Despite the technical benefits of CNC-knit and the high- Technology Readiness Level (TRL) of the technology in itself, as proved and widely used within the garment sector, the immediate scalability and wide architectural application of graded CNC-knitted membranes is uncertain, especially in the context of the urgent timelines of the green transition. This keeps the architectural CNC-knit at low-TRL for building sector applications. In this setting, custom developed digital design tools become essential not only for design iteration, and further digital fabrication of those advanced materials. This paper explores speculative methods, such as speculative mapping, which can enable early-stage prototyping of possible futures, helping to identify where architectural experimentation intersects with broader socio-technical constraints. They also serve as communication instruments, allowing insights to be shared across diverse stakeholder groups, including policymakers, industry partners, and regional planners, before lock-ins or inequities become institutionalized

The insights presented in this paper build on technologies and practices developed in the DRASTIC project, where higher-TRL demonstrators were tested with major industry partners. In contrast, this phase of the RAW project deliberately focused on lower-TRL experimentation, working with academic research and startup environments, and fragmented supply chains. In doing so, the research sought to evaluate how ecosystem and business modeling tools can be adapted to early-stage contexts where conventional road mapping is too rigid and slow to be useful. Hence, this short paper pursues two interrelated goals:

1. To test the application of ecosystem mapping and business modeling frameworks developed in the DRASTIC project for circular solutions for higher TRL with prototypes at lower TRLs developed in the RAW project, focusing on how these tools support decision-making around exploitation pathways.
2. To extract insights into the broader structural challenges and leverage points affecting the integration of hemp fibers—particularly CNC-knitted tensile membranes—into construction markets, across European contexts, with focus on the Alpine region.

By combining speculative and practical lenses, the study highlights how structured tools can help small actors (such as startups or research groups) rapidly engage with complex innovation ecosystems without oversimplifying them.

METHOD AND MATERIALS

The research design followed a multi-stage, transdisciplinary approach that combined expert elicitation, participatory ecosystem mapping, and speculative business modeling within the context of the European hemp construction sector. The aim was to explore the integration of CNC-knitting as a niche digital fabrication technology within early-stage biobased architectural construction value chains.

In the six months leading up to a 1.5-day co-creation workshop, the first author conducted exploratory conversations with hemp-focused researchers from the RAW project. These dialogues provided early insights into sectoral dynamics and helped identify key actors in the European hemp ecosystem, particularly on the supply side. A preliminary stakeholder map was created by the first author using an adapted TIS framework tailored to the Architecture, Engineering, and Construction (AEC) sector (Vasseur & Kings, 2025), and was iteratively developed through desk research, social media outreach (including LinkedIn posts inviting public input), and feedback from RAW consortium members. This mapping process included a geographic and actor-based giga mapping exercise (Sevaldson, 2011) on a Miroboard, visualizing the relationships across farming, processing, fabrication, and intermediary roles. A co-authored participant list of expert stakeholders was assembled, mostly from the supply chain side. One of the co-authors, with an established network in fast-growing architectural materials, curated a shortlist of invitees based on relevance, regional proximity, and active involvement in hemp-based construction value chains. More than 15 experts were invited, spanning diverse roles—from farmers and intermediary processors to machine developers and yarn producers. Ultimately, 9 participants attended, primarily representing the supply side. These included hemp cultivators, integrators, and entrepreneurs developing hemp-based panels. While their perspectives offered valuable insight into upstream challenges and opportunities, the group did not include digital fabrication actors or CNC-knitting industry representatives beyond the RAW researchers themselves. This absence of digital enablers was notable, given the technical focus of the project. Nonetheless, the participants brought rich and contrasting views on business models and political-economic approaches—ranging from cooperative and commons-based strategies to more traditional capital-driven models focused on scaling through machinery investments and logistics optimization.

The workshop design was iteratively developed to reflect both practical insights and theoretical scaffolding. Throughout this period, the co-authors collaborated continuously,

with parallel workstreams focused on technical developments (e.g., fiber processing and prototyping) and macro-environmental scenario planning.

The co-creation workshop itself was divided into two main stages. On the first day, participants engaged in a structured review and discussion of the ecosystem map, evaluating the proposed actor categories, relationships, and blind spots. The first author facilitated and took extensive notes. The second day began with short provocations and insights sharing from industrial actors (notably in farming, machinery, and fiber processing) and was followed by a speculative business modeling session. In this exercise, the first author and one co-author presented two fictional but grounded business cases: one for a design office, offering the consultancy around design, modeling and digital fabrication prototyping for hemp-based CNC-knitted architectural elements, while another company is a "knit-on-demand" CNC-knitting fabrication firm, that has extensive park of CNC-knitting machines and is able to produce complex textile surfaces using hemp yarn. These two fictional companies were situated within a Circular Business Model Canvas, and participants collaboratively mapped their potential relationships with these models—reflecting on opportunities, constraints, and roles from their own sectors. The discussion is documented in notes, which are mapped onto the canvas.

The ***Thematic analysis of the workshop notes*** focused primarily on *pain* and *gain* points identified by the participants regarding the uptake of hemp-based materials in construction, and the feasibility of integrating niche digital technologies like CNC-knitting. Reflections on the DRASTIC ecosystem mapping and business model tools, applied in the RAW research, were guided by a self-reflective and dialogical analysis between the first and last authors.

RESULTS AND DISCUSSION

The ecosystem map of hemp fibers for AEC anno 2025: In the RAW project, researchers already embedded in the hemp and fiber sectors collaborated with the first author—approaching the industry with a fresh, theory-informed perspective supported by the DRASTIC project and insights from other building materials—to construct a preliminary mapping of key ecosystem actors. This mapping identified a diverse but unevenly connected set of stakeholders. Farmers, often operating at small scale, expressed interest in hemp cultivation but remained constrained by market uncertainty, labor intensity, and limited infrastructure. Processing facilities are largely outdated or absent in Alpine regions, with existing centers often located hundreds of kilometers away, posing significant logistical and economic barriers. Researchers and technologists are advancing niche applications such as CNC-knitting and coreless winding, though their compatibility with current biomass flows remains limited. Intermediary organizations and NGOs play vital roles in connecting the actors, but their influence varies significantly by geography. At the end of the value chain, architects and designers are emerging as innovation drivers, yet struggle with unreliable supply chains, performance validation, and regulatory hurdles. Meanwhile, policy and procurement bodies appear under-engaged, often limited by outdated frameworks and budgetary models that do not yet accommodate bio-based or circular alternatives.

Discussion about possible scenarios for a desirable or likely ecosystem anno 2030: During the workshop discussions on potential ecosystem configurations, participants debated the viability of small-scale, decentralized models versus larger, more centralized approaches to hemp-based construction. This prompted reflection on different business model trajectories, including cooperative structures, commoning practices, and franchise-based replication models. A recurring theme was the importance of knowledge flows and institutional memory, particularly in decentralized systems where technical and organizational know-how cannot be easily centralized or standardized. Several pain and gain points for the wider uptake of hemp in the AEC sector were identified, many of which lie outside the control of researchers and small medium enterprises (SMEs). These include financial bottlenecks, gaps in infrastructure

investment, and the absence of regulatory incentives. As a result, participants emphasized the critical role of financial intermediaries and policy makers in shaping the direction and inclusivity of bio-based innovation systems, particularly through their influence on capital flows, subsidy schemes, and certification frameworks.

Pain points, with focus on the Alpine region: The Alpine region faces a complex constellation of pain points that limit the viability and scalability of hemp-based construction innovations. Foremost among these is the fragmentation of value chains, with cultivation, processing, and fabrication often geographically and institutionally disconnected. This is compounded by a lack of regional infrastructure, particularly decortication and scutching facilities, resulting in high transport costs and inefficient bale logistics. The absence of standards and fiber grading systems further hinders quality assurance, certification, and market integration. Advanced fabrication methods like CNC-knitting and coreless winding are technologically misaligned with currently available hemp yarns, which remain brittle, inconsistent, and prone to breakage. These technical challenges are embedded within broader institutional and policy vacuums, including the absence of support for bio-based construction in public procurement and carbon accounting systems—gaps clearly visible in regions like Tyrol. Beyond technical and regulatory issues, socio-cultural mistrust—such as skepticism toward cooperatives and the persistent stigma around hemp — weakens collaborative models for hemp-uptake, while the high entry costs for specialized machinery and legal compliance exclude many smaller actors. Temporal constraints, such as narrow harvesting windows and processing bottlenecks, exacerbate material inefficiencies. Additionally, both digital and physical disconnects inhibit the integration of locally produced yarns into high-spec fabrication workflows of digital knitting and robotic winding.

Gain Points, with focus on the Alpine region: Despite structural challenges, the Alpine region also presents a number of strategic advantages for advancing biobased construction innovation. There is a notably high level of stakeholder enthusiasm for bio-based materials. This momentum is reinforced by the presence of growing cross-border networks and consortia, which enable knowledge exchange and collaborative experimentation. The cascading value potential of hemp—ranging from high-performance textiles and composites to insulation panels—enhances its economic viability, particularly when value chains are creatively structured. Encouragingly, several yarn producers, along with established flax processors, have shown willingness to experiment with hemp under the right technical and financial conditions. In parallel, digital fabrication methods like CNC-knitting offer significant design adaptability, weight reduction, and reusability, aligning well with circular construction goals. Regionally, political openings are emerging. For example, the Tyrolean government has begun integrating life cycle assessments (LCA) and biobased procurement into public projects, such as regional signage made from hemp composites. Finally, to optimize emerging systems, participants emphasized the role of spatial optimization models for reducing logistics-related emissions and costs. Calls were made for an atlas of CNC-knitting fabrication and decortication facilities, inspired by precedents in urban circularity mapping (e.g., Verga & Khan, 2022), which could serve as critical planning tools for infrastructure and link the actors more efficiently together.

***Economic Geography - Lock-Ins and Transition Dynamics*:** The transition toward a circular, hemp-based construction economy is deeply shaped by economic geography and systemic lock-ins. A clear core-periphery dynamic exists: Eastern European regions such as the Baltic region, Ukraine and East Germany retain large-scale cultivation capacity and processing knowledge, while Western Alpine areas, though lacking infrastructure, are emerging as design and innovation hubs. However, the transition is hindered by bioregional fragmentation, with administrative borders impeding integrated planning. Alternative frameworks, such as watershed-based bioregionalism offer promising pathways for supply chain coordination. Across Europe, knowledge geographies remain uneven: France, Belgium,

and East Germany maintain valuable expertise and machine networks, while regions like Northern Italy and parts of the Alps face discontinuity due to the loss of cooperative models and processing skills. Meanwhile, rising global interest—particularly from China's expanding hemp industry—poses *perceived* geo-economic risks for Europe if coordinated R&D and material sovereignty strategies are not established. Several systemic lock-ins further constrain this transition. Technical lock-ins arise from the incompatibility between CNC-knitting's demand for uniform, high-performance yarns and the inconsistent output of current regional hemp processing. Social and cultural lock-ins—including stigma, mistrust in cooperatives, and aesthetic preferences shaped by retting discoloration—affect both farmer engagement and architectural design uptake. Additionally, policy lock-ins, such as regulatory ambiguities around *tetrahydrocannabinol* (THC) content and procurement practices favor conventional materials

***Niche Opportunities: CNC-Knitted Hemp Membranes*:** CNC-knitted hemp membranes represent a compelling niche within a niche of lightweight tensile structures, offering a high-aesthetic, low-volume entry point into the bio-based construction sector. Their unique materiality and digital fabrication potential make them particularly suited for shading devices, indoor spatial structures, architectural pavilions, and high-end retrofits, where visibility and innovation carry strategic weight. In the context of the RAW project, such applications serve as effective proof-of-concept platforms, generating stakeholder interest and legitimacy while facilitating ecosystem alignment. The scalability of this approach lies in its compatibility with digital fabrication networks, enabling a "knit-on-demand" model where decentralized yarn producers and design offices collaborate through shared digital file systems and CNC-knit fabrication operations. However, full deployment remains constrained by materials R&D challenges, particularly the need to improve yarn consistency, tension performance, and brittleness—issues that demand targeted pre-treatment, extensive testing and eventually specific digital design models, dedicated to the use of natural yarns for large-scale application in order to meet architectural and structural standards.

***A collaborative circular business model for two imaginary firms 'design to production service' and 'CNC-knitting on demand'*:** As part of the business modeling workshop, participants engaged in a speculative design exercise using the DRASTIC collaborative circular business model framework, which integrates material cycles with ecosystem relationships. Two fictional companies were prototyped, both situated in the Innsbruck region: Company A, a "design-to-production service" for spatial and acoustic solutions using hemp-based knitted elements and Company B, a "CNC-knitting on demand" firm. Represented by two RAW researchers, these imagined companies were placed within the model's grey (material flow) and green (ecosystem value) columns, enabling participants to map out phases such as material collection, sale, take-back, and recovery, alongside key relational questions (e.g., who helps whom, with what, and why). The scenario unfolded with Company A offering design services to building owners, while Company B provided knitting-fabrication services, raising questions of supply chain logic, geographic proximity, and economies of scale. Discussion extended into logistical and infrastructural dependencies, such as the number of farmers and hectares required to supply hemp yarn for a building-scale membrane, accounting for rotational farming systems and the need for decentralized knowledge systems. Participants questioned whether digital files might be sent to fabrications in cheaper locations, highlighting geopolitical and economic considerations, including trade tariffs, the role of IP in supply chain optimization, and the possibility of flat-packing or unraveling membranes to reduce transport emissions. Yarn ownership and access to materials sparked further debate, with participants exploring subscription models, adaptive design services, and rental systems, where yarn producers might retain ownership, with textile being returned for unraveling and reuse of remaining yarn for further re-knitting of reiterated designs given the yarn amount. The absence of certification schemes, challenges in material

storage, and the need for open-access CNC-knitting machine parks with custom specifications (e.g. gauge variation to accommodate the variety of hemp yarn thicknesses) were also flagged as critical gaps. While the model helped clarify the relationships and missing actors, especially those responsible for building deconstruction and yarn recovery, were noted, alongside the decentralized nature of existing CNC-knitting research facilities across Europe. A recurring concern was material availability, which remains a limiting factor for scaling up such a speculative business ecosystem before more logistics infrastructure and machine networks are in place.

Discussion of combining and testing the methodological frameworks at Low Technology Readiness Levels: The study explored the applicability of combining and testing established methodological frameworks—particularly the TIS framework and the collaborative circular business model canvas—in contexts characterized by low Technology Readiness Levels (TRLs). While these frameworks had been developed and partially tested within the higher-TRL scope of the DRASTIC project, their application to emerging technologies such as CNC-knitted hemp architectural membranes allowed for a critical examination of their flexibility and limitations.

One key insight was the necessity of clearly defining a tangible product or product range, as services alone were insufficient to anchor stakeholder engagement or support value chain modeling. The TIS framework proved particularly helpful in mapping actor roles and functions, yet during the business modeling phase, participants often defaulted to imagining demand beginning with contractors or product traders, sidelining intermediary roles. Interestingly, while intermediaries received less focus in the initial mapping, pain points related to certification, logistics, and knowledge transfer emerged prominently during the second-day discussions, highlighting their structural importance in enabling or obstructing system-level transitions. This suggests that adapting innovation frameworks to low-TRL contexts not only requires rethinking assumptions about actor behavior and demand pathways, but also foregrounds the fragility of emergent ecosystems still lacking institutional and infrastructural anchors.

Limitations: While the study provides valuable insights into early-stage ecosystem dynamics and circular business modeling, several limitations must be acknowledged. First, the findings are context-specific, shaped by the Alpine region's fragmented infrastructure and the participant group's supply-side focus. The absence of actors from the CNC-knitting fabrication industry or digital technology providers limits the breadth of perspectives on downstream integration and technical scalability. Additionally, as the workshop involved a relatively small and regionally situated group of stakeholders, the generalizability of insights to other geographies or industrial contexts should be approached with caution. Finally, the speculative nature of the business modeling exercise, while useful for exploring future scenarios, may not fully capture real-world constraints faced during implementation at scale.

CONCLUSION

This study explored the potential of applying ecosystem mapping and collaborative circular business modeling at low Technology Readiness Levels (TRLs) within the emerging field of hemp-based digital construction technologies, with a focus on CNC-knitted architectural membranes. By testing speculative mapping tools in real-world stakeholder contexts, the research surfaced critical insights into the infrastructural, regulatory, and socio-technical barriers that currently inhibit the wider uptake of hemp in the AEC sector.

A key outcome was the recognition that transition processes in bio-based construction systems are deeply interdisciplinary and cross-sectoral—requiring engagement not only with architects and engineers but also with logistics experts, geographers, social scientists, innovation managers, and most importantly, practitioners and operators on the ground. The exercise also highlighted the importance of building inclusive ecosystems that integrate both

supply and demand side actors as well as often-overlooked intermediaries, who play a decisive role in certification, quality control, logistics, and knowledge exchange. As both the DRASTIC and the RAW project are still in its early stages, future iterations will benefit from further integration of environmental impact modeling, particularly life cycle assessments, to align design and material strategies with measurable sustainability targets.

The insights from this study and this *test* will directly inform the refinement and final publication of the ecosystem mapping framework and circular business model for the AEC sector currently under development within the DRASTIC project.

Given the structural limitations faced by researchers and SMEs—especially in Alpine and Southern European regions—policy makers are urged to act. Ten actionable steps are proposed: from investing in regional decortication infrastructure and adaptive machinery, to establishing grading systems, launching performance-based certification pilots, and supporting decentralized, cooperative ownership models. Broader measures should include capacity-building in rural communities, cross-sector innovation platforms, and public procurement policies rooted in LCA logic. Finally, regulatory harmonization around Cannabidiol/THC thresholds and material marketing pathways is essential to unlock a truly circular and just bio-based construction future.

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