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CIRCULARITY BY DIGITAL FABRICATION FROM THEORY TO PRACTICE: THE CASE OF THE WOOD ARCHITECTURE AND DESIGN INDUSTRY

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ABSTRACT

This paper examines the application of digital technologies as circularity drivers in the wood design industry analyzing project scalability, material sustainability, and the challenges of transitioning from theoretical research to practical implementation. To this end, a scoping review methodology was employed in a time frame between 2015 and 2023 to identify key concepts, research gaps, and emerging trends, through the web platform Scopus. Since using keywords such as "furniture manufacturing," "CNC," "3D printing," "sustainable material," "sustainability," and "recycle wood," initially retrieved results across diverse fields, the focus was narrowed to architecture and design, but then yielded limited findings, highlighting the lack of sector-specific studies. To address this gap, the review was supplemented with an analysis of relevant case studies. Findings indicate that most documented applications of digital technologies for circular wood design originate in Europe – particularly Denmark – where institutional support and policy initiatives have fostered experimental, university-led projects. Despite their innovation, these cases remain largely unvalidated in academic literature, exposing a disconnect between empirical experimentation and theoretical consolidation. The increase in publications from 2023 suggests a shift toward formal validation of earlier experiments, potentially signaling the emergence of a sustained research trend in this domain.

1. INTRODUCTION

Wood as a foundational raw material, especially from forest-rich areas, is crucial for global construction and manufacturing. Nevertheless, wood-based industry – and architecture and design especially – faces severe environmental and ecological concerns such as deforestation, extensive material waste, and heavy dependence on virgin materials; even as wood is celebrated for its sustainability (Bergsagel & Heisel, 2023; Wagner et al., 2020). These challenges are recognized in international frameworks, including the European Union Circular Economy Action Plan and the United Nations Sustainable Development Goals, which emphasize responsible production, resource efficiency, and climate action.

Addressing escalating concerns regarding sustainability and digitalization, digital technologies like digital prototyping, robotic fabrication, and CNC machining are being recognized as essential tools for optimizing material use and improving production efficiency (Alvarez et al., 2019; Velikov et al., 2016). The potential of these innovations lies in their capacity to minimize environmental impact by enabling accurate material utilization, while offering greater creative flexibility in design. However, beyond the premises, there is still a significant lack of knowledge regarding the effectiveness of application of digital technologies and methods for circularity in wood architecture and design.

To identify key concepts, research gaps, and emerging trends in the integration of digital fabrication technologies in the wood industry, this study applies a scoping review methodology, following the framework of Arksey & O'Malley (2005), to systematically map existing research and experimental practices as publications. The scoping review was conducted using the Scopus database with keywords including "digital fabrication," "CNC," "3D printing," "wood industry," "life cycle assessment," and "sustainable materials." However, the findings of this literature review show that limited existing research on this topic exists: the results of this study outline a significant gap between theoretical advancements and practical application in the industry. Despite innovation in research and development in the field of digital fabrication, many companies seem to continue to depend on traditional methods, limiting their ability to fully leverage digital innovations (Wagner et al., 2020).

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Indeed, the second part of the study is conducted to bridge this gap by examining case studies from leading academic and industry institutions. Studies from 2015 to 2023 were selected, focusing on European architectural publications and case studies. The analysis considered materials, processes, technologies, and sustainability outcomes. In this way, it was questioned how emerging digital technologies can be effectively integrated into wood production processes to reduce waste, enhance resource efficiency, and promote sustainability.

The paper is structured in 4 paragraphs: the Introduction, "Materials and Methods", "Results and discussion", "Conclusions". In "Materials and Methods", a scoping review is conducted on digital fabrication in the wood industry, combining qualitative literature analysis and quantitative bibliometric data. The scope is refined to architectural publications and case studies are analyzed within a time frame 2015–2023 and limited to European institutions, assessing materials, processes, technologies, and sustainability outcomes. In "Results and discussion", gap between theoretical research and practical applications are identified, highlighting challenges in material sourcing, cost efficiency, and scalability. Experimental case studies showing innovative uses of reclaimed timber, bio-based materials, and digital fabrication techniques are examined and their potential and limitations are described. In "Conclusions", it is underlined the transformative role of robotic fabrication, CNC machining, and additive manufacturing in optimizing material use and reducing waste. Key barriers include high costs, slow industry adoption, and scalability issues. Future research outlooks are identified in cost-effective implementation strategies, interdisciplinary collaboration, and industry integration to enhance sustainability in wood fabrication.

2. MATERIALS AND METHODS

This research adopts a scoping review methodology to map the existing literature on the integration of digital fabrication technologies in the wood design industry, focusing on sustainable practices and material efficiency. Scoping reviews are valuable for identifying the scope and extent of research activities, especially in areas that are complex or have not been comprehensively reviewed before (Munn et al., 2018).

We employed both qualitative and quantitative methods to ensure a comprehensive analysis. The qualitative approach involved an in-depth review of existing literature, case studies, and industry reports to understand key themes, trends, and challenges in digital fabrication for sustainable wood design. The quantitative approach consisted of analyzing bibliometric data from the Scopus database, including the number of relevant publications per year, geographical distribution of studies, and keyword frequency to identify research patterns in this field.

To narrow down the focus, we filtered the results to include only publications within the field of architecture, design and building engineering. The rationale for making these filters is that architecture and the built environment are among the largest users of wood and wood products, where material use efficiency, waste minimization, and scalability rank as top priorities. As compared to other fields, architecture operates at close presence to sustainability issues, circular design, and mass implementation. By constraining the scope in this way, the review keeps its conclusions industry-specific and pertinent to real issues in sustainable wood construction and building.

Our primary objective was to map the available literature on the use of CNC, 3D printing, and robotic fabrication techniques applied to wood, emphasizing sustainable practices and material reuse.

We searched the Scopus and Web of Science databases, covering publications from 2000 to 2023 and limited to English-language articles. The search strategy was organized into three main categories: fabrication technology (CNC, 3D printing, robotics), circularity and material reuse (recycling, upcycling, biocomposites), and sector-specific applications (furniture, architectural elements, design objects).

After initial retrieval, duplicate records were removed, and publications were screened based on relevance to experimental fabrication, application scale, and focus on sustainability. Data extraction included bibliometric information, type of fabrication technology, material used, product scale, and circularity considerations. This process allowed a structured comparison between quantitative bibliometric data and qualitative case studies.

Due to the limited findings, we adapted our methodology to include an analysis of case studies. We expanded our research to include case studies published between 2015 and 2023, primarily from European regions, with Denmark being prominently represented. We sourced these case studies from additional sources, including project reports and institutional databases such as the Royal Danish Academy and the University of Stuttgart's Institute for Computational Design, rather than from the scoping review. The evaluation criteria for the case studies included project scale, material usage, sustainability outcomes, and practical challenges during implementation.

By examining diverse applications involving reclaimed timber, bio-based materials, and advanced digital fabrication techniques, we aimed to provide a comprehensive overview of how these innovations are currently applied in the wood industry. Comparing methodologies and outcomes across these projects allowed us to identify key challenges and opportunities for further technological integration.

3. RESULT AND DISCUSSION

While our initial approach focused on a scoping review to assess the broadness of research on digital fabrication in the wood industry, we observed a significant gap between theoretical studies and practical applications (Table 1, Figure 1). From the systematic search, a total of 66 documents were retrieved across different query combinations. After removing duplicates and excluding papers outside the scope of architecture, design, and sustainability, such as those focusing on chemical, medical or unrelated engineering applications, the number of relevant publications

TABLE 1: Limits of detection (LOD) for the regulated HMs (Cd, Pb and Hg). Concentrations on mg/kg are evaluated considering the digestion volume and dilution utilized for the quantifications, where necessary.

Article title	Authors	Source	Year	Citations
Investigation of material properties of composite materials based on wood waste for FDM Additive manufacturing	Beniak, J.; Klepochavà, K.; Holdy, M.; Soos, L.	Waste Forum (3), pp. 156-165	2023	0
Development and carachterization of sustainable PLA/Olive wood waste composites for rehabilitation applications using Fused Filament Fabrication (FFF)	Fico, D.; Rizzo, D.; De Carolis, V.; … Palumbo, E.; Corcione, C. E.	Journal of Building Engineering, 56, 104673	2022	42
Creating novel furniture through topology optimization and advanced fabrication	Ma, J.; Li, Z.; Zhao, Z.lL.; Xie, Y. M.	Rapid Prototyping Journal, 27(9), pp. 1749-1758	2021	27

was reduced to 7. From this smaller pool, Additive Technologies and Their Applications in Furniture Design and Manufacturing (Jarža et al., 2020) emerged as the most relevant quantitative contribution. This paper provides numerical insights into material utilization, efficiency, and recycling potential in 3D-printed furniture, demonstrating the possibilities of additive manufacturing for circular design. However, its relevance is limited for the purposes of this research, as it focuses exclusively on furniture rather than architectural or spatial applications, and it does not address broader sustainability strategies, modularity, or living-lab contexts. Despite these limitations, the study offered a useful quantitative reference point, supporting the integration of advanced fabrication methods into discussions on circularity in wood design.

The identified gap between theoretical studies and practical architectural applications is clearly supported by this evidence from the literature.

The scarcity of literature in the architecture and sustainability domains led us to complement our review with a detailed case study analysis. This shift allowed us to examine real-world applications of digital fabrication technologies, offering deeper insights into their feasibility, challenges, and impact on sustainable wood design.

To select and analyze case studies, we established a set of evaluation criteria, focusing on:

- Materials used (reclaimed timber, bio-based composites, prefabricated elements);
- Processes applied (robotic fabrication, CNC machining, additive manufacturing);
- Technologies and machines involved (3D printing, parametric modeling, automated assembly);
- Sustainability impact (waste reduction, life cycle assessment, material efficiency).

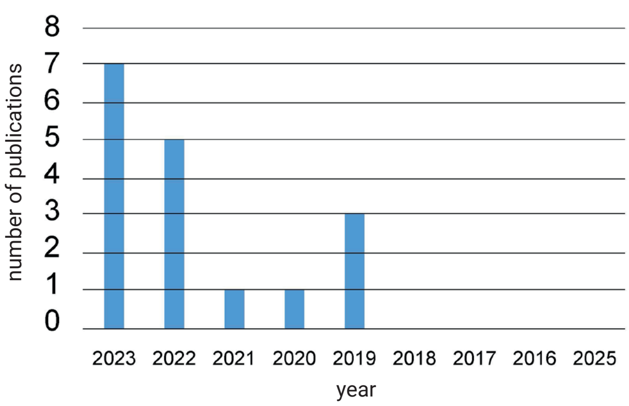

FIGURE 1: Average publication from 2015 to 2023.

The selected case studies, spanning from 2015 to 2023, are sourced from European institutions, with Denmark being particularly active in this field. It is notable that most of the case studies are from 2023, reflecting the recent acceleration in the application of digital construction technologies in timber architecture. The analysis of these cases highlights key challenges in material sourcing, cost efficiency, and structural integrity, while also showcasing innovative approaches to extending the lifespan of wood materials through advanced digital fabrication techniques.

For instance, The Wood ReFramed Pavilion (Figure 2), developed by researchers at the Royal Danish Academy, exemplifies the integration of reclaimed timber into modern construction. This project demonstrates how digital fabrication methods can enhance the reuse of wood while maintaining structural integrity and design flexibility (Browne et al., 2023). Despite its success, challenges such as material availability, ensuring structural safety, and scalability remain significant barriers to broader adoption (Bergsagel & Heisel, 2023).

The livMatS Biomimetic Shell (Figure 3) project, led by the University of Stuttgart, further highlights the potential of digital technologies in timber architecture. This 200 m² structure utilizes bio-based materials and computational fabrication techniques to create a sustainable architectural solution (Wagner et al., 2020). Employing both additive and subtractive manufacturing processes, along with a 4D-printed adaptive shading system, the project illustrates how digital tools can enhance precision and sustainability in complex designs (Alvarez et al., 2019).

Other notable examples include from the 2022 Women in Architecture exhibition, which focuses on reducing material waste by using reclaimed timber off-cuts and crooked oak logs. This project underscores the efficiency of digital modeling in design and assembly processes (Publications, 2016). Similarly, the Wisdome Stockholm project showcases the use of laminated veneer lumber (LVL) in constructing a large-scale timber grid-shell, demonstrating how prefabrication techniques contribute to sustainable, high-performance timber structures (Osnaburgh, 2023).

These case studies offer valuable insights into the current state of digital fabrication technologies in the wood industry. The Wood ReFramed Pavilion highlights the promise of using reclaimed timber but also reveals challenges related to sourcing materials and ensuring structural integrity (Browne et al., 2023; Bergsagel & Heisel, 2023). Addressing these issues is crucial for developing scalable solutions and establishing industry-wide standards that facilitate broader adoption.

The livMatS Biomimetic Shell project illustrates the effectiveness of integrating bio-based materials with computational design to achieve sustainability goals through reduced waste and increased precision (Wagner et al., 2020). Nevertheless, the project's complexity and associated costs present obstacles to widespread implementation, especially in large-scale industrial settings.

The Marina Spa Prototype (Figure 4) and Wisdome Stockholm projects demonstrate how digital fabrication can optimize material usage and minimize waste, emphasizing the significance of modular design and prefabrication in advancing sustainable timber construction (Osnaburgh, 2023).

Together, these case studies provide concrete evidence supporting the discussion of gaps in the literature, particularly regarding scalability, cost, and integration of sustainability strategies (Table 2).

As the case study analysis shows that among the various digital manufacturing techniques, robotic manufacturing, CNC machining and additive manufacturing (3D printing) emerge as the most promising technologies for sustainability. These processes stand out due to their ability to optimize material use, minimize waste and increase design accuracy. For example, CNC machining allows for high precision cutting that significantly reduces undercutting, while robotic manufacturing increases automation and material efficiency, particularly in wood manufacturing. Additive manufacturing, although still in its early stages in wood design, has the potential to reduce reliance on raw materials by enabling circular production models.

From these case studies, 3 key lessons might be summarized:

- Result 1: Material selection plays a critical role in sustainability: Projects that integrate recycled wood, bio-composites, or prefabricated techniques show significant reductions in environmental impact.
- Result 2: Industry adoption remains a challenge: While digital fabrication offers clear benefits, the high initial investment in technology and expertise limits widespread implementation in traditional wood fabrication.
- Result 3: Collaboration between academia and industry is essential: Many projects remain at a laboratory scale with limited real-world applications due to the lack of structured industrial partnerships and practical testing environments.

This gap stems from several factors:

- Slow adoption of advanced digital tools in industry: while research is exploring advanced techniques, many wood manufacturers still rely on conventional methods due to cost concerns and unfamiliarity with the technology.
- Limited interdisciplinary integration: digital fabrication often involves architecture, engineering, and compu-

FIGURE 2: Wood ReFramed Pavilion.Photo by Sara Lohse, 2023.

FIGURE 3: livMatS Biomimetic Shell. Photo by Roland Halbe, 2023.

FIGURE 4: Marina Spa Prototype. Credits: Helen & Hard, 2022.

TABLE 2: Summary table of analyzed case studies.

Project Name	Institution	Objective	Scale	Materials	Workflow	Technologies	Timeline
livMatS Biomimetic Shell	ICD & ISYS, University of Stuttgart	Recycling/Upcycling	Building	Waste wood, spruce boards, cellulose powder, bio-based thermoplastic polyketone	Integration of fabrication processes	Additive & subtractive fabrication, 4D printing, automated assembly	2023
Sourced Wood	IAAC	Reuse/Upcycle	Component	Waste wood	Collecting surplus material from construction sites	Robotic fabrication, optical & CT scanning, computational design	2018
Marina Spa Prototype	Danish Architecture Center	Upcycling/ Reuse	Small Arch	Reclaimed timber flooring off-cuts, crooked oak logs	Integrated digital delivery	Robotic machining, scanning, computational design, laser projection	2022
Wood ReFramed	Royal Danish Academy	Reuse/Upcycle	Building segment (prototype)	Reclaimed timber	Exploring novel structural applications	Robotic machining, scanning, computational design, heuristic algorithms	2023
eGrow Willow	Karlsruhe Institute of Technology	Recycle/Upcycle	Building elements	Willow, Earth	Integrating closed-loop systems	Lightweight fabrication, scanning, computational design	2023
Weaving the Shimoni Cave	Royal Danish Academy	Recycle/Upcycle	Object		Hand-woven structure guided by computational design	LiDAR scanning, Tri-Mesh Remeshing	2022
Osnaburgh Pavilions	Xylotek	Reuse	Small Arch Pavilion	Oak (glue-laminated), locally sourced timber	Collaborative design processes	Minimal machinery, hand tools for on-site fabrication	2023
RawLam	CITA	Recycle/Upcycle	Small Arch (pavilion)	Timber	Flow from forest to timber product	Robotic machining, scanning, computational design	2022
Wisdome Stockholm	Design-to-Production, Zürich; Bliding Oscarson, Stockholm	Reuse	Small Arch	Laminated Veneer Lumber (LVL)	From competition to completed dome	Digital prefabrication, parametric modeling, CNC, design for manufacture & assembly	2022

tational design, but collaboration between these disciplines and industry professionals is sparse.
- Scalability issues: most academic research is conducted at the prototype or small-scale level, making it difficult to implement findings in large-scale industrial settings without further testing and refinement.

The intersection of the bibliometric screening and the case studies lies in that robotics and automation, responsible for most publications in the quantitative search, are also the center of experimental works such as Wood ReFramed and Marina Spa where robotic milling and automated assembly enabled reuse of piecewise timber with high precision. Prefabrication using CNC also appears in literature and practice, as with Wisdome Stockholm. Additive manufacturing, on the other hand, appears in indexed literature, particularly on the scale of furniture and prototyping but not yet on architecture-scale projects in the cases investigated. Scalability issues, logistics, and contractor cooperation, however, are sufficiently documented in case studies but hardly appear in the bibliometric body. In combination, both threads highlight the importance of CNC and robotics in achieving circularity and note that experimental investigations provide pragmatic lessons to be gleaned from the scientific literature, and that expressing results in standard terms remains a prevalent shortcoming across methodologies. These gaps are therefore supported by evidence from both the scoping review and the case studies, confirming that additive manufacturing is mostly at the furniture/prototype level, while robotics and CNC show promise in both literature and practice.

In the final analysis, despite the advancements demonstrated in case studies, the gap between theoretical research and practical application remains evident. While digital technologies hold significant potential for enhancing sustainability in the wood industry, further research is necessary to address challenges related to scalability, cost-efficiency, and industry acceptance. Overcoming these hurdles is essential to fully harness the benefits of digital fabrication in promoting a more sustainable and efficient wood industry.

4. CONCLUSIONS

This study offers a detailed examination of digital fabrication as a strategic driver for advancing circular economy practices in the wood industry. By integrating qualitative analysis with international case studies analysis, it demonstrates how principles such as reuse, repair, modularity, and upcycling can be effectively applied to valorize wood waste. Technologies like CNC machining, robotics, and 3D printing emerge as key enablers, though their adoption varies: robotics and CNC systems show strong alignment between theory and practice, while additive manufacturing remains confined to furniture and prototyping applications.

The combined bibliometric and case study approach reveals practical challenges—scalability, logistics, and interdisciplinary coordination—that are underrepresented in academic discourse. These insights help delineate which digital strategies are currently feasible and where clearer industry standards and support mechanisms are needed.

Through its scoping review and targeted case analysis, the research provides a foundational mapping of existing practices and gaps, setting the stage for future framework development. Subsequent studies should aim to bridge the divide between conceptual research and real-world implementation by proposing cost-effective solutions, sector-specific guidelines, and collaborative models linking academia and industry.

As digital fabrication technologies continue to evolve, their integration into mainstream production will be essential for achieving scalable, sustainable, and resource-efficient wood design systems. This work lays the groundwork for further inquiry into their role in circular economy transitions and material waste reduction.

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In particular, Paragraphs 1 and 2 should be attributed to F.B.; Paragraphs 3 and 4 should be attributed to S.S.

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