

The Role of Digitalization and Human Aspects in the Use of Digital Product Passport for Sustainable Upcycling (De)Construction Waste

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Abstract: The construction industry generates considerable amounts of Construction and Demolition Waste (CDW) and demonstrates the need for innovative solutions toward a circular economy. This paper describes the integration of digitalization and human aspects using the Digital Product Passport (DPP) for the upcycling of construction waste. DPP increases traceability, quality assurance, and resource optimization in sustainable (de)construction. The application of digital tools and Zero Defect Manufacturing (ZDM) principles improves logistics, waste management, and minimizes environmental impact. A case study on timber waste management demonstrates the practical application of DPP and digital platforms in optimizing sorting, classification, and upcycling. The findings highlight the importance of combining digital innovation with human expertise to achieve sustainable construction practices and to promote a circular economy.

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Keywords: Digital Product Passport (DPP), Zero Defect Manufacturing (ZDM), digitization in construction, construction waste management, circular economy, sustainability, logistics optimization.

1. INTRODUCTION

The construction sector generates vast amounts of Construction and Demolition Waste (CDW), accounting for 38.4% of total waste in the EU (2022) and contributing significantly to global carbon emissions (“Bringing Embodied Carbon Upfront,” 2024). Inefficient material use and poor supply chain transparency exacerbate resource loss and environmental damage (Ma et al., 2024). To address this, transitioning from a linear to a circular economy is essential, prioritizing reuse, recycling, and material traceability (Langley et al., 2023). In this context, digitalization has emerged as a significant facilitator by providing new opportunities to improve traceability, reduce waste, and promote collaboration among stakeholders (Jensen et al., 2023). As such, sustainable solutions should be adopted urgently to enforce circular economy principles that prioritize the reuse and recycling of Construction and Demolition Waste materials.

Digitalization is key to enabling this shift, offering solutions like the Digital Product Passport (DPP) under the Ecodesign for Sustainable Products Regulation (*ECO-Design Regulation (EU) 2024/1781 of the European Parliament*, 2024). DPPs enhance traceability, quality control, and lifecycle management, optimizing decision-making and resource circularity, figure 1 (Psarommatis and May, 2024; Voulgaridis et al., 2024). However, technology alone is insufficient human factors play a decisive role in successful adoption.

Stakeholder engagement, behavioral barriers, and workforce skills significantly impact the effectiveness of digital tools.

Designers, contractors, facility managers, and policymakers possess distinct objectives and viewpoints within the construction sector. Consequently, DPPs and other digital strategies must effectively incorporate inclusive, human-centric collaboration and innovative automation. Challenges such as reluctance to change, limited awareness, and skepticism about recycled materials must be overcome through education, training, and incentives (Osei-Tutu et al., 2022).

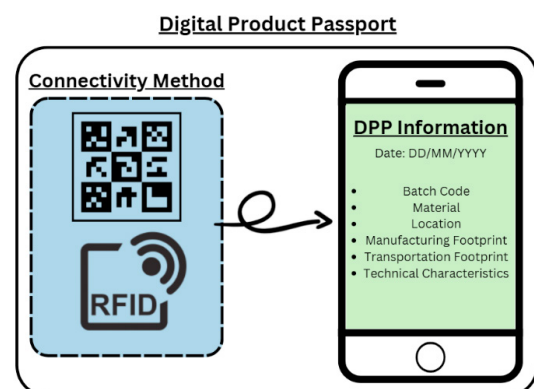


Figure 1. Digital Product Passport concept

Workforce upskilling in digital literacy and sustainability is critical for enabling adoption (Rodrigo et al., 2023). Moreover, digital tools like Zero Defect Manufacturing (ZDM) improve material recovery (Psarommatis et al., 2020; Psarommatis, Foivos et al., 2024), ZDM is an advanced manufacturing approach aimed at minimizing defects through real-time

monitoring, data analytics, and predictive quality control, but human expertise remains crucial in decision-making, quality assessment, and adaptive upcycling strategies (Caiazzo et al., 2022).

This paper examines the integration of DPPs in construction waste upcycling, with a focus on the CIRCULess timber waste case study. It explores how digital tools—DPP, dynamic scheduling, decision support systems, and ZDM—enhance circularity when combined with stakeholder collaboration and human-centric decision-making, paving the way for a sustainable (de)construction industry.

2. STATE OF THE ART

2.1 Digital Product Passport and circular economy in construction waste

DPP becomes an important tool for the circular economy. It provides detailed information about the product lifecycle and improves material traceability. (Jensen et al., 2023) underline the potential of DPPs to support decision-making during the product lifecycle, allowing stakeholders to optimize resource use and minimize waste in construction projects. (Psarommatis and May, 2024) show that DPP can interact with current systems, promoting circularity and providing practical indicators for sustainability.

DPP plays an important role in managing construction waste. (Berger et al., 2023) explain how sharing data through DPPs helps recover materials and solve problems like material differences and reuse in construction waste. (Langley et al., 2023) show principles for orchestrating the circular economy using DPPs. They highlight the importance of communication between stakeholders to achieve sustainable construction.

Recent studies suggest that expanding a Digital Product Passport to track real-time performance data can accelerate circular economy transitions by enabling more proactive maintenance and targeted reuse (Walden et al., 2021). For instance, embedding low-cost sensors in construction materials can produce granular data on material stress and contamination levels, thereby identifying the most suitable upcycling pathways (Ferreira et al., 2022). When combined with cloud-based platforms, the DPP's enhanced monitoring capabilities can automatically alert stakeholders when materials become available for secondary use, further improving resource efficiency and reducing landfill reliance (Voulgaridis et al., 2024).

2.2 Human aspects in construction waste upcycling

The integration of human aspects in construction waste upcycling is essential to achieve sustainable circular economy practices in the construction sector. The use of digital tools such as the Digital Product Passport (DPP) and Zero Defect Manufacturing (ZDM) holds great potential for improving waste management processes. However, the effectiveness of these tools is significantly influenced by human factors, including stakeholder engagement, behavioral barriers, occupational safety considerations, and workforce skills.

Effective stakeholder engagement is vital for implementing circular economy principles in construction. (Ababio and Lu, 2023) highlight its role in enhancing material traceability and

transparency for better waste sorting and upcycling. Barriers, such as limited shared understanding and poor communication, can be addressed through digital platforms that enable real-time data sharing and improve decision-making (Rodrigo et al., 2023). Participatory approaches involving stakeholders in developing and implementing digital solutions are crucial to overcoming resistance to new technologies (Abdulai et al., 2024). Behavioral and cultural factors also impact adoption, with barriers like the perception of recycled materials as inferior and limited awareness requiring mindset shifts (Osei-Tutu et al., 2022). Education, training, and sustainability-focused policies, alongside recognition of circular economy achievements, can drive cultural change and support innovative practices (Vayona et al., 2024).

The integration of human-centric digital innovations is critical for improving construction waste management efficiency and safety. (Chen et al., 2023) highlight how augmented reality (AR) and human-robot collaboration (HRC) enhance waste sorting efficiency while improving occupational safety and health (OSH). Human involvement is essential for tasks where robots struggle, such as recognizing complex waste compositions, with AR interfaces keeping workers engaged and improving sorting quality (Talla and McIlwaine, 2022). Adopting digital tools for waste upcycling also requires workforce upskilling. Training programs addressing the digital skills gap should focus on digital literacy and technologies like DPP and decision support systems, fostering positive attitudes toward digital tools and sustainability for long-term success (Rodrigo et al., 2023).

2.3 Technological integration in construction waste upcycling

Advances in digital tools greatly improve the efficiency of CDW recycling. (Gu et al., 2019) show new approaches to recover valuable materials from construction waste using automated sorting and recycling. (Cenci et al., 2023) review the gaps in recycling practices and emphasize the need for innovative technologies to improve material recovery rates. (Bruno et al., 2022) investigate how material composition affects economic profitability in manual dismantling, offering ideas for optimizing recycling processes of construction materials.

Although digital tools and DPPs show significant promise, challenges remain in fully integrating them into the construction industry. (Langley et al., 2023) have noted that standardization and interoperability issues need to be addressed. Additionally, (Adisorn et al., 2021) highlight the obstacles to stakeholder collaboration that hinder the scaling of the DPP.

The literature emphasizes that combining digital product passport data with human expertise provides a sound basis for recycling construction waste. These tools improve material traceability, optimize waste management, and promote collaboration between stakeholders, enabling a transition to sustainable (de)construction practices. However, challenges such as standardization and stakeholder alignment still need to be addressed if the full potential of digital product passports is to be realized.

Digital product passports, blockchain-based smart contracts, and digital twin technology are needed to upcycle waste (Hewa et al., 2021). Digital twins simulate material degradation and reuse scenarios in real time, while blockchain verifies secondary material records (Centobelli et al., 2022). By integrating these systems with the DPP, construction companies can perform predictive analytics for upcoming demolition projects, automate sourcing decisions, and ensure transparent contractual obligations. This enables proactive planning of upcycling routes. In addition to reducing operational inefficiencies, this technological integration fosters a more collaborative ecosystem by bringing together demolition teams, engineers, and designers to work toward common circularity goals.

3. CIRCULARITY IN CONSTRUCTION USING THE DPP

3.1 Theoretical framework and integration of digital tools

DPP is an important circularity tool that helps stakeholders track material source, life cycle, and quality. The integration of digital tools together with DPP reduces resource use and environmental impact during construction processes. Altogether, digital tools provide an important foundation for adding circular economy principles in construction waste management. Here we present several digital tools and their benefits.

3.2 Digital Product Passport (DPP)

The DPP is a key component in the circular construction system, and provides a comprehensive digital record of the life cycle of materials. By storing detailed information on the origin, composition and end-of-life options of materials, DPP offers transparency and traceability across the entire supply chain. Construction materials embedded with RFID tags contain unique identifiers that connect to the DPP database, facilitating automated updates on usage, location, and quality. This connectivity guarantees that upcycled materials possess a verified provenance, minimizing contamination and enhancing compliance with the circular economy (Voulgaridis et al., 2024). The DPP contains information on material composition, manufacturing history, usage, regulatory compliance, and real-time quality assessments. This comprehensive dataset enables informed decision-making for material reuse, reducing reliance on raw materials while optimizing circular construction practices.

This facilitates more effective decisions on recycling and reuse of materials, as well as collaboration between stakeholders who can access shared data via a digital platform. In addition to meeting regulatory sustainability requirements, DPP improves the efficiency of reuse and resource recovery. The integration of DPP with BIM, RFID, tracking, and regulatory frameworks improves construction traceability and materials reuse. To comply with the European Ecodesign for Sustainable Products Regulation, DPPs must lessen construction waste and increase material circularity.

3.3 Dynamic Scheduling Tool (DST)

A Dynamic Scheduling Tool is an important component that helps optimize resource allocation and logistics for the recycling processes of construction waste. The algorithms used in the DST adapt to real-time conditions to improve

transportation and recycling of materials. The optimization of routes and schedules helps minimize delays, reduce fuel consumption, and decrease the carbon footprint. Dynamic scheduling considers material availability and demand, integrates logistics and waste management and contributes to the sustainability of construction processes.

3.4 Decision Support System (DSS)

The Decision Support System uses artificial intelligence to analyze large datasets and provide conclusions for waste management and upcycling strategies. By identifying the most suitable pathways for recycling or reuse based on material quality and environmental impact, DSS enhances the decision-making process. It quantifies the economic and environmental benefits of various processes, offering a strategic tool for planning sustainable construction practices. Additionally, DSS promotes data-driven collaboration by integrating sustainability metrics that are accessible to all stakeholders.

3.5 Zero Defect Manufacturing (ZDM)

Zero Defect Manufacturing improves the quality of the upcycling of construction materials, ensuring the highest standards of quality and minimal waste. Using real-time monitoring and advanced quality control mechanisms, ZDM finds and addresses defects early in the process. This methodology reduces material loss and improves the usability of recycled materials, contributing to the creation of high-quality outputs. By integrating with DPP and DSS, ZDM forms a cohesive system that enhances the reliability and efficiency of circular construction workflows.

Figure 2 shows a schematic framework for digital tools in circular construction. It illustrates the integration and flow between the key tools: Digital Product Passport, Dynamic Scheduling Tool, Decision Support System, and Zero Defect Manufacturing. The interaction of all those tools enables circular construction outcomes.

The schematic framework shows how the four key tools are connected with each other and the roles they play in achieving circular construction.

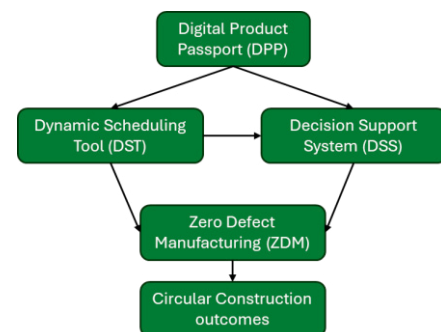


Figure 2. Framework for digital tools in circular construction

Digital Product Passport is central in the framework, acting as the foundation and accumulating data about the lifecycle of materials. This data provides transparency and traceability, which are fed into other tools, for example, the Dynamic Scheduling Tool uses data from the DPP to optimize the routing and timing of material transport based on material availability and requirements; the Decision Support System

uses DPP data to evaluate recycling and upcycling pathways, their impacts and to support strategic decision-makings.

Dynamic Scheduling Tool adapts schedules to real-time conditions and improves logistics. This tool makes transporting more efficient, minimizes emissions and delays. Its output directly supports ZDM by ensuring that materials arrive in optimal condition and at the right time for processing. DSS analyzes data from DPP and combines it with the data from the Dynamic Scheduling Tool. It calculates the environmental and economic indicators of different waste-management strategies giving stakeholders valuable advice for planning. ZDM uses inputs from the DSS and the optimized logistics provided by the Dynamic Scheduling Tool to ensure high-quality upcycling. By identifying and addressing defects early, ZDM minimizes material loss and increases the quality of outputs. Finally, all tools work together to achieve circular construction outcomes, which include material reuse, reduced waste, and lower environmental impacts. In such an interconnected system, each tool contributes to overall efficiency, transparency, and sustainability in construction waste upcycling.

3.6 Human aspects in the process

The effective implementation of DPP, DST, DSS, and ZDM requires an understanding of the influence of human-centric factors on their adoption and use. These tools, while highly technical, rely on human input, engagement, and collaboration to achieve their full potential in promoting circular economy principles in the construction industry.

DPP plays a pivotal role in providing traceability and transparency throughout the lifecycle of construction materials. Its effectiveness depends on human engagement at various stages of data collection, input, and analysis, and requires collaboration between different stakeholders, including material suppliers, contractors, and waste management firms. To overcome human-related barriers, training programs should focus on enhancing digital literacy and demonstrating the practical benefits of using DPPs. For example, by showing how DPPs can streamline compliance with regulatory requirements and improve decision-making, stakeholders can be more motivated to adopt this tool.

DST optimizes logistics and resource allocation in real-time; however, human factors such as resistance to change and a lack of familiarity with digital tools can hinder its adoption. To address these challenges, organizations must invest in workforce training that emphasizes the practical benefits of DST, such as enhanced workflow continuity and adaptation to fluctuations. Additionally, integrating human input into the scheduling process ensures that local knowledge and contextual factors are considered, making the tool more adaptable to real-world conditions. By incorporating feedback loops and involving users in the development of DST algorithms, companies can increase acceptance and trust in the tool.

While DSS can analyze large datasets and recommend optimal recycling pathways, human interpretation of these insights is crucial for effective decision-making. Ensuring that users understand the outputs of the DSS and how to apply them in

their daily operations requires targeted training. This includes teaching users how to assess the environmental and economic implications of different upcycling strategies and encouraging collaborative decision-making among stakeholders. Moreover, human involvement is essential for validating the recommendations provided by the DSS.

ZDM focuses on minimizing defects and maximizing the quality of recycled materials. Human oversight is crucial in identifying and addressing quality issues early in the process to reduce material loss and improve the usability of upcycled outputs. To successfully implement ZDM practices, workforce training on advanced quality control systems, such as vision-based inspection and IoT sensors, is essential. This training should emphasize the role of human operators in monitoring automated processes and intervening when necessary to prevent defects. Additionally, fostering a culture of continuous improvement can enhance the effectiveness of ZDM. Encouraging employees to provide feedback on quality control processes and participate in identifying areas for improvement helps create a more engaged and proactive workforce.

The successful implementation of digital tools in construction waste upcycling depends on addressing human-centric factors at every stage of the process. By focusing on stakeholder engagement, workforce training, and collaborative decision-making, organizations can maximize the benefits of DPP, DST, DSS, and ZDM. These tools, when combined with human expertise and input, can drive the construction industry toward more sustainable and circular practices, reducing waste and minimizing environmental impact.

4. TIMBER CASE STUDY

The construction and demolition sector generates large volumes of timber waste, which is often not used because of contamination, poor traceability, and lack of quality control. In the context of the CIRCULess project, timber waste has been identified as a critical material stream for upcycling, having the potential to be repurposed into high-value products. Our case study shows the impact of the application of digital tools on timber-waste management and upcycling processes.

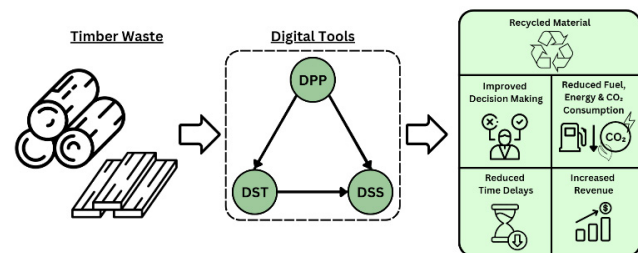


Figure 3. Timber case study and the expected benefits

4.1 Application of digital tools

DPP will be used in the CIRCULess project to improve traceability of timber materials, processing history, and quality attributes. Stakeholders across the supply chain can access real-time information on material availability and characteristics. This approach enhances traceability, separating high-quality timber for upcycling from lower-quality materials that will be used for alternative purposes.

Dynamic Scheduling Tool will be used to optimize logistics, improve transportation, and sort timber waste. Using real-time data from the DPP, the algorithm optimizes routes for transporting timber from demolition sites to processing facilities, reducing fuel consumption and emissions. Moreover, adjustments to scheduling will be made to assess fluctuations in material availability and maintain continuous workflow while minimizing delays.

Decision Support System will be used to improve strategic decisions. The DSS will analyze the data from the DPP and DST, provide insights into better recycling pathways. For instance, our tool can recommend making engineered wood products out of used timber or applying it for structural applications in new construction projects. The DSS also calculates the environmental and economic factors of these pathways, helping stakeholders make decisions that are aligned with sustainability goals.

Zero Defect Manufacturing will be used to ensure quality outputs. ZDM methodologies are going to be integrated into the timber upcycling process to minimize defects and material losses. Advanced quality control systems, including vision-based inspection and IoT sensors, will be used to determine timber quality at each stage of processing. Defective materials will be identified and removed in early stages, leaving only high-quality outputs for further production. This approach reduces waste and improves the reliability as well as the marketability of the upcycled timber products.

4.2 Expected results

Based on these actions, we estimate the following improvements. Optimized processing can improve material recovery by 20-30% compared to traditional methods. The use of recycled timber could reduce the need for virgin timber by 25-35%. The optimization of logistics could reduce CO₂ transport emissions by 15-25%. High-quality upcycled timber products may increase revenue by 20-30% over traditional recycling practices.

The human impact falls into three areas: workplace safety through automation and feedback loops, job transformation via digital skill development and continuous learning, and enhanced decision-making driven by data insights that foster collaboration and trust. These align with Industry 5.0, promoting a sustainable, resilient, and human-centric industry. The tools improve working conditions by reducing hazardous exposure, upskill the workforce, and encourage socially responsible innovation, addressing both occupational health and broader goals of fairness, inclusion, and sustainability in industry.

Our estimations are based on the combination of DPP with digital tools, using improved traceability, better logistics, and high quality of the final products. The exact outcomes will depend on implementation specifics; however, these estimates demonstrate the transformative potential of digital solutions in timber waste management.

5. DISCUSSION AND CONCLUDING REMARKS

The integration of the Digital Product Passport and advanced digital tools provides a new pathway for solving construction

and demolition waste challenges. These tools improve traceability, optimize logistics, and enhance decision-making, contributing to the circularity and sustainability of construction processes.

The case study on timber waste within the CIRCULess project demonstrates the potential of these tools to improve material recovery rates, reduce the consumption of virgin resources, and lower carbon emissions while driving economic benefits. When using digital tools, the construction industry can transition from a linear to a circular economy, addressing critical environmental concerns and improving collaboration among stakeholders. Despite these benefits, several major issues must be addressed:

Although there are limitations, this study reveals that DPPs and digital tools can sustainably control building waste. First, this study approximates performance using modeling techniques and past case studies instead of actual implementation data, so introducing variability. Second, DPP and digital tools may have limited scalability depending on industry-wide standardizing and regulatory support needed by them. Third, behavioral opposition, stakeholder collaboration, and data interoperability could all hinder the application of these technologies.

Even with well-developed DPP frameworks, construction and demolition firms, and other stakeholders must share and update material data. Clear economic, regulatory, or reputational incentives for transparent reporting could boost collaboration and adoption.

Digital platforms and IoT sensors can automate data collection and analytics, but human expertise is essential for nuanced decision-making. Regular training, user-friendly tools, and strong communication can help automated processes and human judgment collaborate. Standard data formats and waste management best practices can accelerate DPP adoption with legislative support. Early adopter incentives and noncompliance penalties may broaden acceptance and create a level playing field. The timber case study shows how digital tools can improve waste management, but different materials and local conditions may require different approaches.

Assessing digital solutions' environmental and economic benefits. Clear metrics like ROI timelines or life-cycle savings help stakeholders allocate resources. Regarding cybersecurity and risk management, cloud-based, real-time data exchange requires strong security. Trust between parties can be maintained through blockchain technology or encrypted databases to protect sensitive material. Standardization, interoperability, and stakeholder alignment are needed for digital innovations to succeed. Future research should refine and apply these tools to other materials to increase industry scalability. In construction, digital innovation and human-centric approaches drive sustainable transformation for responsible and efficient (de)construction.

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