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Enabling Circularity through Dynamic Material Passports: A Framework Integrating Digital Twin Technologies and Data Governance in the Built Environment

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Abstract

Achieving circularity and sustainability in the built environment requires advanced mechanisms for tracking and managing material flows across the building lifecycle. Material passports (MPs) have emerged as key digital tools to enable material traceability, reuse, and lifecycle intelligence. However, conventional MPs remain static and limited in supporting dynamic decision-making for sustainable construction practices.

This study introduces a novel framework for Dynamic Material Passports (DMPs), developed to enhance material transparency, enable circular resource flows, and support lifecycle-oriented sustainability strategies. The framework leverages digital twin technologies to enable real-time updates and continuous alignment between physical building assets and their digital counterparts. It also incorporates structured data governance mechanisms, drawing from emerging practices in interoperability, blockchain, and stakeholder access control to ensure secure, transparent, and scalable information management. The framework is developed in alignment with Canadian digital construction priorities and standards (e.g., CCMC, NMS) but is designed for global applicability.

By embedding digital twin integration and data governance directly into the structure of DMPs, the framework addresses key barriers to circularity, including data fragmentation, limited reuse planning, and lack of lifecycle accountability. The proposed approach contributes to advancing sustainable construction practices and enabling more effective circular economy (CE) strategies across the built environment.

Keywords: Dynamic Material Passports, Digital Twin, Internet of Things, Circular Construction, Sustainable Built Environment, Data Governance, Lifecycle Data Management

Highlights

- This study introduces a framework for Dynamic Material Passports in construction.
- The framework links Digital Twins and data governance to enhance circularity.
- It advances lifecycle transparency and supports sustainable building practices.

1 Section 1- Introduction

The global building and construction sector is responsible for over one-third of global energy-related CO_2 emissions and consumes more than 50% of extracted raw materials, making it one of the most resource-intensive industries (IEA, 2023; UNEP, 2022). Meeting the targets outlined in the Paris Agreement and the UN Sustainable Development Goals (SDGs) necessitates a fundamental transformation from linear, resource-intensive 'take-make-dispose' models towards regenerative, circular systems.

The circular economy (CE) framework offers a systemic approach to resource efficiency by prioritizing material retention through reuse, refurbishment, remanufacturing, and recycling. Implementing CE in the built environment requires robust, interoperable digital infrastructures capable of tracking and managing materials across the building lifecycle. Material Passports have emerged as pivotal tools in this domain, providing structured, digitally accessible records of a building's materials and components, their composition, and their potential for recovery. Despite their potential, most MP implementations remain static and dependent on manual updates, reducing their effectiveness for real-time decision-making. Recent advancements in Digital Twin (DT) technologies—virtual replicas of physical assets linked via real-time data streams—present opportunities to transform MPs into Dynamic Material Passports (DMPs) capable of continuous updates, predictive analytics, and lifecycle optimization. This paper proposes an integrated DMP framework that leverages DT technologies alongside robust data governance protocols to address these limitations. The framework aligns with Canadian digital construction priorities while offering scalability and adaptability to international contexts.The scalability of the DMP framework presents distinct challenges for small- to medium-sized construction projects when compared to large institutional or infrastructure developments. While large-scale projects typically operate within established Building Information Modeling (BIM) ecosystems, supported by advanced digital infrastructures, specialized data management expertise, and regulatory oversight, smaller organizations often encounter significant barriers. These include limited financial resources, restricted training capacity, and fragmented workflows that inhibit the seamless integration of DMPs and associated Digital Twin systems (buildingSMART Canada, 2025).

In the Canadian context, the effective implementation of DMPs will depend on their alignment with both national and provincial regulatory frameworks, notably the National Building Code (NBC) and standards such as Ontario's Building Code and British Columbia's Energy Step Code. Harmonizing DMP data structures with these regulatory instruments is essential to ensure consistency, interoperability, and traceability across jurisdictions, thereby supporting the material circularity objectives embedded in national sustainability policies.

Future work will therefore focus on developing scalable implementation strategies and cost-efficient digital toolkits tailored to diverse project scales and governance capacities. Emphasis will be placed on lightweight Digital Twin architectures, open data standards, and adaptive governance models that enable smaller construction enterprises to participate effectively in Canada's digital transition towards a circular built environment.

2 Section 2- Background

2.1 Material Passports and Circular Construction

Material Passports (MPs) are structured digital documents containing information on the materials and components within a building, detailing their characteristics, origin, composition, and potential for reuse, recycling, or recovery. They originated from European initiatives such as Buildings as Material Banks (BAMB), aiming to create transparency in material flows and facilitate circularity (Munaro & Tavares, 2021). By enabling traceability, MPs can reduce waste, increase material recovery rates, and foster secondary material markets.
In Europe, MPs are increasingly integrated into national building codes and sustainability assessment schemes, for example, the Netherlands' material data requirements and Finland's circularity indicators. However, adoption in North America remains limited due to the absence of standardized frameworks, fragmented regulations, and low industry awareness (Cruz Rios et al., 2023). Current implementations largely operate as static, design-stage documents, updated manually and rarely maintained throughout the operational phase, reducing their relevance for end-of-life planning and adaptive reuse.

Recent research has provided valuable insights into the implementation of MPs across diverse construction contexts. A comprehensive review by Markou et al. (2025) synthesizes current advancements in MP development and application, emphasizing their role in enabling data-driven circularity, resource recovery, and lifecycle transparency within the built environment (Markou et al., 2025). The study categorizes implementation strategies based on technological maturity, data governance models, and integration with BIM-based digital workflows, highlighting that successful adoption often depends on establishing standardized data ontologies and interoperable platforms. Complementing this, Atta, Islam et al. (2021) present an applied case study demonstrating how the incorporation of MPs within a Building Information Modelling (BIM) environment can enhance material traceability and information exchange throughout a project's lifecycle (Atta, Islam, et al., 2021). Their work illustrates the potential for MPs to function as dynamic repositories that connect material datasets with building performance metrics, thereby supporting circular design decision-making. Together, these studies reinforce the importance of aligning MP initiatives with digital twin principles, data standardization efforts, and industry-specific regulatory frameworks—foundational elements further developed in the present DMP framework proposed in this paper.
This static nature limits the capacity of MPs to adapt to evolving conditions in materials, building performance, and regulatory landscapes. Dynamic Material Passports (DMPs) address these shortcomings by embedding real-time data integration, enabling adaptive strategies for maintenance, renovation, and resource recovery.

2.2 Digital Twin Technologies in the Built Environment

Digital Twin technologies enable the creation of dynamic, virtual representations of physical assets, continuously updated through data streams from Internet of Things (IoT) sensors, Building Information Modelling (BIM) process, and operational databases. These tools facilitate predictive analytics, performance optimization, and advanced asset lifecycle management. Within the built environment, DTs have been applied to a range of functions, including predictive maintenance, energy efficiency enhancement, and occupant comfort optimization (Opoku et al., 2023).

When integrated with Material Passports (MPs), BIM-enabled DTs can provide real-time updates on material condition, automate documentation processes, and support data-driven decision-making for maintenance and end-of-life interventions. For instance, a DT can identify the progressive deterioration of façade panels and automatically update the corresponding MP records, thereby enabling timely and informed choices regarding repair, reuse, or recycling strategies.

Despite their potential, the integration of MPs and DTs remains limited, primarily due to interoperability constraints, heterogeneous data standards, and the absence of robust governance frameworks.

2.3 Data Governance for Material Intelligence

Data governance establishes the rules, processes, and responsibilities for managing data assets. In the context of DMPs, data governance ensures data integrity, security, and accessibility across diverse stakeholders, including designers, contractors, owners, regulators, and recyclers (Lawal & Rafsanjani, 2023).

Key governance mechanisms include:
- Role-based access control (ensuring only authorized stakeholders can view or modify data)
- Blockchain-based transaction logs for material exchanges
- Semantic ontologies enabling interoperability across platforms (Hunhevicz et al., 2023)

Without robust governance, DMP adoption faces risks related to data misuse, privacy breaches, and lack of trust among stakeholders.

3 Methodology

The development of the proposed DMP framework followed a mixed-methods research approach combining systematic literature review, stakeholder consultation, and iterative design refinement. The methodology was structured into the following phases:
Phase 1 – Systematic Literature Review: A comprehensive review of peer-reviewed articles, industry reports, and policy documents (2018–2024) was conducted to assess the current state of Material Passports, Digital Twin technologies, and data governance frameworks in the built environment. This analysis revealed critical gaps: (a) the static nature of most MPs, (b) limited integration of real-time data streams, and (c) insufficient governance protocols for multi-stakeholder environments.
Phase 2 – Stakeholder Engagement: Structured interviews and focus group discussions were held with representatives from construction firms, technology providers, policymakers, and standardization bodies. These sessions aimed to identify practical requirements for interoperability, access control, and data ownership in DMP deployment. Stakeholders emphasized the need for open yet secure data-sharing mechanisms to support both project-level and policy-level objectives.
Phase 3 – Conceptual Framework Design: Using insights from Phases 1 and 2, a conceptual DMP framework was developed that integrates DT technologies with data governance mechanisms. The framework is structured into three core layers: (1) Physical Asset Layer, representing the building and its material components; (2) Digital Twin Layer, providing real-time synchronized data on material condition and lifecycle status; and (3) Governance Layer, ensuring secure, standardized, and role-based data access.
Phase 4 – Validation and Refinement: The framework will be validated through proof of concept process, expert review and application to selected pilot case scenarios in Canada. Feedback informed refinements to the interoperability architecture, metadata standards, and governance policies.

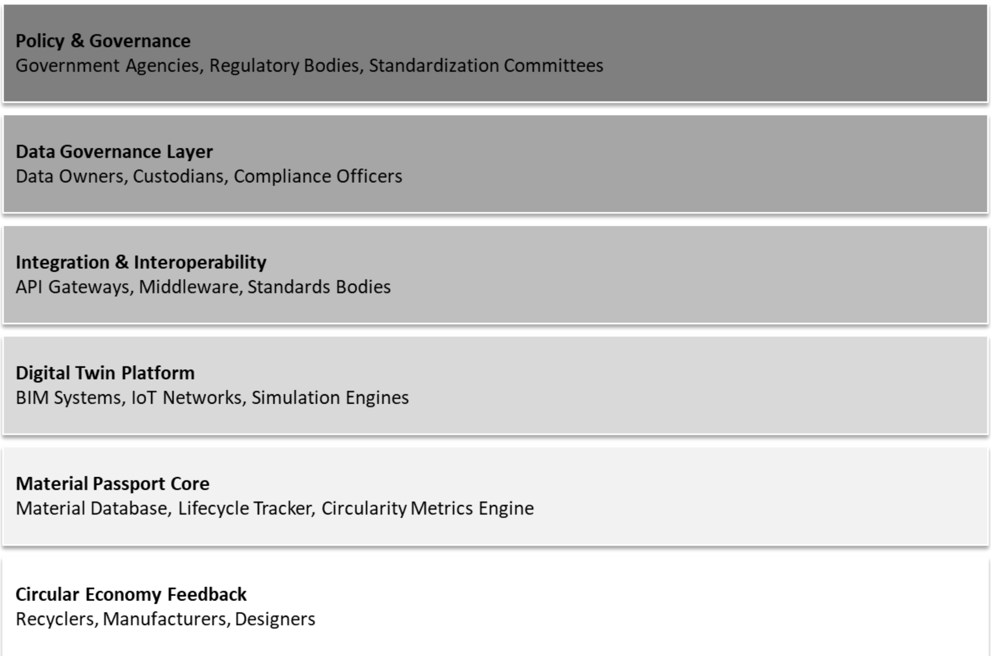

Figure 1: Conceptual framework for the Dynamic Material Passport integrating governance

As shown in Figure 1, the conceptual framework for the DMP integrates multiple layers of functionality, governance, and stakeholder interaction to enable a fully interoperable, lifecycle-based data environment. At the top layer, policy and governance actors (standards bodies, regulatory agencies, and policy-makers) establish the enabling frameworks, harmonized definitions, and data governance principles. The integration layer connects digital twin platforms, BIM systems, IoT sensors, and lifecycle assessment (LCA) tools, ensuring structured, interoperable data flows. The core DMP system layer houses the passport database, material classification schema, circularity indicators, and security protocols. The user layer encompasses direct system users—architects, engineers, contractors, facility managers, deconstruction teams—who interact with the platform through standardized workflows. The circular economy ecosystem layer extends the DMP's impact to recycling facilities, secondary material markets, and remanufacturers, ensuring the preservation of material value across multiple lifecycles.

4 Results and Discussion

The proposed DMP framework demonstrates the feasibility and strategic value of integrating BIM-based Digital Twin technologies and data governance structures to create a living, dynamic repository of material intelligence. The framework proposes the integration of DT technologies with MPs while standardizing material data management, aligning with ISO 19650, and incorporating Canadian-specific adaptations.

As depicted in Figure 2, the framework integrates MPs with DTs to create a digital twin system for DMPs. Various digital technologies can be utilized for data collection, analysis and sharing of MPs. Depending on the building's lifecycle stage, different technologies can be utilized for data collection. During the design stage, BIM plays a central role in providing the necessary data for MP compilation. In the use stage, Internet of Things devices (such as embedded strain gauges, temperature sensors and moisture sensors) and Radio Frequency Identification (RFID) technologies can be employed to gather material information. At the end-of-life stage, Remote Sensing technologies, such as Geographic Information System (GIS), Laser Scanning (LS) and Ground Penetrating Radars (GPRs) can be utilized to collect data

on materials. For analyzing MPs, technologies like Artificial Intelligence (AI), virtual reality (VR) and computer vision can assist in predictive maintenance and material sorting.
Ensuring data security is a crucial aspect of the DMPs system. The use of Cryptographic technologies can enhance the credibility and security of material information shared among different stakeholders. Utilizing ISO 19650, the interoperability across platforms can be enhanced, resulting in a seamless integration between MPs and DT technologies. The persistence of data over time across multiple owners and governments, as well as archiving, may also be managed based on classical cataloguing and data archiving systems, such as existing property ownership archives and asset management systems databases. Ultimately, a distributed and hybrid approach will evolve based on the prevailing regulatory environment, building codes, development policies, and market forces.

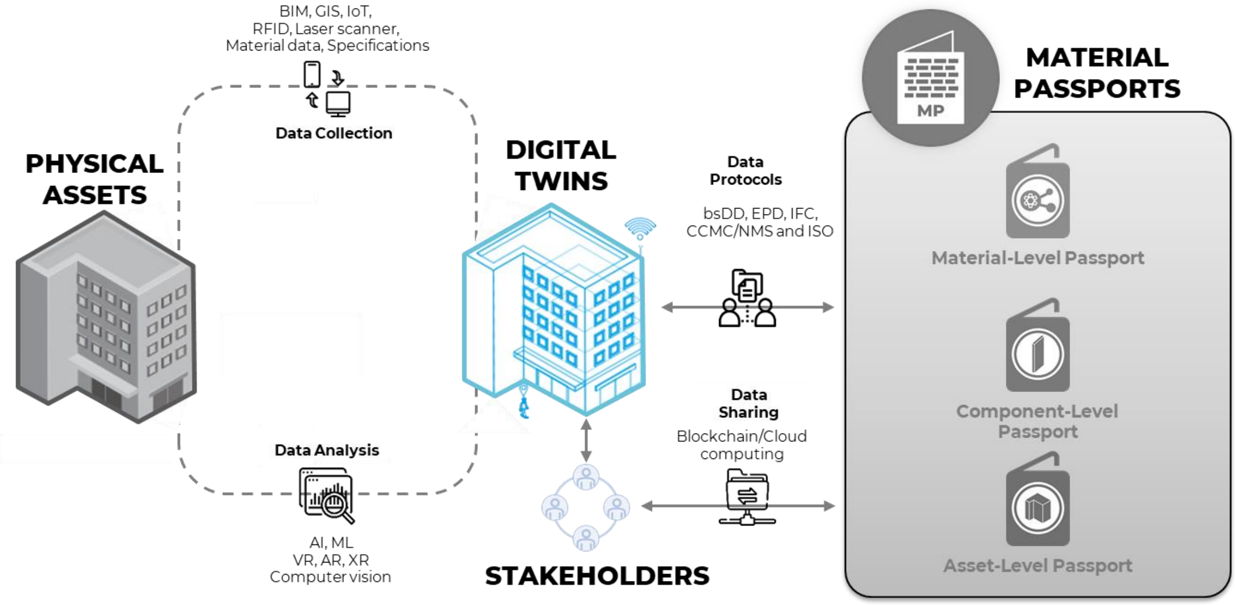

Figure 2: Dynamic Material Passport integrated with the digital twin ecosystem (Ahmadi et al, 2025)

For integration of DMPs with data governance principles, key findings include:

1. Enhanced Real-Time Traceability: By embedding BIM-based DT systems within the DMP, the material inventory can be updated in near real-time, reflecting changes due to wear, replacement, retrofitting, or repurposing. This addresses a major limitation of static MPs, ensuring that decisions—whether for maintenance, resale, or recycling—are based on current data.
2. Lifecycle Intelligence: The continuous synchronization between the physical asset and its digital counterpart enables predictive modelling of material performance and service life. This supports proactive maintenance, optimized refurbishment cycles, and reduced unplanned material waste.
3. Governance as an Enabler: Robust data governance is not simply an administrative layer but a critical enabler of trust and adoption. By implementing role-based permissions, immutable transaction records, and semantic interoperability, the DMP becomes a trusted source of truth for all stakeholders. This governance ensures that sensitive commercial data is protected while allowing necessary transparency for regulators and recyclers.
4. Global Novelty: The integration of DT and governance into MPs is a globally emerging field, and the proposed framework positions Canada at the forefront of this innovation. This presents Canada with a leadership opportunity to influence international standards and best practices.

5. Policy and Market Implications: The framework can inform emerging policies on embodied carbon, material efficiency, and waste reduction by providing reliable, verifiable data streams. In the market, it can catalyze new business models such as material leasing, buy-back programs, and component-as-a-service schemes.

Figure 3, the operational workflow illustrates how data governance principles are embedded in the DMP system from data capture to material reuse. The process begins with data input and verification, sourced from manufacturers, product declarations, and digital twin feeds. Standardization and classification follow, ensuring data compatibility across platforms and compliance with governance protocols. Data integration links multiple digital systems (BIM, LCA, IoT), enabling real-time updates and cross-lifecycle tracking. The analytics and reporting stage provide actionable insights for carbon accounting, circularity assessments, and compliance verification. The workflow culminates in decision-making and circular actions, where material recovery, reuse, and resale are informed by reliable, transparent data. Each step includes responsible actors, from manufacturers and project teams to regulators and circular economy market players.

Figure 3: Operational workflow of the DMP system showing integrated data governance and stakeholder roles from input to circular outcomes

The relationship between DT, governance, and MPs is inherently symbiotic. DTs provide the real-time operational data that transforms MPs into dynamic assets. Data governance ensures that this operational intelligence is shared, stored, and used in ways that build trust across the value chain. Without DT integration, MPs remain static; without governance, they lack credibility; without MPs, DTs lack a structured framework for material-level insights. The DMP unites these elements into a cohesive tool for circularity.

Blockchain technology shows promise for improving transparency and traceability in Material Passports (MPs) within construction. It enhances data integrity and lifecycle tracking but faces major hurdles: poor interoperability, lack of standardization, and limited integration with BIM and other digital tools. These issues reduce its overall efficiency. Additionally, most blockchain-based MPs are static, requiring manual input and lacking real-time updates—a drawback in dynamic construction environments. Without seamless connectivity and automated data flows, the role of blockchain in advancing circular economy goals remains limited. This underscores the need for dynamic MPs in the sector (Markou, Ioannis, et al., 2025).

5 Conclusions and Future Work

This study has presented a pioneering framework for Dynamic Material Passports that integrates Digital Twin technologies and robust data governance mechanisms. The research addressed critical limitations in current MP implementations—specifically, their static nature, lack of interoperability, and absence of governance structures capable of supporting multi-stakeholder collaboration.

The proposed approach offers several key contributions:
- Operationalizes circular economy principles by enabling real-time, verifiable material traceability.
- Enhances decision-making through predictive analytics and lifecycle intelligence.
- Builds trust among stakeholders via transparent, role-based governance protocols.

In practical terms, adopting DMPs can accelerate progress towards national and international sustainability targets, inform policy frameworks on embodied carbon and material efficiency, and stimulate innovation in circular business models.

Future work will focus on piloting the DMP framework in live projects, refining data interoperability standards, and developing metrics to quantify the economic, environmental, and social impacts of DMP adoption. The insights gained from these pilots will further position Canada as a leader in sustainable and digital construction practices.

Building on the conceptual framework and initial validation presented in this study, the next phase of research will focus on empirical implementation and quantitative evaluation of Dynamic Material Passports (DMPs) in real-world construction settings. Specifically, future work will include:

- **Pilot Case Studies**: A series of Canadian building projects—spanning new construction, retrofits, and deconstruction scenarios—will be selected to operationalize the DMP framework. These pilots will test the integration of BIM-based Digital Twin systems, IoT-enabled material tracking, and governance protocols across diverse lifecycle stages. Each case will be documented to assess practical challenges, stakeholder engagement dynamics, and regulatory alignment.

- **Quantitative Impact Assessment**: The pilot applications will generate measurable data on material recovery rates, lifecycle carbon reductions, reuse potential, and governance efficiency. These metrics will be used to evaluate the effectiveness of DMPs in enabling circularity, improving decision-making, and supporting compliance with sustainability targets.

Comparative analysis across case studies will highlight contextual factors influencing DMP performance.

- **Interoperability and Standardization Metrics**: Building on ISO 19650 and Canadian standards (e.g., CCMC, NMS), future work will develop and test interoperability benchmarks for material data exchange. This includes metadata schemas, semantic ontologies, and blockchain-based audit trails to ensure secure and scalable deployment.
- **Stakeholder Feedback and Policy Integration**: Structured feedback loops will be established with project teams, regulators, and market actors to refine the framework and inform policy recommendations. Insights from these engagements will support the development of guidelines for national adoption and international harmonization.

Details of the pilot case studies—including project profiles, data collection protocols, and preliminary findings—will be shared in the next phase of this research. These results will provide the quantitative foundation needed to validate the DMP framework's scalability, economic viability, and environmental impact.

Future phases of this project will detail the implementation costs, training requirements, and adoption timelines for Canadian construction firms. While initial investment in digital infrastructure and workforce training is expected, pilot applications will help quantify cost-benefit outcomes and inform scalable strategies. These findings will support realistic adoption planning and industry-wide readiness.

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Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Conflicts of Interest

The authors declare no conflict of interest.

References

Ahmadi, L., Bilal, M., Olumo, A., Mollaei, A., Jalaei, F., Ebrahimi, N., Mozaffari, H., Kim, J., & Haas, C. (2025). Enhancing Circularity in the Building Industry: A Review of Material Passports and Digital Twin Technologies. Journal of Construction Engineering and Management, DOI: 10.1061/JCEMD4/COENG-16899.

Çetin, R., Öztürk, U., & Peker, E. (2023). A framework for implementing material passports in circular construction: Barriers and strategies. Journal of Cleaner Production, 402, 136726. https://doi.org/10.1016/j.jclepro.2023.136726

Cruz Rios, F., Grau, D., & Chong, W. (2023). A review of material passport implementation challenges and solutions in circular construction. Journal of Construction Engineering and Management, 149(3). https://doi.org/10.1061/JCEMD4.0001300

El Jazzar, M., Marzouk, M., & El-Anwar, O. (2024). Digital twin adoption for building lifecycle assessment and optimization. Automation in Construction, 155, 105059.

Hunhevicz, J. J., Hall, D. M., & Nägeli, M. (2023). Distributed data governance in digital construction:

Blockchain-based approaches and interoperability standards. Advanced Engineering Informatics, 55, 101915.

International Energy Agency (IEA). (2023). Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2023

Lawal, A., & Rafsanjani, H. (2023). Data governance frameworks for the built environment: Enabling interoperability and security. Journal of Information Technology in Construction, 28, 15–34.

Munaro, M. R., & Tavares, S. F. (2021). Material passports for the circular economy: Concepts and applications in the built environment. Resources, Conservation and Recycling, 174, 105735.

Opoku, D. G. J., Perera, S., & Osei-Kyei, R. (2023). Digital twin applications in the built environment: Trends and future directions. Automation in Construction, 143, 104556.

Sinaeepourfard, A., Maroto, C., & Pijoan, A. (2024). Semantic interoperability in construction: Ontology-based approaches for digital twins and material passports. Journal of Building Engineering, 78, 107659.

United Nations Environment Programme (UNEP). (2022). Sustainable Building and Construction: Facts and Figures. https://www.unep.org/resources/report/sustainable-building-and-construction-facts-and-figures

Markou, Ioannis, Derek Sinnott, and Ken Thomas. "Current methodologies of creating material passports: A systematic literature review." Case Studies in Construction Materials (2025): e04267.

Atta, Islam, Emad S. Bakhoum, and Mohamed M. Marzouk. "Digitizing material passport for sustainable construction projects using BIM." *Journal of Building Engineering* 43 (2021): 103233.

buildingSMART Canada, "Digital Construction Platform Roadmap", 2025, https://buildingsmartcanada.ca/mission/resources/.