Materials Research Proceedings 72 (2026) 461-469 https://doi.org/10.21741/9781644904336-45

Integrating BIM, Virtual Reality, and Material Passports for Early-Stage Circular and Low-Carbon Material Selection

Zeeshan Jawed SHAH[1,2,a *], Hussam AL QURAN[1,b] and Rui BARREIRA[1,c]

[1]Prince Mohammad Bin Fahd University, Al Khobar, Saudi Arabia

[2]Multimedia University, Cyberjaya, Malaysia

[a]zshah@pmu.edu.sa, [b]rdacosta@pmu.edu.sa, [c]halquran@pmu.edu.sa

Keywords: Building Information Modelling (BIM), Virtual Reality (VR), Material Passports, Circular Construction, Embodied Carbon, Early-Stage Design, Design Science Research, Decision Support System, Sustainable Material Selection

Abstract. The construction sector requires decision-support workflows that address embodied carbon and circularity before detailed design constrains material choices. Although material passports, Building Information Modelling (BIM), and Virtual Reality (VR) each offer partial support, an integrated early-stage workflow for material selection remains underdeveloped. This study proposes a BIM-integrated, VR-enabled material-passport framework for comparing low-carbon and circular material alternatives in context. Using a design science research approach, the study develops a four-layer framework comprising a data layer, passport layer, interaction layer, and decision layer, and implements it as a proof-of-concept prototype in a bounded classroom fit-out case. BIM objects are linked to passport records containing identity, embodied carbon, reuse and recovery potential, disassembly logic, lifespan, and end-of-life information, which are visualized through an immersive comparison interface. The prototype is evaluated against a conventional BIM-based workflow using decision time, decision confidence, perceived understanding, usability, and benchmarked selection quality, while expert and user reflections are used to identify implementation barriers. Initial findings suggest that the integrated workflow is technically feasible, improves in-context accessibility of sustainability information, and supports clearer comparison-oriented reasoning, although gains in decision speed remain sensitive to onboarding time and data quality. Persistent barriers include interoperability, data consistency, standardization, and stakeholder ownership. The study contributes an integrated framework, a prototype workflow, and implementation priorities for more decision-ready circular construction.

Introduction and problem framing

The construction sector is central to climate mitigation because it consumes large quantities of virgin resources, generates major waste streams, and locks environmental impacts into projects at the design stage. Circular-economy research therefore argues for a shift from linear material practices toward reuse, recovery, long life, and better lifecycle transparency, while embodied-carbon research shows that these concerns must be addressed early, when material alternatives are still flexible [1,2,3,4].

Within this transition, material passports have emerged as structured records for documenting composition, provenance, disassembly, recycling pathways, and residual value, BIM has matured as the main structured environment for project information, and VR has shown growing value for spatial understanding and collaborative review. Yet these streams are still weakly connected. Material-passport studies report fragmented data models and weak interoperability; BIM-based carbon workflows often remain assessment-oriented rather than decision-oriented; and VR studies rarely connect immersive review to structured circularity intelligence for measurable material-selection tasks [5,6,7,8,9].

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

Materials Research Proceedings 72 (2026) 461-469 https://doi.org/10.21741/9781644904336-45

Accordingly, this paper addresses three linked questions: how a BIM-integrated, VR-enabled material-passport framework can be designed for early-stage low-carbon and circular material selection; whether such a workflow can improve decision quality, speed, confidence, and understanding when compared with a conventional BIM workflow; and which interoperability, information-sharing, and adoption barriers shape practical implementation. The study responds through design science research, a bounded classroom fit-out case, a comparative proof-of-concept evaluation, and barrier analysis.

The contribution is threefold. First, the paper integrates BIM, VR, and material-passport intelligence into a single early-stage decision-support logic. Second, it translates that logic into a lightweight prototype architecture linking BIM objects, passport attributes, and immersive comparison functions. Third, it identifies the technical and organizational conditions required for broader adoption in circular construction practice.

Focused literature background and gap synthesis

Material-passport research establishes the importance of lifecycle traceability, reuse potential, and structured component-level datasets, but it also shows that passport methods remain fragmented across different schemas, platforms, and project contexts. At the same time, BIM is increasingly used for embodied-carbon and circularity assessment, especially in early design, yet many workflows still depend on later-stage information, detached databases, or static dashboards. In practice, this limits rapid iteration between design alternatives and sustainability implications [5,6,7,4,10]. Recent reviews also stress that passport value depends on governance: data must remain updateable across design, construction, operation, and end-of-life stages, yet most current implementations are project-specific or static.

VR research consistently reports gains in immersion, spatial comprehension, communication, and collaborative review in construction contexts. Recent circularity-oriented BIM-VR studies further suggest that immersive interfaces can make sustainability information easier to interpret. However, robust evidence remains limited on whether VR materially improves low-carbon and reusable-material choice when compared with a conventional BIM workflow. The unresolved gap is therefore not the value of the individual technologies, but the absence of a coherent, interoperable, and empirically oriented BIM-VR-material-passport workflow for early design [11,8,12,9]. This matters because early-stage designers need comparative support under uncertainty, not only detailed lifecycle records after decisions have already been made.

Another important issue in the literature is decision-system maturity. Digital circularity tools increasingly connect model data, carbon databases, and visual dashboards, but many still stop at reporting rather than supporting action. What remains underdeveloped is a workflow in which designers can inspect alternatives in context, understand why one option performs better, and immediately reflect that choice back into the model. The present study is positioned precisely at this point of transition from sustainability assessment to sustainability-oriented design decision support.

Table 1. Literature gap synthesis. The synthesis below is derived from the reviewed literature and positions the present study directly against the three core research issues.

Theme	What literature already does	What is missing	Response in this study
Material passports	Defines passports as lifecycle datasets for traceability, reuse, and recovery.	Harmonized fields, dynamic updating, and interoperable implementation remain weak.	Uses a compact BIM-linked passport schema for early design.
BIM and embodied carbon	Supports carbon and circularity assessment using model-based information.	Assessment often remains detached from rapid material selection and multi-criteria comparison.	Moves BIM from assessment toward decision-oriented material comparison.
VR for design review	Improves immersion, understanding, communication, and collaborative review.	Limited evidence links VR directly to low-carbon and circular material choice.	Uses VR as the interaction layer for passport-based comparison.
Cross-domain integration	Emerging studies show feasibility of BIM-VR and circularity integration.	No widely validated BIM-VR-material-passport workflow exists for early-stage decisions.	Develops and tests an integrated proof-of-concept workflow.

Conceptual framework

The proposed framework is designed as an early-stage decision-support system rather than a passive data repository. Its purpose is to transform BIM model data into structured material-passport intelligence and to present that intelligence in an immersive environment where carbon and circularity trade-offs can be examined in context. This emphasis on early design is important because the environmental consequences of material selection are strongest when alternatives are still open and before procurement decisions narrow the option set.

The framework consists of four linked layers. The data layer stores BIM geometry, object properties, quantities, material assignments, and linked sustainability datasets. The passport layer structures these inputs into a consistent component record containing identity, composition, embodied-carbon data, reuse and recovery potential, disassembly logic, lifespan, and end-of-life information. The interaction layer uses VR to expose these records through immersive visualization, element selection, filtering, and alternative comparison. The decision layer captures user-facing outcomes such as selection quality, decision speed, confidence, and perceived understanding. In practical use, these layers support a multi-criteria reading of material alternatives, where lower carbon must be balanced against recoverability, service-life fit, and ease of future disassembly.

Conceptually, the framework treats the passport as the translation layer between raw model information and designer judgment. It is the passport structure that turns scattered sustainability data into a comparable record. VR then acts as the cognition layer, making those records legible at room scale and in relation to the actual building scene. This distinction clarifies why simply attaching environmental data to BIM objects is not enough; the information also needs a usable interaction environment if it is to support confident early-stage choice.

The conceptual logic is BIM data -> passport enrichment -> VR-based comparison -> material decision. A feedback loop returns the selected option to the BIM and passport layers so that design representation and sustainability information remain synchronized. The same loop also reveals the main implementation constraints highlighted in the literature, namely inconsistent data structures, weak interoperability, limited standardization, and unclear ownership of passport maintenance across stakeholders. Figure 1 illustrates the conceptual framework of the proposed BIM–VR-enabled material passport system, showing the progression from BIM object data to material-passport enrichment, VR-based comparison, and material-selection outcomes, together with the feedback loop for iterative design refinement.

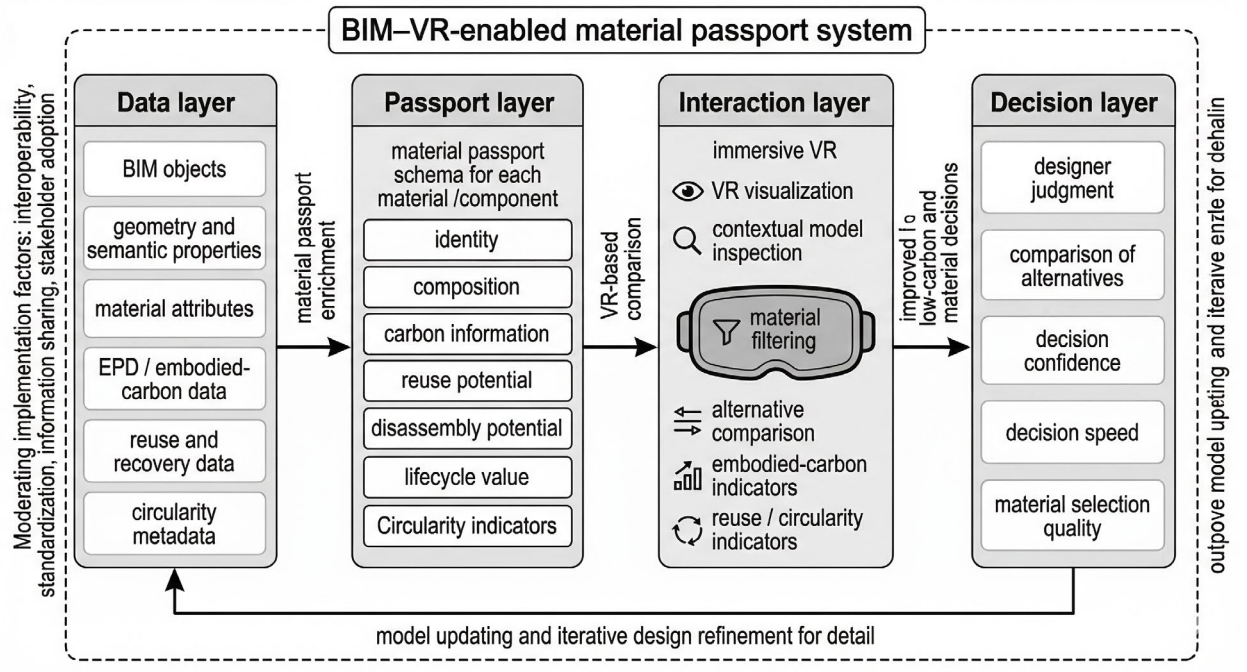


Figure 1. Conceptual framework of the BIM-VR-enabled material passport system.

Research design and methodology

This study adopts design science research because its primary outcome is an artifact: a BIM-integrated, VR-enabled material-passport framework for early-stage material selection. The research proceeds through five phases: requirement identification from the literature, development of a compact passport schema, mapping of passport fields to BIM parameters and linked datasets, implementation of an immersive prototype, and proof-of-concept evaluation in context [13,14].

The comparative design is intentionally modest but methodologically useful. A bounded pilot allows the artifact to be demonstrated under controlled conditions while revealing where the workflow helps, where it slows users down, and where missing data reduces trust. This is especially relevant for circular material selection because uncertainty is highest at early design, exactly when a structured but flexible decision environment is most needed.

Table 2. Research design and measurement variables. Table 2 summarizes the proposed research design and the main variables used to evaluate decision benefit and implementation barriers in the proof-of-concept study

Element	Operationalization
Research strategy	Design science research with proof-of-concept comparison and barrier reflection
Case study	Bounded classroom fit-out with alternative finish and fit-out packages
Condition A	Conventional BIM/material comparison workflow
Condition B	BIM + VR + material-passport workflow
Core measures	Decision time, confidence, perceived understanding, usability, and selection quality
Barrier sources	Expert feedback and post-task reflections coded thematically

Participants and evaluation procedure**.** A total of 16 participants were recruited for the proof-of-concept evaluation of the proposed BIM–VR–material-passport workflow. The sample was intentionally heterogeneous but domain-relevant, comprising graduate students in architecture or

construction management (n = 8), junior design professionals such as architectural assistants or BIM coordinators (n = 5), and sustainability or circular economy researchers (n = 3). This composition reflects the multidisciplinary nature of early-stage material selection while keeping the study aligned with the proof-of-concept scope of design science evaluation. None of the participants had prior exposure to the specific prototype. Most participants had prior familiarity with BIM, but no regular prior experience with material passports, and prior VR-based material-selection experience was limited. Ages ranged from 23 to 34 years (mean = 26.7, SD = 3.1); 11 participants identified as male and 5 as female. All participants were fluent in English and were based in Saudi Arabia or Malaysia. Informed consent was obtained from all participants, and the study followed institutional ethical requirements for low-risk human-subject evaluation.

The evaluation used a within-subjects, counterbalanced design in which each participant completed two conditions: (A) a conventional BIM-based material comparison workflow and (B) the proposed BIM + VR + material-passport workflow. In Condition A, participants used the BIM model together with material schedules, manufacturer datasheets, and a spreadsheet of embodied-carbon and circularity attributes. In Condition B, the same underlying BIM information was delivered through the immersive prototype, where BIM objects were linked to structured passport records and viewed through an in-context comparison interface. Counterbalancing was used to reduce order effects: eight participants completed Condition A followed by Condition B, while the remaining eight completed Condition B followed by Condition A. A washout interval of at least 48 hours was maintained between the two sessions.

In each condition, participants completed four equivalent material-selection subtasks within the bounded classroom fit-out case: ceiling tile selection, partition finish selection, door leaf selection, and floor finish selection. For each task, participants were asked to choose the option that best balanced low embodied carbon and circularity criteria, including reuse potential, disassembly logic, and recyclability, while remaining suitable for classroom use in terms of durability, maintenance, and functional performance. Each session followed a standardized sequence of briefing, task execution, post-condition questionnaire, and final reflection; the VR condition also included a short onboarding tutorial on headset controls and interface navigation. Decision time was recorded for each task, and post-condition measures captured decision confidence, perceived understanding of carbon and circularity implications, and usability using the System Usability Scale [17,18]. After completing both conditions, participants provided brief open-ended reflections on strengths, weaknesses, and encountered barriers. To evaluate selection quality, two domain experts independently scored the final choices against a predefined rubric covering embodied carbon, reuse/recovery potential, disassembly clarity, and service-life appropriateness; the averaged expert score was used as the final benchmark. Qualitative reflections were then coded thematically to identify technical, informational, organizational, and adoption-related barriers [19].

Framework implementation / system architecture

The prototype operationalizes the framework as a modular pipeline: BIM authoring model -> passport database -> VR engine -> decision-support interface. The BIM model provides the primary source data through semantically defined objects and element parameters. For each relevant component, the prototype extracts a compact set of fields including unique ID, category, quantity, material assignment, and location, then links these records to passport attributes such as manufacturer or source, embodied-carbon value, reuse potential, disassembly status, expected lifespan, and end-of-life scenario.

Within the VR environment, selecting an element opens a contextual passport panel and enables side-by-side comparison of candidate materials. The interface supports element highlighting, filtering by carbon or circularity criteria, and in-context inspection of the classroom scene, so users do not need to move constantly between model views, schedules, and detached spreadsheets. The

Materials Research Proceedings 72 (2026) 461-469 https://doi.org/10.21741/9781644904336-45

architecture is intentionally lightweight to keep the proof of concept reproducible while still demonstrating how immersive review can become a decision layer rather than a visualization add-on. Figure 2 presents the system architecture and workflow pipeline of the proposed BIM–VR-enabled material passport framework, showing how BIM model data are transformed into passport records, linked to the VR environment, and delivered through a decision-support interface for material comparison and selection.

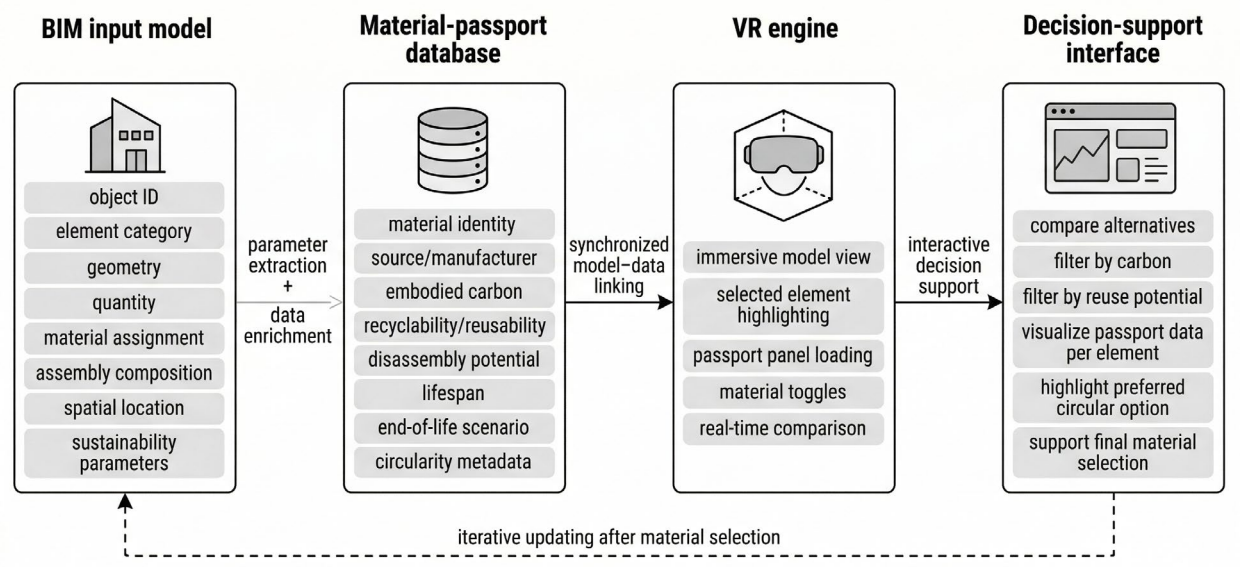


Figure 2. System architecture and workflow pipeline of the BIM-VR-enabled material passport framework.

This modular structure also provides a basis for later extension toward live EPD synchronization, multi-user review, or AI-assisted material recommendation, but the present paper focuses on showing a clear and testable early-stage workflow.

Results and discussion

The proof-of-concept comparison involved 16 participants across graduate, professional, and research backgrounds, providing an initial cross-section of likely early-stage decision users. These barrier categories also clarify the pathway from prototype to practice. Technical feasibility alone will not produce adoption if passport records remain difficult to populate, if manufacturers report data inconsistently, or if project teams do not agree on how carbon and circularity criteria should be represented. For that reason, implementation should be understood as a socio-technical problem involving standards, data stewardship, training, and workflow integration rather than software design alone.

Table 3. Qualitative summary of proof-of-concept findings.

Finding area	Initial interpretation
Technical feasibility	BIM objects, passport records, and VR views can be linked in a coherent workflow.
Information accessibility	Carbon and circularity attributes are easier to inspect in context than in detached schedules.
Decision support	The integrated workflow supports comparison-oriented reasoning rather than simple data lookup.
Main barriers	Interoperability, data completeness, field standardization, and ownership of updates.
Implementation implication	Adoption requires governance, standards, and training in addition to interface refinement.

Materials Research Proceedings 72 (2026) 461-469 https://doi.org/10.21741/9781644904336-45

The proof-of-concept implementation demonstrated that BIM object data, passport records, and a VR review environment can be linked within a single workflow. At component level, the prototype allowed users to select classroom elements and retrieve a structured passport containing the attributes most relevant to early comparison: identity, embodied carbon, reuse and recovery potential, disassembly logic, lifespan, and end-of-life scenario. This confirms the technical feasibility of moving from a static material inventory toward a decision-oriented, component-based circularity interface.

From the user perspective, the strongest benefit of the prototype was contextual interpretation. Passport information was viewed in situ, while alternative materials could be compared without leaving the immersive scene. Initial evaluation indicated that the integrated workflow improved the visibility and comprehensibility of carbon and circularity trade-offs, even when decision-speed gains were sensitive to onboarding time and data quality. In other words, the main value of the system lay in clearer reasoning at the point of choice rather than in simple automation alone.

Barrier analysis showed that practical deployment depends on more than interface design. The most persistent constraints were interoperability between BIM and passport datasets, incomplete or inconsistent sustainability information, difficulty standardizing passport fields across products, and uncertainty over who should create, verify, update, and use passport records across project stages. These findings align with the wider literature and indicate that implementation readiness will require governance and standardization as much as technical refinement [7,10,12]. The barrier themes therefore operate as design requirements for the next iteration of the framework, especially around standardized field definitions, responsibility matrices, and more stable data exchange routes.

Taken together, the findings position the framework as an integrative step toward circular, low-carbon decision support in the built environment. The study extends BIM from an information container toward a decision substrate, positions VR as an interface for sustainability reasoning, and shows how material passports can function as structured intelligence for design comparison rather than as end-of-life documentation alone.

Theoretical and practical implications follow directly from this integration. The paper connects three strands that are usually treated separately: material-passport traceability, BIM-based environmental assessment, and immersive design review. For practice, the proposed workflow offers a front-end environment for comparing finish packages, evaluating low-carbon substitutions, and communicating trade-offs to clients or multidisciplinary teams at the stage when changes remain most effective.

An additional practical implication is the possibility of assisted recommendation. Once passport fields are standardized and linked to decision rules, the same workflow could support semi-automated ranking of alternatives or guided exploration of sustainable options. Emerging interactive material-selection research points in this direction, suggesting that future systems may combine immersive review with AI-supported filtering and recommendation while still leaving the final judgement to the designer [20].

Several limitations remain. The study is bounded to a small fit-out case and a prototype-level implementation, so the findings should be interpreted as indicative rather than generalizable. Future work should test live database synchronization, larger project contexts, multi-user review, and stronger standardization of passport fields and responsibilities. These steps are necessary if BIM-VR-material-passport workflows are to move from research prototypes to routine circular-construction practice. A further research priority is collaborative use: material decisions are rarely made by one actor alone, so future versions should support shared review between architects, engineers, clients, and facility stakeholders. In addition, the participant sample was convenience-based and relatively small, so the findings should be interpreted as indicative of proof-of-concept utility rather than statistically generalizable to all construction-project settings.

Conclusion

This paper proposed a BIM-integrated, VR-enabled material-passport framework for early-stage low-carbon and circular material selection. By linking BIM objects to structured passport records and exposing those records through an immersive comparison environment, the framework addresses a persistent gap between sustainability information availability and actual design decision support.

The proof-of-concept case showed that the approach is technically feasible and useful for making carbon and circularity information more accessible in context. At the same time, the study confirmed that broader implementation will depend on stronger interoperability, more consistent data, clearer standardization, and defined stakeholder responsibilities. Overall, the paper argues that immersive material-passport workflows offer a credible pathway toward more transparent and decision-ready circular construction.

References

[1] F. Pomponi, A. Moncaster, Circular economy for the built environment: A research framework, Journal of Cleaner Production 143 (2017) 710-718. https://doi.org/10.1016/j.jclepro.2016.12.055

[2] G.L.F. Benachio, M.C.D. Freitas, S.F. Tavares, Circular economy in the construction industry: A systematic literature review, Journal of Cleaner Production 260 (2020) 121046. https://doi.org/10.1016/j.jclepro.2020.121046

[3] K.M. Rahla, R. Mateus, L. Bragança, Selection criteria for building materials and components in line with the circular economy principles in the built environment: A review of current trends, Infrastructures 6(4) (2021) 49. https://doi.org/10.3390/infrastructures6040049

[4] B. Huang, H. Zhang, H. Ullah, Y. Lv, BIM-based embodied carbon evaluation during building early-design stage: A systematic literature review, Environmental Impact Assessment Review 112 (2025) 107768. https://doi.org/10.1016/j.eiar.2024.107768

[5] M. Honic, I. Kovacic, G. Sibenik, H. Rechberger, Data- and stakeholder management framework for the implementation of BIM-based material passports, Journal of Building Engineering 23 (2019) 341-350. https://doi.org/10.1016/j.jobe.2019.01.017

[6] I. Atta, E.S. Bakhoum, M.M. Marzouk, Digitizing material passport for sustainable construction projects using BIM, Journal of Building Engineering 43 (2021) 103233. https://doi.org/10.1016/j.jobe.2021.103233

[7] S. Çetin, D. Raghu, M. Honic, A. Straub, V. Gruis, Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings, Sustainable Production and Consumption 40 (2023) 422-437. https://doi.org/10.1016/j.spc.2023.07.011

[8] M. Johansson, M. Roupé, Real-world applications of BIM and immersive VR in construction, Automation in Construction 158 (2024) 105233. https://doi.org/10.1016/j.autcon.2023.105233

[9] E. Sahebzamani, N. Forcada, Enhancing sustainable construction decisions: Integrating BIM and VR for circular economy assessment, Building Research & Information 54(1) (2025) 1-21. https://doi.org/10.1080/09613218.2024.2449441

[10] A.V. Reyes, D. Olmez, J. Grout, A. Carr, Digital material passports in the AEC industry: A scoping review and conceptualisation of future research challenges, Architectural Engineering and Design Management (2025) 1-21. https://doi.org/10.1080/17452007.2025.2579731

[11] M. Umair, A. Sharafat, D.-E. Lee, J. Seo, Impact of virtual reality-based design review system on user's performance and cognitive behavior for building design review tasks, Applied Sciences 12(14) (2022) 7249. https://doi.org/10.3390/app12147249

[12] C. Keles, F. Cruz Rios, S. Hoque, Digital technologies and circular economy in the construction sector: A review of lifecycle applications, integrations, potential, and limitations, Buildings 15(4) (2025) 553. https://doi.org/10.3390/buildings15040553

[13] A.R. Hevner, S.T. March, J. Park, S. Ram, Design science in information systems research, MIS Quarterly 28(1) (2004) 75-105. https://doi.org/10.2307/25148625

[14] K. Peffers, T. Tuunanen, M.A. Rothenberger, S. Chatterjee, A design science research methodology for information systems research, Journal of Management Information Systems 24(3) (2007) 45-77. https://doi.org/10.2753/MIS0742-1222240302

[15] M. van der Zwaag, T. Wang, H. Bakker, S. van Nederveen, A.C.B. Schuurman, D. Bosma, Evaluating building circularity in the early design phase, Automation in Construction 152 (2023) 104941. https://doi.org/10.1016/j.autcon.2023.104941

[16] B. Sanchez, M. Honic, F. Leite, P. Herthogs, R. Stouffs, Augmenting materials passports to support disassembly planning based on building information modelling standards, Journal of Building Engineering 90 (2024) 109083. https://doi.org/10.1016/j.jobe.2024.109083

[17] J. Brooke, SUS: A quick and dirty usability scale, in: P.W. Jordan, B. Thomas, I.L. McClelland, B.A. Weerdmeester (Eds.), Usability evaluation in industry, CRC Press, 1996, pp. 189-194.

[18] A. Bangor, P. Kortum, J. Miller, An empirical evaluation of the System Usability Scale, International Journal of Human-Computer Interaction 24(6) (2008) 574-594. https://doi.org/10.1080/10447310802205776

[19] V. Braun, V. Clarke, Using thematic analysis in psychology, Qualitative Research in Psychology 3(2) (2006) 77-101. https://doi.org/10.1191/1478088706qp063oa

[20] S. Zhong, B.A. Aseniero, A.I. Groom, A. Harsuvanakit, B.J. Lee, D. Zhao, D. Benjamin, Towards interactive AI-assisted material selection for sustainable building design, in: Proceedings of the Designing Interactive Systems Conference Companion, ACM, 2025, pp. 567-573. https://doi.org/10.1145/3715668.3736354