

BREAKPOINTS IN DATA CONTINUITY ACROSS CONSTRUCTION REUSE PROJECTS

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Abstract

This study investigates where and why material identification and digital representation fail to persist across reuse life cycles. Digital material tracking in circular construction is commonly organized through separate data pipelines for logistics and design, resulting in discontinuities as building elements move between projects. A unified analytical framework is proposed and used to define six recurring classes of breakpoints in data continuity. These breakpoints are empirically identified and analyzed across eight construction reuse case studies. The findings establish a systematic breakpoint typology and provide recommendations for continuity-oriented data infrastructures that support traceable material reuse in construction.

Introduction

Material reuse is increasingly promoted as a key strategy for advancing circular construction (De Wolf et al., 2024), yet its practical implementation remains limited. While reclaimed materials are often physically available, their integration into new projects is constrained by insufficient or unreliable data (Wijewickrama et al., 2021). In many reuse scenarios, design decisions are hindered not by material scarcity but by uncertainty regarding material identity, condition, and provenance.

Across multiple reuse projects, data continuity was repeatedly observed to break as building elements move through typical reuse stages, including deconstruction, transport, planning and material storage, and construction. These process stages are illustrated in Figure 1 through the example of the Huber Pavilions, former student workshop pavilions at ETH Zurich, which were disassembled in 2022 and served as a source project for several recipient projects on and off the university campus (Knecht, 2022; De Wolf, 2025).

Each construction project establishes its own physical and digital infrastructures, including modeling environments, documentation practices, physical identification and labeling methods on building elements (Byers et al., 2024c). These infrastructures are typically optimized for a single project and its immediate life cycle (Whyte and Hartmann, 2017; Papadonikolaki et al., 2020). When elements are transferred between projects, their associated physical and digital systems are rarely maintained or preserved. Each

of these infrastructural components, shown in Figure 2, namely the physical storage, physical element, physical data carrier, user interface, ID, digital model, and digital storage, exist at each process step depicted in Figure 1 but may change or be lost between these steps and along the reuse process.

Based on these recurring observations, this study argues that material data discontinuities in reuse projects emerge in part because information is handled through two established yet poorly connected data pipelines: supply chain logistics and design. Logistics-oriented approaches in practice commonly focus on tracking, aggregation, and inventory management and rely on standardized identification and data exchange systems, such as GS1, which define globally unique identifiers, hierarchical packaging structures, and event-based tracking across supply chains (GS1, 2025). In research, emerging track-and-trace frameworks extend these logistical principles to construction materials, and even reuse (Byers et al., 2024a). Design-oriented workflows generally rely on digital representations as the primary means of organizing and managing project information. In contemporary construction practice, this role is most commonly fulfilled by Building Information Modeling (BIM) environments, which use internally defined element identifiers, object hierarchies, and project-specific data structures to support design, coordination, and fabrication (ISO, 2018).

As illustrated in Figure 2, both logistics- and design-oriented pipelines address identification and representation, but operate according to different data structures: logistics emphasize persistent identifiers across inventories and transactions, while design environments prioritize context-dependent model elements and project-bound semantics. When these two structures are not aligned, material identities are frequently reduced, duplicated, or detached from physical elements altogether.

Despite growing interest in digital integration and reuse, there remains limited empirical documentation of how and where these logistic and design data pipelines break down in practice as materials move between projects. Therefore, this study investigates where and why material data continuity breaks down between logistics and design in reuse-oriented construction life cycles.

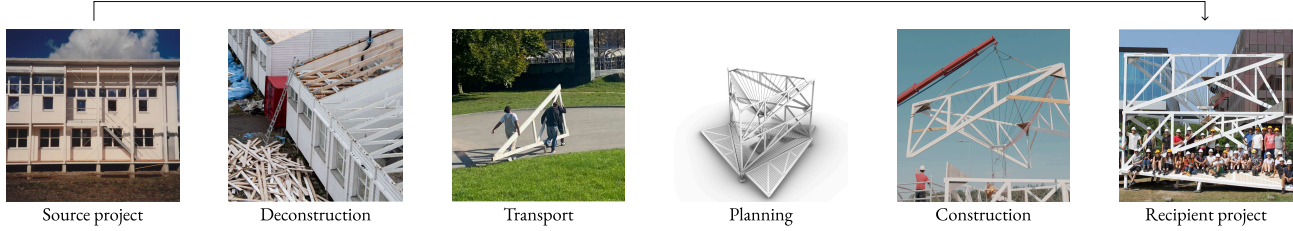


Figure 1: Process stages of construction reuse, illustrated through the Huber Pavilions' deconstruction and material reuse. Photo and model credit is provided in the Acknowledgments section.

Research design

Through direct involvement in multiple reuse projects, recurring overlap and misalignment between logistic and design-related data flows were observed, particularly for identification and digital representations of elements. Based on these observations, a combined analytical framework was formulated that integrates logistics and design perspectives across digital infrastructures corresponding to physical components, namely data carriers, user interfaces, IDs, digital models, and digital storage (Figure 2). Upon establishing this framework, potential breakpoints in persistence of data across reuse cycles were identified. In line with the framework, a set of past reuse projects were analyzed to determine where and why these breakpoints occur. The analysis focused on how material data is structured, transferred, and transformed, with emphasis on its implications for material tracking and tracing. The analysis follows a comparative multiple-case study design (Yin, 2018) to identify recurring patterns and systemic gaps and to synthesize identified breakpoints in current digital infrastructures.

Data collection combines document analysis, including digital models, databases, and material documentation, with process reconstruction of data handovers between life cycle stages. Where available, expert insights are used to contextualize observed data practices.

The goal is to improve understanding of how existing digital systems support, constrain, or disrupt persistence of data in reuse-oriented construction processes.

Proposed framework for data continuity

The integration of infrastructures present in both logistics and design results in the combined infrastructure shown in Figure 2. Rather than treating logistics and design as separate data domains, material identity should be established, accessed, and maintained across both perspectives. The **physical element** is commonly considered only on the logistical side, being transported and stored in a **physical storage** or installed within a building, whilst in design it is abstracted as a geometric and semantic entity and exists only in the form of the digital model. The framework requires the physical element to remain linked to all digital representations, which is facilitated through a physical data carrier, the user interface, and an identifier (ID). **Physical data carriers** (e.g. direct product marking

(DPM), Quick Response (QR) codes, barcodes, and near-field communication (NFC)) provide the primary interface between the physical element and digital systems. By scanning the physical data carriers, **user interfaces** mediate access to element data in logistics. In design, the user interface functions as an access point to the digital model. While these two forms of user interfaces are often implemented separately, the framework highlights their shared function: resolving an identifier into actionable information. The **ID** acts as the key link across all layers. In logistical systems, IDs are often assigned based on type or batch, whilst in design systems, IDs are typically instance-based and embedded in digital models. The framework positions the ID as a shared anchor that must persist across systems and representations to enable continuity, rather than being redefined at each stage. **Digital models** primarily emerge from the design perspective, where elements are represented geometrically and semantically. In the combined framework, the digital model is linked via the shared IDs, which allows material data originating in logistics to be associated with specific modeled elements. The digital infrastructures require **digital storage**. While these are often separated in practice, the framework considers linked or interoperable storage structures to prevent duplication and manual synchronization. Digital storage is thus understood as a shared backend that supports both inventory tracking and design integration. In line with the functionality of the identifiers, this considers both the storage of the digital model and the IDs and how these correspond.

Identified breakpoints

By aligning the combined stack in a single framework, overlaps, gaps and misalignment become apparent. Beyond illustrating the system as a whole, six breakpoints (A–F) were identified and are shown in Figure 2.

Breakpoint A addresses the interface between the physical construction element and the physical data carrier, which is commonly attached, engraved, or imprinted. Since construction and reuse processes typically involve transformations of the element, such as cutting it to the dimensions required for a subsequent project, the connection between the data carrier and the physical element may be disrupted. This can lead to loss of access to the element's identity and the associated stored data.

Breakpoint B highlights discrepancies that arise when

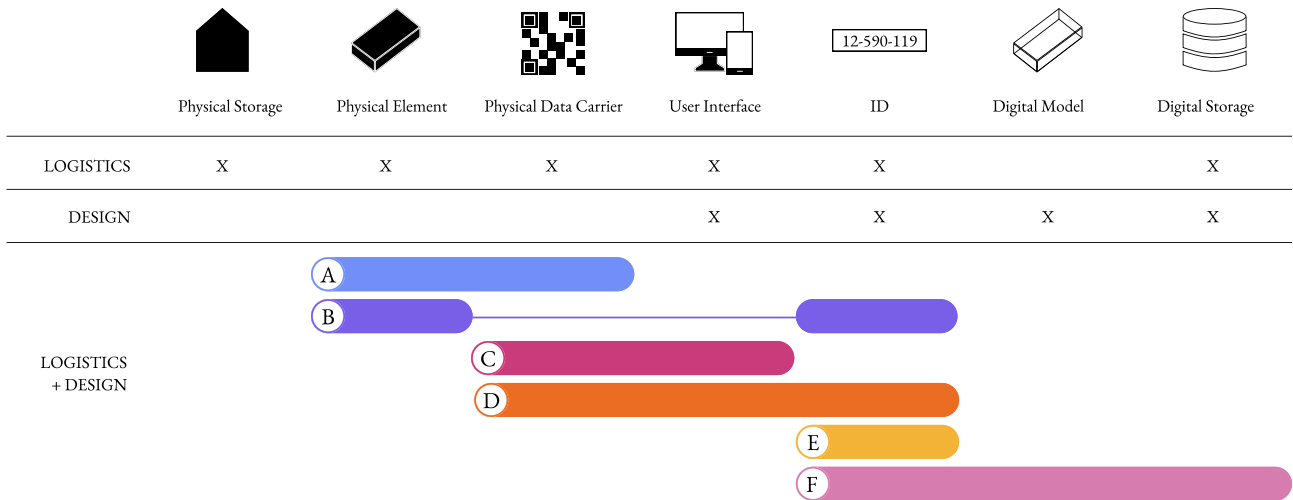


Figure 2: Infrastructure integrating logistics and design and tabular presence of digital infrastructures for identification and representation of construction elements separated between logistics and design. Breakpoints in the separated data pipeline are highlighted and in order: Physical–Digital Interface Loss (A), ID Granularity Mismatch (B), Data Carrier Degradation (C), Static Carrier Limitation (D), Cross-System ID Inconsistency (E), Unlinked Data Repositories (F)(Bottom)

groups of elements are recorded not by instance-specific IDs but by generalized identifiers, such as type-based classifications.

Breakpoint C refers to the physical data carrier and its accessibility via the user interface. In particular, the readability of the data carrier is influenced by its durability, which directly affects long-term data access.

Breakpoint D points to the link between the physical data carrier, the user interface, and the ID. It specifically addresses whether the data carrier is static or dynamic, and thus its capacity for adaptability over time.

Breakpoint E emphasizes inconsistencies in the definition and use of IDs across logistics and design systems, where the ID assigned to a physical element in logistics may not correspond to the ID used in the digital design model.

Breakpoint F addresses data storage, particularly the separation of ID storage and model storage. When these are not linked, duplicate information arises, requiring manual updates on both sides whenever modifications occur.

Breakpoints across case studies

Based on the identified breakpoints, eight case studies conducted at the Chair of Circular Engineering for Architecture at ETH Zurich between 2020 and 2025 were analyzed. Figure 3 synthesizes these case studies by illustrating the flow of digital infrastructures across reuse processes. Source projects are labeled with Roman numerals and recipient projects with Arabic numerals, with the project legend shown in the top-right corner. Instances of identified breakpoints are annotated by breakpoint class (A–F) and project number (1–8). Where multiple materials were used within a single project (e.g., case study 8), an additional index is appended. Figure 3 also includes keywords indicating the specific infrastructural components involved (e.g., QR codes or DPM for physical data carriers and Rhino for digital models). Detailed descriptions

are provided in the following text, which should be read together with the figure for full interpretation. Breakpoint instances are bolded in the text to facilitate efficient cross-referencing between the descriptive analysis and the synthesized overview in Figure 3.

Timber from an automobile warehouse in Geneva, Switzerland (I), was used for the construction of Dome 1 (1), a geodesic dome that was later disassembled and reconstructed as Dome 1.2 (2) and Dome 1.3. For the construction of Dome 1, QR codes were engraved on the timber elements (Byers et al., 2022; Byers and De Wolf, 2023), and assembly logic was recorded directly on the elements using DPM. During the reconstruction of Dome 1 as Dome 1.2, the DPM information was no longer present (**A.2**), while the engraved QR codes remained readable. During reconstruction, elements were temporarily misplaced due to out-of-sequence staging and inaccessible labels. These elements were subsequently identified using the remaining QR codes (Byers and De Wolf, 2023). In case studies 1 and 2, all elements originated from the same source and were reconstructed using identical procedures. Within this context, no functional difference was observed between instance-specific IDs and categorical IDs (**E.2**). QR code content was limited to material properties and nomenclature, while higher-level project information such as assembly and disassembly instructions was not accessible through the system (**F.2**). Following the construction of Dome 1.2, the online material passport was no longer actively maintained (**D.2**).

Dome 2 (3) was built with a similar design as Dome 1, and Dome 1.2, with timber reclaimed from the deconstruction of a music pavilion in Oetwil am See, Switzerland (II). In Dome 2, the technical database did not include mechanisms for privacy or controlled accessibility, allowing unrestricted editing and deletion of material data (**D.3**) (Byers and De Wolf, 2023).

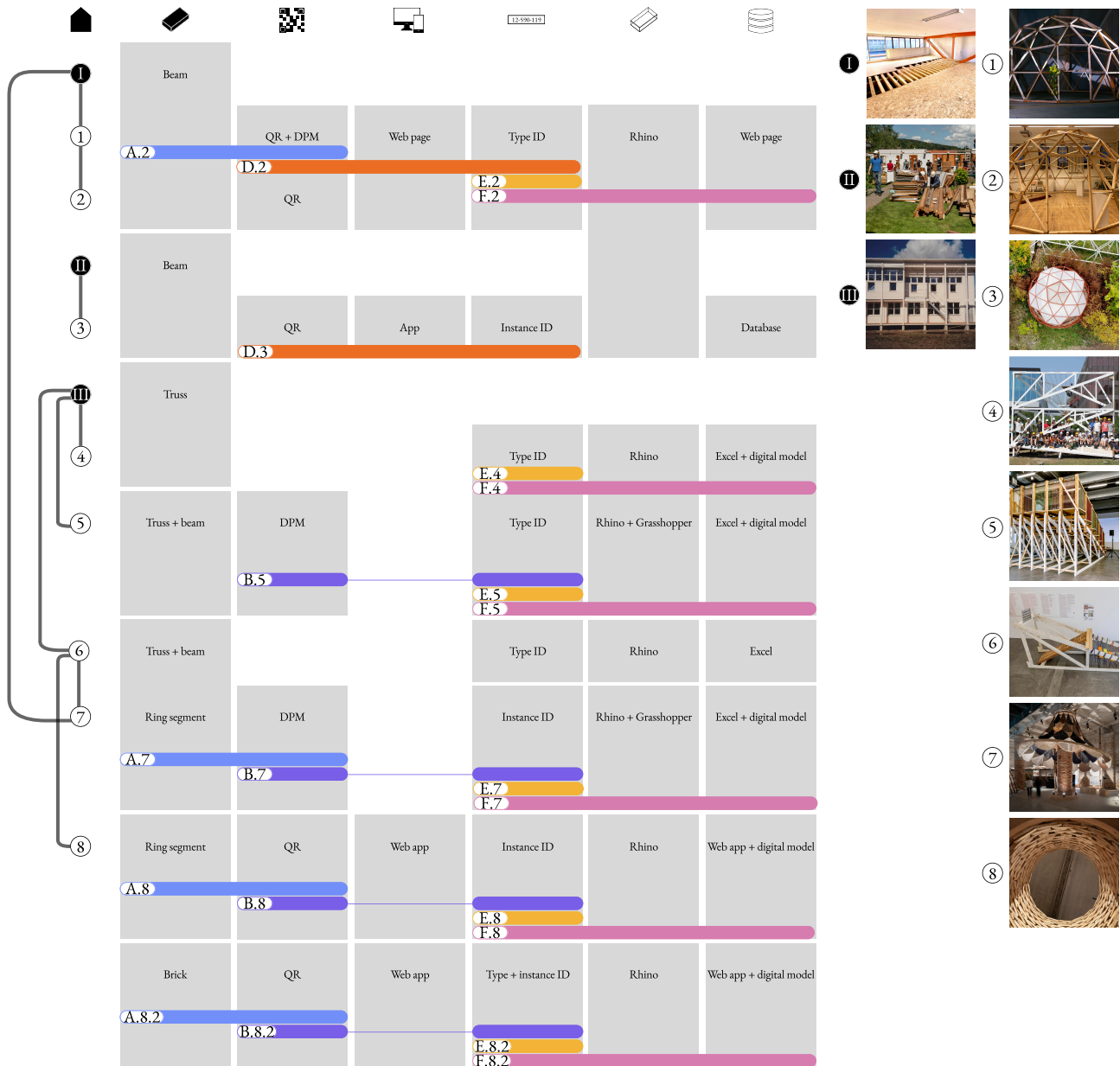


Figure 3: Flow of digital infrastructures across reuse case studies. Breakpoint instances are annotated by class (A–F) and project number (1–8), with additional indices indicating multiple material instances per project. Source projects are labeled with Roman numerals and recipient projects with Arabic numerals (see project legend on the right) in order: automobile warehouse in Geneva, Switzerland (I); music pavilion in Oetwil am See, Switzerland (II); Huber Pavilions (III); Dome 1 (1); Dome 1.2 (2); Dome 2 (3); CircŪbi (4); Mehrwerk (5); playground structures (6); VAMO (7); Insieme (8). Photo and model credit is provided in the Acknowledgments section.

Subsequently, the Huber Pavilions (III) were deconstructed, providing material for further projects, including CircŪbi (4), Mehrwerk (5), and a set of playground structures (6). In case study 4, IDs were not documented for the wooden trusses used, resulting in missing element identification for subsequent reuse (E.4). In addition, discrepancies between Excel-based documentation and the digital model resulted in unlinked ID storage locations (F.4). Case study 5 showed the same patterns of missing or inconsistent element IDs (E.5) and unlinked data storage between documentation and digital models (F.5). Beam IDs were documented only by type, quantity, and dimensions

without instance-specific identifiers (B.5). Only type-based DPMs were present on the physical elements, while beam condition varied.

Following the deconstruction of the playground structures (6), part of the reclaimed material was reused in two additional projects: VAMO (7) and Insieme (8). Insieme also included reclaimed bricks from several sources. Case study 7 sourced material from both source project I and case study 5. Wooden beams from case study 6 were transformed into cold-bent laminated ring segments. The original DPM markings were not transferred or documented for the new elements, resulting in the loss of the phys-

ical element–data carrier connection (A.7). Floorboards sourced from project I were used in a similar transformation process but did not carry documentation of their prior life cycle. Because they had no DPM, they are disregarded here. In this context, beam IDs were documented only by type, quantity, and dimensions and not by instance (B.7). Instance-specific IDs were also not assigned during recycling (E.7), and beams were treated as generically available material, while projects 7 and 8 ran in parallel using the same inventory. Beam IDs were documented in an Excel file by type but were neither referenced in the digital model nor assigned to model elements intended for the ring segments (F.7).

In case study 8, similar transformation-related losses occurred: beams were cut and cold-bent laminated without transferring or documenting DPM information for the new elements and their QR codes (A.8). Prior to this project, beam IDs had been documented only by type, quantity, and dimensions (B.8). Instance-specific IDs were again disregarded during recycling (E.8). A resulting cold-bent lintel was assigned an instance ID stored as a JSON file in a web application; this ID was not linked to the corresponding element in the digital model (F.8). Case study 8 also incorporated reclaimed bricks from multiple sources. The data and identification infrastructure for the bricks followed the same structure as that for the wooden elements, corresponding to observations (A.8.2), (B.8.2), (E.8.2), and (F.8.2). In contrast to the timber elements, some bricks were assigned instance-specific IDs due to documented damage and repair histories.

Results

Physical–digital interface loss (Breakpoint A)

Repeated loss of physical data carriers (A.2, A.7, A.8, A.8.2), namely DPM, during disassembly and element transformation indicates that data carrier strategies tied to original geometries are vulnerable in fabrication-intensive reuse workflows. To maintain the connection between physical elements and their data, and thus their identity, data carriers must persist through material transformation. Other approaches may be to use different data carriers during certain process stages to ensure the presence of data carriers (Dervishaj et al., 2023) or to enforce protocols for reattaching data carriers and recording provenance and transformation events in respective models (Guillem et al., 2025). Such protocols should include unique element identifiers, timestamps and actors involved in transformation, descriptions of geometric and material changes, and links to updated digital representations (e.g., BIM elements or graph nodes), enabling traceability across transformations within a shared data infrastructure.

ID granularity mismatch (Breakpoint B)

The reliance on type-based IDs (B.5, B.7, B.8, B.8.2) obscures instance-specific differences between elements, which become relevant when material condition or history varies within the same type. As each project is dif-

ferent and neither the future use of materials nor the respective requirements of data granularity can be predicted, one approach might be to use a multi-level ID schema. This would mean defining both a type ID and an instance ID with structured metadata, enabling differentiation by condition and role through semantic data models and ontologies (Kebede, 2024; Forth et al., 2025). The brick reuse in case study 8 demonstrates that combining type-based and instance-specific IDs can mitigate several of the challenges observed in breakpoints B, E, and F, when element-specific histories are relevant. Nevertheless, the added value of maintaining instance-specific identifiers depends on their relevance for the recipient project: while tracking large numbers of interchangeable elements of the same type (e.g., bricks) may provide limited benefit, instance-level identification becomes essential when element-specific properties or regulatory requirements, such as fire safety labels on doors, must be individually verified. Complementary work builds on these observations by proposing instance-level tracing methods that address limitations of type-based identification in reuse scenarios (Vangelova et al., 2026). In practice, such multi-level ID systems could be implemented using graph-based data structures, where type nodes define shared properties and instance nodes capture condition, provenance, and transformation history, enabling flexible queries depending on project requirements.

Data carrier degradation (Breakpoint C)

Breakpoint C was not directly represented and observed in the analyzed used cases. Beyond the analyzed cases, Byers and De Wolf (2023) highlight that insufficient durability and readability of physical data carriers can undermine long-term data accessibility. Future implementations may therefore require redundancy strategies, to ensure continued accessibility even if individual carriers degrade.

Static carrier limitation (Breakpoint D)

The absence of long-term maintenance and access-control mechanisms highlights governance-related challenges for material passport systems when reuse cycles extend beyond a single project (D.2, D.3). Versioned records and stable persistent links (e.g., URLs encoded in carriers) that update as element information evolves, supported by access control in the backend, may respond to this challenge (Hunhevicz, 2023; Byers and De Wolf, 2023; Byers et al., 2024b). Such mechanisms align with emerging data space approaches, where persistent identifiers are resolved through federated services and access rights are managed across stakeholders, ensuring that data remains accessible and trustworthy beyond individual project life cycles.

Cross-system ID inconsistency (Breakpoint E)

While instance-specific IDs did not provide measurable benefits in homogeneous reuse scenarios (case studies 1 and 2), later case studies suggest their relevance increases in multi-source and parallel reuse contexts (E.4, E.5, E.7, E.8, E.8.2). Unifying the ID logic across logistics and

design databases encourages the use of BIM as a shared digital representation to link external identifiers to model data. Digital product passport research also emphasizes interoperable identification across supply chain and design systems (Zhang and Seuring, 2024; Vangelova et al., 2025) and the need for consistent identifiers in BIM exchange. This could be supported through semantic or knowledge graph models, where persistent identifiers act as nodes linking BIM elements, logistics records, and external data sources, enabling consistent referencing across systems and lifecycle stages.

Unlinked data repositories (Breakpoint F)

The recurring separation between ID storage (e.g., Excel, Rhino model, web apps) and digital design models (e.g., BIM and Rhino) reveals a structural limitation in current infrastructures, where material allocation and tracking remain manual (F.4, F.5, F.7, F.8, F.8.2). Integration of ID storage and digital model syncing could employ cloud-based data spaces that reduce redundancy and support linked data for the design phase (Bucher, 2019; van Zandwijk et al., 2025a). Beyond technical fragmentation, the separation of ID storage and model storage also exposes limitations in data longevity and governance, as material information must persist beyond individual software tools and project-specific repositories, which may motivate future exploration of distributed and decentralized data infrastructures (Bucher et al., 2025). Building on distributed data storage, data spaces could automate currently manual synchronization processes by enabling real-time data exchange between stakeholders, reducing coordination effort and improving data consistency across tools (van Zandwijk et al., 2025b; Hagedorn et al., 2025).

Discussion

This study proposes that integrating logistical and design data pipelines has the potential to improve data continuity across stakeholders in reuse-oriented construction. The contribution is threefold. First, a framework is defined that integrates logistics and design perspectives within a shared data infrastructure. Second, breakpoints within this framework, namely where data continuity is disrupted, are identified and defined. Third, instances of these breakpoints are examined and analyzed across multiple case studies. Based on these findings, recommendations for addressing material data-related challenges in reuse projects are derived.

The results show that material identities are frequently detached from physical elements during transformation, reduced to type-based classifications, or stored in isolated systems that are not linked to design models. As a result, logistical inventories and design representations diverge, forcing manual coordination and limiting digitally integrated workflows. Data resolution typically drops after initial construction or first reuse cycles, when material passports and identifiers are no longer maintained or integrated into subsequent planning phases, which aligns with

findings by Whyte and Hartmann (2017) and Papadonikolaki et al. (2020). This also indicates that one primary barrier to linking logistics and design lies in the absence of consistent cross-system IDs. Without robust interfaces between physical elements and digital identities across life cycle phases, material data cannot reliably support reuse-oriented design decisions. The results of this study help address these structural discontinuities by making data breakpoints between logistics and design explicit, thereby providing a basis for developing continuity-oriented infrastructures that enable traceable and effective material reuse in circular construction.

Research on digital product passports and material passports in both product and construction sustainability states persistent, unique identifiers as a prerequisite for lifecycle traceability across design, use, deconstruction, and reuse (Byers et al., 2024c, 2025). To extend traceability beyond static documentation, semantic and ontology-based data structures are increasingly proposed to represent enriched metadata, provenance, and relationships resulting from material transformation (Vangelova et al., 2026). At the same time, interoperability research in BIM emphasizes aligning identifier-based data structures with cross-system standards to enable consistent integration across logistics databases, digital design models, and fabrication workflows (Forth et al., 2025). Despite these advances, material identity is still frequently detached from physical elements, reassigned new identifiers, or reduced to coarse classifications, disregarding materiality and product decomposition completely. This raises the question of whether increased data granularity and detailed representation in design and construction actually improve data continuity into subsequent reuse phases. In this context, emerging construction data space initiatives and decentralized data infrastructures provide a promising direction, addressing persistent identification, provenance tracking, and cross-organizational data exchange at scale, complementing the breakpoints presented in this study.

Limitations and outlook

This study is based on a limited number of case studies, most of which were analyzed retrospectively and conducted at the same institution, the Chair of Circular Engineering for Architecture at ETH Zurich. All case studies are short-term, student-led, pavilion-scale projects, intentionally designed as exploratory testbeds to assess data carrier feasibility, with limited incentives for maintaining track-and-trace beyond the course duration. While this allows for in-depth analysis of reuse processes, it limits the generalizability of the findings. In addition, data collection relied partly on informal expert insights in cases where partial data was unavailable. Although these insights provide critical contextual understanding, they introduce a degree of subjectivity that cannot be fully eliminated. The study does not propose or validate a specific technical implementation, data standard, or software system. Instead, it adopts an analytical and diagnostic perspective to

identify recurring infrastructural challenges across reuse scenarios. As such, the findings do not constitute a prescriptive solution but rather highlight structural conditions that future systems must address. Validation of the identified breakpoints will require applied system development and longitudinal testing in further reuse projects. To support analytical rigor despite these limitations, all case studies were examined using the same framework and evaluated against the same set of breakpoints (A–F). Multiple case studies allowed isolated incidents to be distinguished from recurring patterns, strengthening internal validity. While the results remain context-dependent, the systematic application of the framework and transparent mapping of observations to breakpoints provides a robust basis for further empirical and technical investigation. Future research should focus on translating the identified breakpoints into implementable system architectures, for example by combining persistent identifier systems, semantic graph models, and construction data spaces to enable FAIR (Findable, Accessible, Interoperable, Reusable) (Wilkinson et al., 2016) material data across reuse cycles. In addition, questions of long-term governance and incentive alignment remain critical: responsibilities for maintaining data quality, storage, and access must be shared across stakeholders, potentially supported by decentralized governance infrastructures (Hunhevicz et al., 2024) that reduce individual burden while preserving collective value.

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Credits in Figure 1: (Source project) Photo by gta Archiv / ETH Zurich (Estate of Benedikt Huber); (Deconstruction) Photo by Elias Knecht, Master student, ETH Zurich; (Transport) Photo by Elias Knecht, Master student, ETH Zurich; (Planning) 3D Model by Elias Knecht, CEA, ETH Zurich; (Construction) Photo by Ivy Filmstudio, CEA, ETH Zurich; (Recipient project) Photo by Elias Knecht, CEA, ETH Zurich.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 5.2 in order to increase clarity. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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