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Research article

QR Code-Based Material Passports for Component Reuse Across Life Cycle Stages in Small-Scale Construction

Brandon S. Byers[1], Catherine De Wolf[1]

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Abstract

The rise of attention to the circular economy in the built environment faces a pervasive problem that buildings are designed to last longer than the careers of those who built them. Predicting how to best preserve and convey information on building construction and materials from the beginning to the end of life is difficult. This paper explores the impact of track and trace technology, specifically quick-response (QR) codes, on reusing elements at the end of a building's life. In two case studies, we tested the effectiveness of using a material passport (MP) in small-scale construction, providing insights into the digital and physical processes. Ultimately, QR codes are shown to be good stores of static information but are not optimized for dynamic process information during construction life cycles. Despite the challenges of ensuring sustainable, circular construction, the results of this study should motivate those in the construction industry to implement and improve these processes in anticipation of future policy, environmental, and economic demands.

Keywords: Circular Construction, Circular Economy, Material Passport, Product Passport, Reuse, Construction 4.0

1. INTRODUCTION

The rate of global resource consumption for the Architecture, Engineering, and Construction industry (AEC) is increasing as development grows at an unprecedented rate (Global Alliance for Buildings and Construction et al., 2019). The extraction and production of construction materials have significant environmental impacts, so it can be expected that as development continues, so will natural resource depletion and greenhouse gas emissions (WorldGBC & Ramboll, 2019). A circular economy broadly aims, among other things, to reuse materials as much as possible to reduce waste, eliminate the emissions from reprocessing, and conserve materials through their extended use (Kirchherr et al., 2017; Stahel, 2016). Seminal work defines three mechanisms to distinguish circular from linear economy models: slowing, closing, and narrowing (Bocken et al., 2016): slowing resource flows extends the life of products, closing connects the loop between post-use and production, and narrowing focuses on using fewer resources per product.

The built environment faces many challenges in adopting and implementing circular economy principles. Specific inhibitors such as the isolation of information, lack of digitized data, poor collaboration, negative public perception, lack of knowledge retention, and market unavailability all make the conversion of existing linear economy processes difficult (Bucher & Hall, 2022; Torgautov et al., 2021; Wijewickrama et al., 2021; Williams, 2022). To begin addressing some of the identified challenges, research is emerging that focuses on how digital technologies may enable circular practices (Çetin et al., 2021).

[1] ETH Zurich, Institute of Construction and Infrastructure Management, Chair of Circular Engineering for Architecture, Zurich, Switzerland, corresponding author: byers@ibi.baug.ethz.ch

This paper explores technologies (including material passports and the digital platforms that host and create them) that have been found to be critical in this transition (Honic et al., 2019; Kovacic et al., 2019; Wijewickrama et al., 2021). As defined by the Buildings as Material Banks initiative, material passports (MPs) are “(digital) sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse” (EPEA Nederland BV & SundaHus i Linkoping AB, 2017). Our research aims to explore both the digital and physical (phygital) applications of quick-response (QR) code-based MPs to track building elements through their life cycle. Evidence is lacking in both practice and academic literature about how to implement MPs and component tracking across a building’s full life cycle. The 60-year average use phase of a building limits opportunities for experimental studies on how MPs impact a building through a full lifecycle (Dwaikat & Ali, 2018).

This paper first provides a background of the research and practice of using QR codes for construction and supply chain tracking. After illustrating gaps in knowledge and practice, we define the problem statement of how tracking technology affects phygital processes for reuse before providing a further description of the research methodology, both physical and digital. Then we discuss the results for the construction processes, and subsequently for the digital processes. Lastly, the paper emphasizes the limitations but integrates the findings with current literature and discusses implications to practice and society at large. The results and observations from this study can inform practitioners in developing best practices and policymakers on the challenges and limitations of tracking building materials. This paper contributes to a better understanding of the practical implications of implementing QR code-based MPs in construction processes, facilitating more informed decisions in the industry; a demonstration on how digitalization can improve information accessibility and contribute towards circular construction and Industry 4.0; and a discussion on challenges and potential solutions in relation to component tracking and data storage for the physical MPs.

2. BACKGROUND

2.1 State of Research

A global survey of companies in AEC revealed that a rapidly growing niche of small businesses focuses on products related to new technologies, such as Internet of Things (IoT) and material platforms (Guerra et al., 2021). Although much of the research on integrating IoT or track and trace (T&T) with circular construction is typically limited to frameworks (Copeland & Bilec, 2020), one of the most complete and relevant research examples of T&T for building components builds a system based on radio-frequency identification (RFID), cloud technologies, and building information modeling (BIM) (Swift et al., 2017). The system allows for bi-directional and “on element” data transfer for a dynamic data repository. Yet the amount of data stored locally, at the edge of the network of building systems, is limited, as is installation and battery life. RFID is currently explored most extensively in the context of the construction management process for tracking workers or elements on-site (Montaser & Moselhi, 2014; Valero et al., 2015).

QR codes are one example of T&T technology found to be cheap and easily scalable, thus justifying their focus for this study (Byers et al., 2022). The interest in the use of QR codes for physical asset tracking continues to expand in parallel to RFID applications (Byers et al., 2022; Gligoric et al., 2019; Ventura et al., 2016). A similar, yet under-researched, and perhaps more promising technology for life cycle management and smart construction is near-field communication (NFC) technology (Byers et al., 2022; Jansen et al., 2022; Merezeanu & Florea (Ionescu), 2017). Integrations with web platforms and blockchain solutions are emerging (van Groesen & Pauwels, 2022), although the academic literature is often limited to application and installation (Byers et al., 2022; Ventura et al., 2016). Additional research emphasizes the emerging role of an information broker within the circular supply chain, who helps manage information sharing across the construction supply chain, to bridge element information and digital platforms (Wijewickrama et al., 2021).

Challenges in the context of MPs and component tracking include data storage, modeling, and access. Some work has begun to explore the challenges around access to data with common data environments (Bucher & Hall, 2020), the connection between cloud and BIM storage solutions (Ness et al., 2020;

Swift et al., 2017), and, similarly, the connection between BIM, MPs, and traditional spreadsheets (Honic et al., 2021). Individual product MPs aggregated into full building MPs have been demonstrated (Munaro et al., 2019) for a wood frame house in Brazil. Often, the research into data storage for AEC is limited to relational database structures (Kovacic et al., 2019; Tang et al., 2019) due to ease of use and easier integration with BIM tools.

2.2 State of Practice

Within Europe the construction industry is responsible for one half of all extracted materials, one half of total energy consumption, one third of total water consumption, and one third of the waste generated (Commission & Environment, 2022). The typical process in Switzerland of reusing building elements in AEC involves third-party material hunters or specialty architecture firms to find or possess knowledge on buildings about to be demolished (De Wolf et al., 2020; Gordon et al., 2023). Limited financial incentives for testing materials often lead to reused materials no longer being used structurally; they can only be repurposed for non-life-threatening applications (Iacovidou & Purnell, 2016). The United States faces an unfortunate reality that part of the building stock is being demolished before design life span is reached (Guerra et al., 2021). Implementing circular strategies in the US is often inhibited by budget and upfront costs, schedule and project timeline, lack of awareness and change resistance, current construction business model, and lack of regulation and guidelines (Guerra et al., 2021).

In general, government agencies have an important role in catalyzing circular economy practices due to the high upfront costs and poor initial profit incentives (Govindan & Hasanagic, 2018). Additionally, general organizational and managerial knowledge about circular economy processes is needed, which may also accelerate technological adoption to aid the transition (Govindan & Hasanagic, 2018). The European Commission has released procedures and guidelines for a European Digital Product Passport to streamline information tracked and transferred for products (Adisorn et al., 2021). While this currently does not apply to building products, some discussion is underway on if and how future product passport legislation may eventually become required in the AEC industry.

Although other industries are witnessing an increase in the adoption of T&T technologies, the state of practice of tracking building components is still in its infancy. Some examples of industrialized and prefabricated construction companies use MPs and digital platforms for their manufacturing and Just-in-Time delivery models (Barreto et al., 2017). Some proof-of-concept case studies have experimented with these approaches on actual construction projects (Ghosh et al., 2020; Ness et al., 2020), but these studies are limited in scope and timeframe.

Industries other than AEC use T&T methods and database technologies, for example the automobile industry (and similar manufacturing industries), where each part is identified and data is stored in a central repository (Barreto et al., 2017; Pollok et al., 2004) – especially important if cars need to be recalled for part defects. Global Standards 1 (GS1), a non-profit organization that works to homogenize data templates for goods distributed across the world (Gligoric et al., 2019), has applied tracking technology to consumer goods like clothing, groceries, and other off-the-shelf items. They have begun to collaborate with buildingSmart International, a nonprofit organization committed to developing open digital data-sharing standards and applying similar tracking standards to building products (buildingSMART International & GS1, 2021).

2.3 Problem Statement and Contribution

Though research has explored the impact and effects of using RFID for building component tracking, there has been limited exploration of implementing QR codes for tracking purposes (Lee et al., 2018) and the effects of T&T technologies over multiple life cycles of building components. Considering that the practice commonly uses spreadsheets, which are highly prone to error (Panko, 2008), little work explores tradeoffs when scaling from spreadsheets to fully developed databases. Although QR codes have been applied to aid in asset management and circular construction (Gligoric et al., 2019; van Groesen & Pauwels, 2022; Ventura et al., 2016), documented evidence of testing this method remains sparse (Lee et al., 2018). This scarcity is partly because buildings and infrastructure possess significantly longer life cycles than other QR code-tracked assets, like those in manufacturing or consumables, making it challenging to observe the effects of component tracking throughout a life cycle.

By accelerating the life cycle of the structure and engaging in the experimentation, we addressed the research question: How does the introduction of tracking technology affect the physical and digital processes for component reuse in circular construction? This is explored through the deconstruction and reconstruction of a small-scale structure with QR codes on the elements. In addition to being (to our knowledge) the first documented instance of such an experiment, this work illustrates the comparative advantages of increasing the level of technical approaches to store data of the MP as tested by the reconstruction of the same structure. Thus, the main contributions of this paper are:

- Observations from QR codes on physical construction through a complete life cycle
- Testing of different digital T&T storage systems for multiple life cycles
- Application and integration of the physical and digital MP

3. RESEARCH METHODOLOGY

This study employed an explanatory double case study to investigate the real-life phenomena of implementing material passports during construction via a replicable structure. Both case studies went through the construction phases using different material passport strategies for contrasting findings and direct comparison, and one of the case studies went through additional deconstruction and reconstruction processes. As advised in Yin's work (Yin, 2013) the relevance, purpose, and replicability of the case studies allows for direct comparison and knowledge generation. Multiple sources of data were used to create a comprehensive view of the application of QR codes in the construction process. This included visual documentation of the construction process, notes on the usability of the QR codes at various stages of construction, and records of the digital data attached to each QR code. Note due to the exploratory and specific nature of these projects, the method is more internally rather than externally valid, and thus the results are not fully generalizable.

3.1 Research Design & Materials

The primary methodological approach used in this work is process-driven (Aydemir & Jacoby, 2022), which emphasizes learning as a result through implementing and disseminating the observations of the study. Despite the increasing amount of high-level framework papers on circular economy (Kirchherr, 2022), the AEC industry is defined by its derivation to material processes. Therefore, to investigate the impact of building component tracking throughout a structure's life cycles, we actively participated in the implementation, testing, and observation of the case study applications. The tested workflow for this paper focuses on two project and two processes as shown in Table 1: Digital Processes) the material tracking and data storage method through QR codes, and Physical Processes) the construction and deconstruction process utilizing QR codes for tracking and tracing the components.

Table 1. Matrix of Analyses in this Paper

	Physical Processes	**Digital Processes**
Dome1 into Dome1.2	Initial construction of Dome1, deconstruction, transport, and reconstruction into Dome1.2	Engraved QR codes linking to a static web page material passport
Dome2	Initial construction of Dome2 (same design as Dome1)	Attached QR code tag linking to a full-stack database application for material passports

On the part of the digital approach, the selection of the data tracking method is primarily discussed in the author's previous paper (Byers et al., 2022). Data storage techniques have evolved in terms of complexity and functionality, transitioning from basic spreadsheets to a comprehensive full-stack program. Finally, the study compares data modeling and storage approaches, contrasting the native spreadsheet format with an open standard file and data interchange format. The examined structure is a wooden geodesic dome built from reused materials, with two iterations depicted in Figure 1.

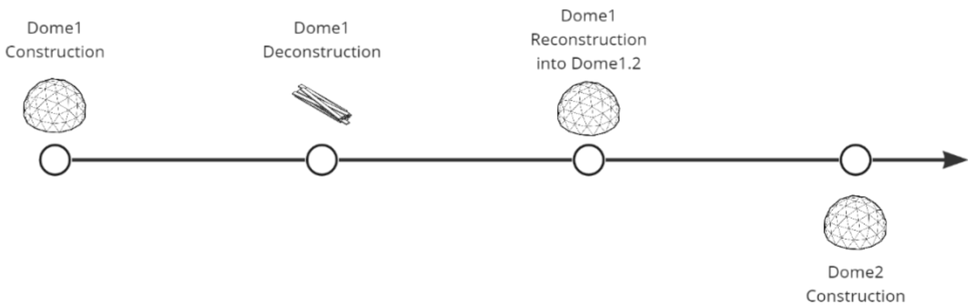

Figure 1. Timeline of Dome Construction Processes

3.2 Construction Activities for Case Study Application

The first-person construction experience, supplemented by additional qualitative observations from the core construction team, informed the results and discussion of this paper. The construction of Dome1 was undertaken in January 2022 with reused and recovered materials (Byers et al., 2022; Gordon et al., 2023). The deconstruction at the end of the usable life of Dome1 happened in February 2022 and the materials were transported to a new site where the same structure using the same materials was rebuilt into Dome1.2. Dome1.2 has since been deconstructed and reconstructed in a different location, but those additional life cycle(s) exceed the scope of this study. Dome2 was constructed using the same design as Dome1, but with a different set of salvaged and reused materials and a different approach to QR code engraving (i.e., using a separate tag instead of engraving directly into the material). Dome2 focuses on using different data storage and modeling from Dome1, and at the point of publication remains in the same location on its first life cycle. All domes were built with reused materials. Figure 2 below provides illustration to the construction processes of the domes.

Figure 2. a) Construction of Dome1, and b) Construction of Dome2

4. FINDINGS

This section of the paper first investigates the physical construction processes and how the use of QR code MPs affected each life cycle stage. Afterwards, the implementation of the different digital processes is discussed.

4.1 Physical Process: Life Cycle Construction Stages

Throughout the construction life cycle, the application of QR codes primarily serves as an investment for future users. There is added time and costs for the application process, and it needs to be decided on which component, where on the component, and how the tracking mechanism will be applied. One observed utility of the QR codes during the construction process was that some of the components were missing in the staging area and found to have been prematurely installed in the dome. QR codes allowed for verification and replacement in situ. Note that the element ID was stored within the QR code MP, and a shorthand version was manually written on the end of the beam typically hidden behind the connectors for easy visibility.

For Dome1, the QR code was laser engraved into the raw wood component directly as described in (Byers et al., 2022). The QR code is read through the contrast between the engraved and not engraved pixels. Therefore, the disadvantages in this application are the potential for wearing down the code or covering the code with layers of paint. Albeit engraving into the raw wood provided a better aesthetic and ensured a permanent association between the code and component.

For Dome2, the QR code was engraved into a separate plastic label, which was then affixed to the wood, previously treated with natural paint. The disadvantage of this approach was the added material cost and time for the tags and screws, the added potential of the tag being torn off (unintentionally or maliciously), and the mismatched aesthetic of the tag and painted wood. The benefits of this approach allowed batch engraving of the QR code tags, which reduced time, as well as allowing the opportunity of changing the applied tag in the future, which increases adaptability.

During the use stage of the domes, the QR codes provide a specific utility: information to the user. Occupants of the dome would scan the codes out of curiosity about what was digitally connected to each physical component. In a full implementation for circular construction, this life cycle stage and use case could provide purchasing opportunities for the user, or the option to download information on the existing component that could be used to design future structures from reused components.

During the deconstruction stage of Dome1 it was to be transported and reconstructed in another location. Through the disassembly, the elements were visually inspected for defects, but none were found and therefore the same set of elements could be reused for the next iteration. The date of deconstruction is used for the end of the existing life cycle of the elements, but the database was not updated.

At any transportation stage for the domes, QR codes were not utilized. When implemented throughout the entire supply chain, the QR codes could be used for the driver and receiver to scan and verify that each component matches their invoices and manifests. Additional T&T utility could come from RFID or GPS-enabled trackers for live location tracking of the asset. Given the static nature of information storage of QR codes, this alludes to a notable nuance of this method: information is more readily input during prolonged use cases rather than uncertain transport instances.

During the reconstruction stage, upon arriving at the site the materials had been staged out of order from the assembly process. Thus, the first step for reconstruction was sorting and staging the elements according to their type. Primarily, the written shorthand element name was used and the QR code supplemented information as necessary. After partial reconstruction of Dome1 into Dome1.2, again, a few pieces were missing according to the construction sequence. As the written labels were no longer visible in the constructed pieces, the QR codes were used to verify the ID of the installed elements and it was discovered that a couple of elements were installed in the incorrect location and swapped out with the appropriate piece.

4.2 Digital Process: Data Storage and Modeling for Material Passports

QR codes function by transforming a string of data into a 2-dimensional grid, which is readable by cameras. Though it would be possible to embed some information on the building components natively into a QR code, the longer the string, the denser and more complex the QR code matrix becomes. In this study the QR code is used to reference a Unique Resource Identifier (URI) to retrieve only what is necessary by the client.

Tim Berners-Lee, the inventor of the web, suggested a five-star rating system for linked open data, the concept behind making data both human- and machine-readable while linking it to other relevant information (Tim Berners-Lee, 2009). It is becoming increasingly important for MPs to utilize linked-data technologies to semantically enrich the application of building component information within its context (Soman et al., 2022). The linked open data deployment scheme is rated as follows:

- 1-star: data is available on the Web in any format
- 2-stars: data is available as structured data (e.g., Excel instead of image scan of a table)
- 3-stars: data is available in a non-proprietary open format (e.g., CSV instead of Excel)
- 4-stars: URIs and open standards from W3C are used to denote things (e.g., RDF)
- 5-stars: data is linked to provide context

4.2.1 Google Sheets and Spreadsheets

In the initial development of this case study, the proposed minimal viable solution was linking QR codes to a Google Sheet to host material data. Google Sheets acts as a web-based spreadsheet, similar to a relational database, where it is simple to assign permissions for document management and for users to edit the data. The challenges associated with Google Sheets include storage capacity, ownership and accessibility, and scalability. If multiple components are on one sheet tab, then a QR code cannot direct to a discrete item because of the shared URL. It was found that mobile viewers of Sheets on some mobile operating systems always defaulted to viewing the first sheet. If each component has a unique file type, it presents issues with memory storage capacity. Hosting a new file for each component and establishing relationships between files for the same building becomes a challenge.

4.2.2 GitHub Pages and HTML

The solution implemented for storing the product MP for Dome1 was developed as a webpage using HTML and hosted on GitHub Pages. GitHub Pages allows for great flexibility of design through a web hosting approach with significantly fewer restrictions on storage and scaling. The problems with GitHub Pages are its accessibility and edit-ability, which are comparatively less than Google Sheets and require some coding knowledge. In theory other contributors could push code updates (i.e., element updates on further life cycles) for the website owner to accept and publish. However, without any immediate incentive to do so, the material database was not updated beyond this reconstruction stage. The lack of updates could be attributed to gap in technical knowledge to do so. There is not an existing incentive for this to take place as the reuse of this structure could be completed without supplementary information from the material passport due to its simplicity.

Though the solution developed emulates a relational database on each building component's webpage, it provides the opportunity to store additional files if hosted in the site, such as .obj or .pdf files of product drawings on the same page if hosted in the repository. Within each product's page is a button that downloads the HTML table in a CSV file format as seen in the proof of concept developed and shown in Figure 3, thus allowing for the extraction of that product data in the form of a relational table. This option allows users to utilize product data in other capacities such as AutoDesk's datalink solutions. Figure 3 is a screenshot of one of the actual material passports used for Dome1 and Dome1.2 and shows information from all known lifecycles.

Component AF-03

Life Cycle	CID	Project Name	Project Location	Install Date	Removal Date	Material	Material Sub-Type	Height (mm)	Width (mm)	Length (mm)	Weight (kg)	Condition
1	:S-AA11:	Fiat Factory	Geneva, CH	unknown	15.10.2021	Wood	Pine	135	95	2550	12.62	Good
2	:S-AA11<_:S-AD54:	CEA Dome	Zurich, CH	25.01.2022	03.02.2022	Wood	Pine	66	46	1094	1.28	Good
3	:S-AA11<_:S-AD54:_:S-AF03:	CEA Dome	Zurich, CH	03.02.2022	unknown	Wood	Pine	66	46	1054	1.235	Good

Figure 3. Screen Capture of GitHub Pages Database Site for Dome1

4.2.3 NoSQL Database and Full-Stack Material Passport Platform

For Dome2, a more comprehensive database application was developed and tested using a MERN stack (an acronym of the programs MongoDB, Express, React, and Node.js) (Shiji Cheriyamulla, 2022). MongoDB is a NoSQL (Not-Only Structured Query Language) database that allows for functionality beyond relational tables (the system used by spreadsheets). The advantage of this application is to allow for data tree structures of storage that collapse into higher levels. For example, a single reused wooden element will have similar meta-properties (e.g., the wood species), but could have additional properties that vary over different life cycles (e.g., location and condition). Using a tree structure allows for greater data flexibility in storage and accessibility. The developed application met the database requirements to create, read, update, and delete (CRUD) information. This functionality was not fully accessible in the HTML technical solution.

In the database application for Dome2, using MongoDB in the background allowed students with access to bulk upload material information produced during the construction process. MongoDB uses a binary JSON (BSON) document-style data type. The application was programmed so anyone who uses the website has access to the CRUD operations, which is great for the classroom environment but will produce difficulties in full project implementation without dealing with the concerns of privacy and access rights to information. Unlike a static spreadsheet or HTML page, this could create problems for maintaining long-term data for elements that have longer life cycles, especially if companies close. An added benefit of using a full-stack approach with a machine- and human-readable document store is that it allows for data extraction and analytics. BSON and JSON files are readily usable for analytics on things such as average life cycle, common sourcing locations, typical material type, etc..

5. DISCUSSION

5.1 Discussion on the Physical Process

Overall, in the context of this research, the QR codes were found to be most useful for verifying element IDs in the construction process and for users to learn about the story of the individual elements and the structure in general. There was a lack of incentive for continuous updating of the status as the life cycle extends and materials are reused beyond the control of the researchers. The simplicity of the structure and construction process does not necessitate its updating and the informality of construction precludes the necessity for formal material documentation. Table 2 compares the advantages and disadvantages of using QR codes on construction elements per life cycle in the context of small-scale construction. These advantages and disadvantages are not exhaustive of all potential impacts of using QR codes, or other track and trace technologies. For example, the material passports could have housed information on deconstruction or transport logistics in a different application but were not determined to be useful in this context.

Table 2. Observed Effect of QR Codes during Building Life Cycle Stages

Construction Stage	QR Code Advantage	QR Code Disadvantage
Construction	Construction sequencing; final material takeoff; inventory tracking	Slow for quick reference to the element name; increased initial preparation costs
Use	User access to material information	If visible, disrupts aesthetic; if not visible, information is unavailable
Deconstruction	Nonapplicable	Should update the status for each element
Transportation	Nonapplicable	Nonapplicable
Reconstruction	Access to element name; access to construction drawings	Slow for quick reference to the element name; implies status was updated

The implementation process for engraving the QR codes lasted about six minutes on average per component and is discussed further in the author's previous work in (Byers et al., 2022). The construction activities for this project were not baselined to a similar project without material passports to determine any potential time savings. During the construction process reading a QR code to verify the element ID can be time-consuming and inefficient, which led to manual inscriptions of the element ID on the element itself. Alternate iterations may involve engraving the element ID directly onto the component for easier reading. The speed of conveying and accessing information on components is a pressing challenge.

The structure's elements were designed so that they all fit into five different geometric categories of dimensions. The authors discovered that in this case study (where all materials had the same origin and were reconstructed in the same manner), there is no advantage to endowing each element with a specific element ID instead of a general categorical ID. This would have allowed for easy replacement in the construction process instead of looking for the unique element. Although, in instances where materials need to be tested for reuse and were subject to different environmental or structural conditions, it may still be critical to maintaining unique element identification.

Another observation during the reconstruction process was that in addition to displaying material properties and nomenclature at each QR code link, it would have been advantageous to also store general project information in a higher-level database of the project (e.g., assembly and disassembly instructions). For example, at the reconstruction site, the original drawings and construction procedure were temporarily misplaced and could have easily been replaced if stored and accessed through each element's QR code. In addition, the MP could have stored a 3D model of the element or structure for use by future designers. Like the transportation stage, the construction and reconstruction phases are transient and dynamic states, thus not conducive to active and manual information or state recording. For full implementation, one possible use would be the scanning of the material as soon as it is installed for progress tracking, and for validating procurement processes against design and construction processes.

MPs may offer value in complex assemblies by providing detailed information about the various layers and materials involved. This includes data on material properties, composition, performance, connections, and environmental impact. In more complex projects, where multiple layers and materials are integrated, the ability of MPs to capture and communicate this detailed information becomes even more critical. It enables stakeholders to make informed decisions regarding disassembly, material separation, and reuse opportunities. Though details on where and how to attach the material passport connection to the physical component remain unresolved.

MPs can play a significant role in streamlining labor-intensive urban mining processes by providing accessible and comprehensive data about components even before disassembly. By incorporating MPs into urban mining practices, stakeholders can assess the value and suitability of components for reuse or recycling more efficiently. This can reduce the need for manual sorting and assessment, saving time and labor. Access to data on components' material composition, condition, and performance through MPs enables targeted and informed decision-making during the disassembly and recovery processes, enhancing resource efficiency.

Ultimately, these case studies contributed to a better understanding of the practical implications of implementing QR code-based MPs in construction processes, facilitating more informed decisions in the industry. Implementing the physical construction processes revealed challenges and potential solutions in relation to component tracking and data storage for the physical aspect of MPs. QR codes allow for easy implementation and utilization on discrete construction elements.

5.2 Discussion on the Digital Process

To facilitate a component's reuse, it should be determined what properties are needed and how to communicate them over a materials passport platform (Çetin et al., 2021). Multiple stakeholders need to know different properties at different stages in the life cycle, which is coupled with relative inaccessibility to acquire product data. In addition, it is not known exactly what information will be needed for building components in the future to facilitate its reuse. As found in this case study, when practitioners develop MP solutions, incentive systems for continuous or repeated data input must be established to inhibit data paucity. These findings inform future MP system design.

Using a storage facility as a NoSQL database or webpage has disadvantages because of the lack of homogenous data input, which might inhibit reuse or material comparison by stakeholders interested in the materials. Although, the flexibility of these formats allows for the adaptability of evolving demands and use cases of the future. Further organizing and scaling data eases access to information for future architects, contractors, owners, and planners. Table 3 explores several methods of data storage when connecting a QR code to the component MP.

Table 3. Comparative Impact of Different Data Storage Approaches for Component Information

Data Storage	**Linked Open Data Rating** (Tim Berners-Lee, 2009)	**Advantages**	**Disadvantages**
Spreadsheet	★★	Low-tech solution with short learning curve; easy data input; easy to modify	Not native data file type; user access management; storage location; not full database functionality
HTML Webpage and CSV files	★★★	Easy access to information; low coding requirements; more structured than spreadsheet	Centralized access; lack of data type flexibility; challenges with hosting; not fully database functionality
Software Application and JSON files	★★★	Multiple data types; easy data input; user access and readability; full database implementation; structured data; web friendly	Requirements for browser and database hosting; efforts for user account management; software development efforts

The digital processes of the MPs in this work demonstrate how digitalization can improve information accessibility and contribute to the transition towards circular construction and Industry 4.0. Complexity on the digital storage and linkage of MPs increases with the complexity of the project and may be achieved through integration with existing data platforms, such as BIM systems, where information on different layers and materials can be stored and accessed. Additionally, linking MPs to other material databases, sensor networks, and standardized data-sharing protocols may allow for comprehensive data retrieval, analysis, and decision-making related to multi-layered assemblies. The implementation of MPs in complex assemblies would require enhanced data management systems capable of handling diverse and interconnected information.

5.3 Limitations

On the account of the nature of the construction project, several limitations inhibit the case study exploration to be directly compared to an implementation on a full building. Dome1 existed for only about a month before deconstruction, and Dome1.2, similarly, was only used for about two months before deconstruction and transport. Lastly, Dome2's first life cycle will have reached about one year by the time of this paper's submission. Moreover, the construction style of the dome resembles a pavilion more than an inhabitable building as it is not enclosed, there is no foundation, nor are there mechanical and electrical systems. The components are not nested or embedded materials, which allows for easy access to the QR codes, a condition not often found in practice.

The online MP was no longer kept updated after the construction of Dome1.2, which highlights research opportunities on incentive structures for future stakeholder interaction with data repositories. Similarly, with the technical database approach for Dome2, the application was not yet developed for privacy and controlled accessibility. This approach allows any user to add and update material information but also implies that any future user could delete information.

In addition, the material tracked in this study was limited to wooden structural members. In a full-scale construction project, decisions will need to be made on what scale and what quantity of materials should be tracked. For example, it is not reasonable to track every dowel fastener but does make sense to track large modular items such as structural steel. Additionally, engineered and off-the-shelf elements provide discrete materials with parameters to track, while certain bulk construction materials, like aggregate or backfill, are difficult to track due to their amorphous geometry and continuous scale of measurement. This limitation is even more magnified in practice when dealing with the complexities of combining approaches for reuse, recycling, and traditional landfill. Further work should explore developing a set of heuristics on what building components should be tracked for circular construction benefits.

6. CONCLUSION

This study explored how adding a tracking technology affects the physical and digital process of component reuse in circular construction. QR codes were attached to the building elements of a wooden geodesic dome that linked to a building component MP. The impacts of the MP were explored across the element life cycles and through different digital storage techniques. Bringing information on building elements back down to the level of the element is a method to democratize information and bring knowledge back to the lowest level. Information silos are a big inhibitor in the construction industry for productivity and adapting to Industry 4.0 (Wijewickrama et al., 2021); therefore, this work can aid in addressing the issue. As society now operates in the information age, the AEC industry must maintain the pace of productivity to achieve social, environmental, and economic objectives. Relatedly, information is seen as critical for implementing a circular economy (Bucher & Hall, 2020; Lützkendorf, 2019) as access to the supply chain and opportunities for analytics open up.

Though this case study application looked at QR codes, the medium of material passports may be agnostic, and this sets a precedent for future research and practitioners to illustrate the advantages and disadvantages of tracking components through construction stages. The data from the elements could be further linked to Building Information Models and material take-offs for better construction management planning and informed design from reuse. Nevertheless, utilizing T&T devices on construction projects, particularly on elements or structures with short life cycles, can already yield benefits to future designers from reuse, asset managers, contractors, and policy makers.

Future work will look at the use of linked building data and semantic web technologies to open opportunities for exploring connection types and provide metadata for the components on their life cycles. These technologies may be used to link separate component material passports to other projects without necessarily needing to be stored in the same database or modifying the URL. Data persistence and storage should be explored so that the data can extend and be accessible beyond the component's life cycle. This problem also lends itself to future research in using computational systems like decentralized ledgers and blockchain technology as persistent storage. Lastly, work should continue to develop data templates and how they can integrate with policy as well as the demands from the market on what information should be tracked. Data modeling of components will open opportunities for big data analytics and stakeholders to make more informed decisions and begin to make predictions on efficiency and access to materials.

The work and contribution of this paper compares the phygital impacts of using QR code-based MPs in construction. Within the physical processes, the advantages and disadvantages of using QR codes at each life cycle stage were examined. For the digital processes, the advantages and disadvantages of the varying degrees of technical complexity for a data storage solution were examined. Ultimately, this paper demonstrates how digitalization can improve information accessibility and contribute to the transition towards circular construction and Industry 4.0. From the examination of both processes practitioners of circular construction can be better informed for the development and implementation of a building component tracking solution for MPs.

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AUTHOR CONTRIBUTIONS

Brandon Byers: conceptualisation, methodology, testing, analysis, writing
Catherine De Wolf: funding acquisition, conceptualization, methodology, review and editing

DECLARATIONS

Competing interests The authors declare no competing interests.

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