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USING ENGRAVED QR CODES TO CONNECT BUILDING COMPONENTS TO MATERIALS PASSPORTS FOR CIRCULAR CONSTRUCTION

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Abstract

There is an increased need for tracking building component information through its lifecycle(s) in order to reduce risk and uncertainty for reuse. Existing literature for material tracking focuses primarily on RFID for location tracking on equipment. However, Quick Response (QR) codes were used in this case study because of the low cost, speed of implementation, and accessibility. QR codes were applied to the structural wooden members through laser engraving. This proof of concept analyzes the challenges and advantages associated with using QR codes as the chosen tracking technology as well as engraving them as a permanent fixture.

Introduction

Increasing data availability and transfer is shown to assist the adoption of circular economy principles in the built environment and facilitate reuse (Hedberg and Sipka, 2021; Hossain et al., 2020). The circular economy within the built environment aims to minimize raw material input and waste within construction through more efficient resource strategies such as reuse, recycling, removal of excess, and even refusing new construction (Çetin et al., 2021; Kirchherr et al., 2017). Through decoupling economic growth from further resource consumption it is possible to reduce the carbon emissions associated with construction from new materials (Arup, 2016; Iacovidou and Purnell, 2016). There is an increased interest in adopting tracking technologies as one component of Internet of Things (IoT) into the built environment to increase data availability and transfer (Gligoric et al., 2019; Merezeanu and Florea (Ionescu), 2017; Valero et al., 2015). Ghosh, et al. explored patterns and trends with IoT in the construction industry from 417 papers and identified four thematic clusters: structural health monitoring, construction safety, optimization and simulation, and image processing (Ghosh et al., 2020). Another in-depth review of IoT devices and building information modeling found four thematic clusters: construction and operation monitoring, health and safety management, construction logistics and management, facility management (Tang et al., 2019). Both reviews in this field demonstrate a dearth of research on using IoT for building component lifecycle tracking. Component lifecycle tracking is useful for reducing embodied energy buildings through reuse.

Most data storage and transfer happens through external documentation or electronic drawing sets, but maintaining continuity with the represented physical objects introduces potential for error or loss of continuous connection (Hedberg and Sipka, 2021). In addition, many barriers still exist in adopting material tracking systems, such as technical competence of the users, data management, and perceived cost impact (Moretti et al., 2019). Previous studies have looked into the application of Radio Frequency Identification (RFID) as the primary technology used on building elements for tracking (Copeland and Bilec, 2020; Merezeanu and Florea (Ionescu), 2017; Montaser and Moselhi, 2014; Moretti et al., 2019; Swift et al., 2017; Valero et al., 2015), but this overlooks a low-cost and accessible alternative: Quick Response (QR) codes.

This research uses a case study project to test and analyze methods of applying tracking technologies to building components to digitally house material information via materials passports. As defined in a report from project Buildings as Material Banks (BAMB), material passports 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 and SundaHus i Linkoping AB, 2017). Lützkendorf states that preliminary initiatives for material passports, though needed, have been unsuccessful because the demand for information needs to be strengthened (Lützkendorf, 2019). The author ends with recommending further research on storing and updating product data over lifespans (Lützkendorf, 2019). Implementing the use of a material passport facilitates reuse and incentivizes capturing material value through extending the total lifecycle of the material (Hoosain et al., 2021). This paper starts with a comparison of different asset tracking technologies and aims to demonstrate the feasibility of using QR codes to bridge a component to its digital material passport through engraving.

State of the Art

Comparison of Asset Tracking Approaches

Different methods exist for the tracking of assets that range from traditional approaches such as using pen and paper to digital technologies such as barcodes, QR codes, and RFID. The traditional approach involves relying on pen and paper to track company assets. Lack of proper and scalable organizational ability leads to wasted time searching for records and instant information exchange is difficult using this approach. Additionally, transparency among the project participants is difficult to keep up, due to the fragmentation of information.

A spreadsheet-based asset tracking system offers some benefits over using pen and paper. Spreadsheet files are available to multiple users and there is no need for searching of the physical location of your asset records. However, due to manual data entry, spreadsheets are prone to error, and it is difficult for multiple team members to access and update the files simultaneously. Digital tracking methods speed up the data transfer process through technology and are often used in combination with mobile devices. Using a barcode to track assets, for example, avoids many of the issues in connection to human errors that come with spreadsheets and manual tracking methods.

Digital tracking technologies all serve the same purpose: storage of small amounts of data, unique identification of items, and the transfer of the information. Connecting the tracking devices to each other and to the internet facilitates data transfer as the IoT enables the monitoring, controlling, and analyzing of processes. This makes it possible to collect and share data on the construction process using small tags for example. Multiple types of sensors and tracking technologies exist, including barcodes, QR codes, active RFID, passive RFID, Bluetooth low energy (BLE) devices, and near-field communication (NFC) devices. Table 1 provides a comparison of these solutions. Checks in parenthesis indicate the tracking technology can fulfill the requirement but is not perfectly suited for it or requires additional measures.

Asset Tracking for the Built Environment via RFID

A commonly used method for material tracking are radio frequency identification (RFID) tags. RFID is a wireless non-contact system that is based on the exchange of information by means of electromagnetic signals. The collected information is then transferred to a computer system, where the data can be stored and managed by means of an application (Valero et al., 2015). The power source is an essential property of a tag as it determines the tag's potential read range, lifetime, cost, functionalities, needed orientation, and physical form. Active RFID tags have their own power source (e.g. a battery), which enables them to have a much longer operation range than passive tags. Passive tags do not have their own power source, nor can they initiate communication. They obtain their power by harvesting energy from incoming radio frequency signals. The third type of RFIDs are semi-passive, which have an internal power source but cannot initiate communication.

To develop continuous tracking, previous research has explored a bi-directional repository for building architectural elements (Swift et al., 2017). The case study involved tracking a doorframe at the end of life in one building to be further tracked and used in a new build (Swift et al., 2017). A further paper on this case study developed the concept of connecting the cloud to the RFID tag and BIM (Ness et al., 2020). RFID tags were not used in this case study for multiple reasons. In the practice of circularity, RFID tags can be reused if prior data is properly deleted, and new data is written on to them.

Table 1. Requirements for tracking systems of building components

Requirements	Barcode	QR-Code	RFID-Active	RFID-Passive	BLE	NFC
Reduction of human error	✓	✓	✓	✓	✓	✓
Line-of-sight range	Low	Low	High	Low	Moderate	Very low
Automatic Identification	✗	✗	✓	✓	✓	(✓)
Simultaneous Identification	(✓)	(✓)	✓	✓	✓	(✓)
Wireless data transfer	✓	✓	✓	✓	✓	✓
Analysis of movement patterns	✗	✗	✓	✗	✓	✗
Real-time location tracking	✗	✗	✓	✗	✓	✗
Two-way communication	✗	✗	✗	✗	✓	✓
Ease of Application	High	Very High	Moderate	High	Moderate	Moderate
Relative cost of implementation	Very low	Very low	Very high	Low	High	Very high

This case study did not have access to used RFID tags to apply and the aim of the project was to minimize any new material needed for construction. RFID tags also have initial capital costs from both the tags and the readers. Although those capital costs are lower than the laser engraver used for the scope of just this project, the relative cost of implementation is generally higher for RFID than QR codes. Lastly, is the issue of accessibility. As noted in Table 1, QR codes have a notably increased ease of application from the ability to be read by users without the need of special equipment. Because of this reason, barcodes were not chosen either.

Asset Tracking for Circular Economy via QR Code

BLE and NFC devices were not used because, similarly, there is a hardware requirement we could not address without purchasing new materials. BLE also has a device energy demand, as does active NFC, but NFC can be used passively without an energy demand on the tag. However, passive NFC also has the limitations of necessarily needing to be within a few centimeters of the reading device. There is additional hardware limitation of devices capable of reading NFC and BLE, whereby external phone attachments, limited applications and operating systems, or separate readers are needed to interact with these solutions.

QR codes are a system that can be easily managed and allows a relatively large amount of data to be stored. The QR codes consist of small black squares arranged on a grid with a white background, and technical imaging devices (e.g., cameras) are used to read QR codes. The image is processed algorithmically by a software according to the QR code standard until the captured image is interpreted and the data contained in the code can be read (Ventura et al., 2016).

QR codes have been shown to integrate with IoT infrastructure in the built environment for pairing sensors used in building energy modeling (Madsen et al., 2021). The use of QR codes for digital product passports in the circular economy of manufacturing has been explored in academia (Gligoric et al., 2019) and through industry solutions in fashion ("circular.fashion," n.d.), plastics ("Circularise," n.d.), and consumer products (Stylianos Georgoulas et al., 2017). As multiple industries are increasing interest in tracking products through life-cycles, there has been some work into unique QR code applications, such as engraving into metal product cases (Ventura et al., 2016) and reversible QR code ink technique (Gligoric et al., 2019). Though application techniques and QR codes for circular economies have been often explored for other industries, limited work explores the integration of QR codes within the architectural, engineering, and construction (AEC) industries. This paper aims to expand the existing literature on QR codes for item lifecycle tracking into the AEC industry for digitizing materials passports via engraved QR codes.

Materials and Methods

Case Study Description of the Dome Project

To explore techniques of reuse and digitization through a real use case in construction, part of an automobile warehouse in Geneva, Switzerland was disassembled to reclaim building materials. Primarily large wooden beams were recovered ranging from three to six meters in length. Additionally, metal fasteners, plastic piping, oriented-strand board (OSB), small steel beams ranging 1.5 to 3 meters in length, and miscellaneous furnishings were recovered. In order to test methods of digitization and material tracking a design algorithm inspired by one of the author's previous work (Huang et al., 2021) was used to develop a geodesic dome structure from the recovered building stock. The approach involved cutting the existing wooden beams into specific sizes needed for the structure, then to apply a tracking technology in order to link the materials to a digital material passport. The final construction of the dome as seen in Figure 1 consisted of 161 structural components from the recovered wooden beams, 60 joint nodes from the recovered PVC piping, 120 node caps from the recovered OSB, and approximately 700 new screws.

Figure 1. Dome Project Final Construction

The dome primarily uses sawn lumber, a commonly used building material in residential and low-rise construction. Demonstrating the success of a material passport infrastructure on the scope of this dome provides initial steps for scaling into other forms of infrastructure, such as modular concrete construction. This paper explores the process of laser engraving construction materials in the construction process, as demonstrated in Figure 2, to embed a connection to digital materials passports in elements of the final structure.

Figure 2. Workflow demonstrating the QR code production, laser engraving, subassembly, main assembly, and accessing the materials passport in situ

QR Code Development

QR codes were chosen as the technical solution because of their speed of production, ease of application, accessibility, and because of growing application within the building industry (Elizabeth Rosselle, 2018; "Recommended QR Label Printers," n.d.). Many services publicly available produce and manage QR Codes. Static QR codes are read-only codes; such that once they are produced, the information embedded is permanent and will always house the same data. Dynamic QR codes have the ability to redirect the final routed destination by using an intermediate short URL. A dynamic QR code allows the owner to, effectively, update the stored information on the same QR code produced as well as provide statistics such as number of scans, location, and operating system used to scan.

Initial efforts for producing QR codes involved using the qrcode 7.3.1 package for python (Loop, n.d.). This method produces QR codes with only a few lines of code and allows for some customizability. This method is free and allows anyone to produce their own QR codes, but the disadvantages include only producing static QR codes and not allowing for easy management of the codes *en masse* when produced. A similar approach was tested using functions within Microsoft Excel and Google Sheets to output a QR code when provided a URL. The advantages of using a spreadsheet formula are that all codes are stored within a single document, but the disadvantages of this method are that the codes are only static and the aesthetic and output file format are not customizable.

For the development of the Dome project shown in Figure 2, the program QR Code Generator ("QR Code Generator | Create Your Free QR Codes," n.d.) was chosen to produce and manage the QR codes for the dome as it provided an easy interface for managing the project codes and had more aesthetic customizations. The program allowed the development of dynamic QR codes; however, in project implementation only static QR codes were used because of the added programmatic costs of producing dynamic codes.

Laser Engraving

There are varying approaches to effectively applying the QR code to the material from mechanical fastening, chemical fastening, and engraving amongst others. The technique chosen for application was to laser engrave the QR code directly onto the wooden members as seen in Figure 2. This satisfied requirements such as aesthetics, durability, and accessibility. For this research, a Trotec Speedy 400 CO_2 Laser Engraver was used for application to the wood members. There is no known initial product data on the recovered structural materials, thus it is necessary to test laser settings for optimal readability of the QR codes as shown in Figure 2. The members are visually observed to be a softwood pine-based wood. For the Trotec Speedy the associated software for the engraving is Ruby and the required input file is a vector-based PDF.

Printed Labels

For two of the components, we experimented with removable printed tags as an alternative to directly engraving the codes. These tags are produced from 1.6mm TroLase materials and manually screwed into the wood as seen in Figure 3. This step necessitates more hardware for installation and is more visually abrasive, but allows for simple replacement of the QR code.

Figure 3. Image of Removable QR Code Label

Results and Discussion

Advantages and Disadvantages of QR Codes for Material Tracking

QR codes were used as the technological solution to material component tracking, yet there are many advantages and disadvantages to this approach. A large issue with using QR codes is the system that develops and manages the codes. The disadvantage of using a third-party service (including what was used on this project) is that it is subscription based and has limitations on number of codes produced, number of users, and number of scans. An additional barrier of using QR codes for material tracking is the requisite need for visual access to the material, or at least to the QR code on the material. QR codes are not a sufficient system for embedded or encapsulated materials, such as cast-in-place concrete or insulation behind an exterior wall. In these instances, technologies like RFID, NFC, or BLE have greater advantages. The use of RFID tracking technology for building components is likely most applicable for new construction, where tracking from the manufacturer or producer to staging on the jobsite to final install requires location-dependent data. Whereas QR codes are likely the best approach for building components in situ where location is less important than housing material or product information.

There are several unique advantages to using QR codes. Unlike barcodes, a QR code can be scanned from any angle. The three *eyes* in the corners help the scanning device determine its orientation. QR code systems enable fast and reliable data entry and can hold up to 350 times more data than a barcode. QR codes can be scanned using common mobile operation systems and no special reader is required. An important factor in developing QR codes is optimizing for information stored. The longer the URL stored in a QR code, the more complex and, therefore, likely to be disturbed it will be. This is another advantage of using dynamic QR codes, which often use a shorter URL for the intermediate redirection page. With an increase in prefabricated and modular construction, there are advantages to material tracking using QR codes as evidenced by construction technology companies such as Manufacton, Hilti, and Prescient.

Laser Engraving Results

Table 2 below provides results on the tested laser engraving parameters. The parameters tested include the power and speed (Trotec provides inputs only as percentages), location on sawn lumber, and dots style. The locations tested included the inside (the recently exposed surface after cutting the piece to desired size) and the outside (the previously exposed side during its last use phase). Two dots styles of the QR code were tested, square and round, to examine if this would affect readability of the codes. The engraved codes were systematically tested in two different lighting conditions using two different cameras. The recorded output of "Fails" and "Success" indicate whether the camera recognition technology successfully recognized, read, and directed the QR code to the database.

The engravings took 1 minute 52 seconds each, and the total processing time (including sanding and file preparation) averaged about 6 minutes per component. It was also found that light sanding after engraving further increased the code readability. The Google Lens camera from both the iOS application and native phone camera performed best in yielding most QR codes detected. Figure 4 displays photographs of the resulting engraving trials. Other conditions were experimented with, such as engraving on a knot in test 13, or on a chipped area in test 12. After testing various parameters in the Trotec laser for optimum readability, the final parameters used for all material engraving was 70% Power and 50% Speed within the Ruby Software.

Table 2. Laser Engraving Testing Parameters

Trial Number	Power (%)	Speed (%)	Location (on sawn member)	Dots Style	Results (iOS camera)	Results (iOS camera)	Results (Google Lens)	Results (Google Lens)
					Poor Lighting	*Good Lighting*	*Poor Lighting*	*Good Lighting*
1	50	100	Inside	Round	Fails	Fails	Success	Success
2	50	100	Outside	Round	Fails	Fails	Fails	Fails
3	50	100	Inside	Square	Fails	Fails	Success	Success
4	50	100	Outside	Square	Fails	Fails	Fails	Fails
5	60	100	Inside	Round	Fails	Fails	Success	Success
6	70	90	Outside	Round	Fails	Fails	Success	Success
7	70	90	Inside	Round	Fails	Success	Success	Success
8	75	80	Outside	Round	Fails	Success	Success	Success
9	75	70	Inside	Round	Fails	Success	Success	Success
10	70	50	Outside	Round	Fails	Success	Success	Success
11	70	50	Inside	Square	Success	Success	Success	Success
12	65	50	Inside	Square	Fails	Success	Success	Success
13	60	50	Outside	Square	Fails	Fails	Fails	Success
14	65	50	Outside	Square	Fails	Fails	Fails	Fails
15	70	50	Outside	Square	Fails	Success	Success	Success
16	80	60	Outside	Square	Fails	Success	Success	Success
17	70	50	Outside	Round	Fails	Success	Success	Success

Figure 4. Images from Testing Laser Engraver Settings on the Same Piece of Wood

Laser Engraving Challenges and Benefits

A laser engraver provides unique advantages and disadvantages for the application of QR codes for tracking. Laser engravers work well for many biological-based materials, some plastics, and most metals. QR codes can also be programmed for an error capacity if some of the code becomes destroyed or unreadable on the material. Specifically with engraving QR codes into wood, another potential issue may come from the wood later being treated. If layers of paint or sealant are applied to the wood and seep into the cavities produced from the engraving, then this may negatively affect its readability.

Through testing the wooden components, an unexpected barrier came from the idiosyncrasies of the wood material itself. Within a cross-section of wood are various layers that have different properties including sapwood, heartwood, and the pith (Ramage et al., 2017). Within the heartwood are the growth rings, which vary in thickness and hardness based on summerwood and springwood (Ramage et al., 2017). In addition, the alignment and growth patterns of the grains were inconsistent between pieces. Because the laser maintained a static power and speed setting for each engraving, the final depth varied depending on the subjective properties of the wood resulting in unique artifacts. There are two other factors affecting the success rates of QR code readability: environmental lighting and camera quality. Because of the irregularity of the engraved wood, how the ambient light illuminated the QR codes affected if the cameras could detect the code. Figure 5 compares the same codes turned in different orientations towards the ambient light and illustrates the significance of both the wood grain and lighting conditions.

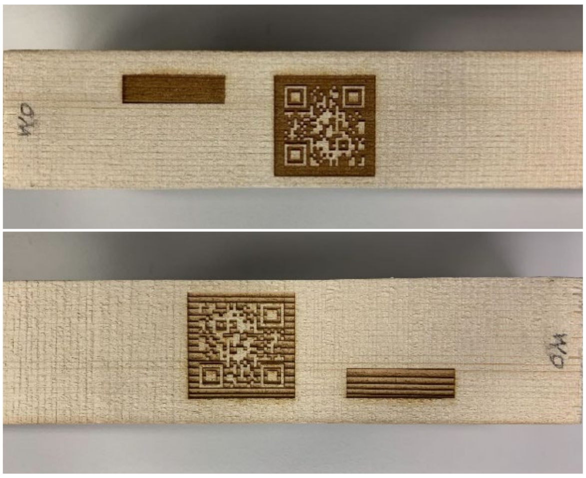

Figure 5. Demonstration of how Light Conditions and Wood Grain Orientation affect Readability of the same QR Code

The barriers to using an industrial laser engraver include the limited bed size and prohibitive costs. An alternative to using a standing machine could be to utilize a portable laser engraver. Using a portable machine allows for application on site in situ and is less expensive. Although, using a portable laser engraver often comes with limitations in the size of engraving area and speed relative to a full standing machine, but for the application of QR codes this is not seen as a significant barrier.

Limitations

A notable concern with the use of tracking technologies, especially a permanent solution such as engraved QR codes, is adaptability. Lumber is a material that is easily replaceable on many job sites as well as easily modified. If a piece of lumber were cut into two pieces then the engraved QR-code would need to reflect this, which could be difficult if the QR code is static. If a static QR code solution is used in tandem with an editable database solution (e.g. have webpages redirect to most recent component data), then this is no longer an intractable problem. In addition, utilizing a QR-code application technique that allows for removal and reuse (e.g. on a tag screwed into the member as shown previously in this paper) is another solution for this issue.

Furthermore, QR codes have a challenge with visibility that radio-based technologies do not have. Building components hidden behind finishes, within a slab, or at too small a scale all experience difficulties being tracked with QR codes. Further difficulties arrive with information fidelity when the component is modified. If one of the engraved wood members in our project is cut in half, then how does the QR code (assuming it wasn't also cut in half) reflect the new member and will the other member receive a new QR code. Parallel to this logistical problem is the data modeling problem: representing a component that was split or combined with other tracked components through its lifecycle. These issues have not been addressed within this paper but will be explored with future work.

This scope of this work was limited to only wooden members in a small-scale structure, yet the successful proof-of-concept can potentially be scaled to additional building elements. For example, structural steel is fabricated and marked in shops before delivery to the construction site, which is an opportunity for integrating tracking technology into existing industry practices. Fiber lasers are already known to be used for engraving into stainless steel without compromising the steel material (Dan Davis, 2018; Gabzdyl, 2008).

Conclusion & Future Work

To approach a circular economy in the built environment we need to address issues of material and information management that currently inhibit reuse (Hossain et al., 2020). This paper provides evidence of the efficacies from using QR codes as a material tracking technology that houses materials passports by bridging the physical asset with electronic documentation. A comparison of potential tracking technologies is provided and a further analysis of RFID and QR codes. QR codes were chosen because of their 1) low cost, 2) speed of implementation, and 3) accessibility. The application method explored was primarily via laser engraving, and two instances of removable tags were also utilized.

Further work is being completed using this same case study on developing a building component database. The QR codes currently link to a web-based proxy repository for storage of a partial material passport. Further infrastructure on developing a backend database and a frontend user-interface will be analyzed to explore what solutions are the most feasible for building component lifecycle tracking. Specifically, there is nascent work in academia and limited work by industry on data modeling at the appropriate scales, such as knowledge graphs and resource description frameworks (RDF), and on storage solutions, such as SQL and NoSQL, for reused components.

Developing and testing this workflow is critical to prove the feasibility of directly connecting virtual data to a physical asset. Uncertainty and risk are two great barriers in the circular economy (Camacho-Otero et al., 2018; Hossain et al., 2020). This workflow proves that continuity of information is possible and can be used to inform future design work and material transactions. This information transfer is an initial layer to develop a dynamic bi-directional connection to Building Information Models or third-party material platforms to facilitate reuse. This paper provides a comparison of different tracking technologies that may be utilized for building components, and it contributes knowledge to the practicalities and challenges associated with engraving QR codes into building components. These contributions in aggregate further facilitate reuse and the circular economy for the built environment.

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