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ENABLING REUSE OF PREFABRICATED CONCRETE COMPONENTS THROUGH MULTIPLE TRACKING TECHNOLOGIES AND DIGITAL TWINS

Arlind Dervishaj*, José Hernández Vargas, and Kjartan Gudmundsson
KTH Royal Institute of Technology, Stockholm, Sweden
*arlindd@kth.se

Abstract

Tracking of building components can be instrumental in reuse for a Circular Economy. Tracking technologies (TT) for building components can be used to identify and access information for decision-making from deconstruction to design for reuse. Prior research has mainly been concerned with single technologies, limited life cycle applicability and new construction. This study aims to explore the potential of combining multiple technologies, such as QR codes, Near-field communication (NFC), and Bluetooth tags, with building information models (BIM) to support reuse along the life cycles of prefabricated concrete components. The benefits and limitations of choices in TT are examined concerning information integration in circular construction.

Introduction

The construction sector significantly impacts the environment, accounting for 50% of all raw materials extracted globally and more than 35% of construction and demolition waste (CDW) in Europe (van Eijk et al., 2021). Circular Economy (CE) approaches can be of great value when it comes to reducing the impact of the sector. As initially put forward by McDonough and Braungart (2002), the CE can be seen as two distinguishable material flows: biological and technical. In the latter, buildings and their materials are used for longer timeframes, refurbished, reused, or recycled as a last resorting solution (Ellen MacArthur Foundation, 2019). Some of the initiatives to achieve the transition to a CE include legislation that supports the reuse of building materials, the development of material passports (MP), digital marketplaces, circularity and cost indicators, and the adoption of technologies to track building components across their life cycle (van Eijk et al., 2021).

This paper examines the potential of utilizing TT for prefabricated concrete elements and proposes workflows for integrating physical components with digital models. Also, of interest to our other ongoing research efforts is to link the physical elements to a material passport (MP). MPs could improve quality assurance, supply and demand management, and data sharing in support of a CE. However, this aspect is outside the scope of the present study while further reading on MPs can be found in the literature (Hoosain et al., 2021).

The paper starts with a background on previous research efforts using TTs, followed by a review of selected tools to capture data and TTs. The methods section describes the workflows for incorporating multiple technologies such as NFC, BLE, and QR codes, into a database and the digital model, for identifying building components and facilitating data exchange across the life cycle of precast elements. The results section presents the laboratory tests on different scenarios of attaching NFC to concrete, including core drills and combined with BLE tags. The discussion explores the potential and limitations of examined tags for enabling the reuse of precast concrete. Through its investigation of TTs and their applicability for circular construction, the paper aims to offer valuable contributions towards sustainable construction practices.

Background

Digitalisation of construction

Digitalization is expected to increase the efficiency and productivity of the construction industry (McKinsey Global Institute, 2020). The range of technologies used, and the adoption of Building Information Modelling (BIM) is growing among architects (Architect's Council of Europe, 2020, p. 6). Construction 4.0 represents a merger of cyber and physical systems, where information and construction processes are based on technology and a network of connected devices and people (Klinc and Turk, 2019, p. 397). Klinc and Turk identify six key technologies relevant to Construction 4.0 which are (1) Internet of People (IoP), (2) Internet of Things (IoT), (3) Robotization and computer-aided manufacturing (CAM), (4) Digital Twins (DTs), (5) Artificial Intelligence (AI), and (6) Cloud-based systems. DT is a digital counterpart of the physical object. There is still no clear consensus on the definition of DT, but a recent definition with a certain level of agreement between academia, industry, and governments from the Digital Twin Consortium (2020) is that of "*a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity*". In the case of reuse, the digital twin applies to the building to be deconstructed and its parts on different levels of decomposition e.g., construction type system, components, and materials. For instance, the DT can be shared in the cloud to gather, store, and communicate information for reuse.

Tracking of building components

In traditional processes, logistics information on building elements and their availability is manually registered in documents and drawings. This is prone to error, time-consuming and not useful for quick data retrieval and sharing among stakeholders. Electronic data entry through devices and computers can reduce errors and facilitate information exchange. However, the digital exchange of information can also lead to fragmentation of processes, people, and information (Turk, 2016, p. 274), where efforts in the field of *computer-integrated construction* aim to address this issue. Concerning TTs, previous studies have mostly been focused on *Radio Frequency Identification (RFID)* for tracking building elements (Alsafouri and Ayer, 2018; Copeland and Bilec, 2020; Montaser and Moselhi, 2014; Seyis and Sönmez, 2022). Several studies used embedded RFID in concrete in new prefabricated construction (Abbott and Chua, 2020; Ikonen et al., 2013; Li et al., 2018; Xu et al., 2018; Zhong et al., 2017). Other studies have examined the integration between RFID and BIM (Motamedi et al., 2016; Tang et al., 2019; Xue et al., 2018). Byers et al. (2022) analysed the use of Barcodes, Quick Response (QR) codes, active and passive RFID, Bluetooth Low Energy (BLE), and Near-field communication (NFC) for some data integration requirements, ease of use, and implementation costs. Then, their study explored the engraving of QR codes on reusable wooden beams for MPs and suggested applicability for steel but not for other materials and construction types. In their study, the QR tags were applied in the laboratory after reclaiming the elements from buildings. However, the reuse of building components supported by tracking technologies from deconstruction to reuse, and for prefabricated concrete structures has not been thoroughly investigated.

Comparison of technologies

Tracking and tracing

In logistics, tracking refers to following the path and knowing the location of delivery in real time. In construction, it would mean having information on:

- Type and number of elements available.
- Estimated time of availability.
- Location of elements.

Tracing means following a delivery path backwards from the current position to where it started. It would mean knowing the history and origin of materials, components, products, or systems for circular construction. TT could in that instance be used to provide information on:

- Previous life cycles, lifespan, ownership, and material composition.
- The material condition of concrete panels, such as cracks, covered/exposed, internal/external use, load-bearing function, and structural properties.
- Location history that may be useful in the life cycle assessment (LCA) modules on transportation.

Figure 1 illustrates the main difference between tracking and tracing concepts.

Figure 1: The basic difference between tracking and tracing

Data capture

Electronic document management represents an improvement over manually registering assets and sharing data. More people can access the information concurrently when using a shared repository. Digital spreadsheets, forms, and lists in shared repositories, such as those from Microsoft and Google allow access to data across devices and computers. A digital repository can host the required formats of data entry. In this study, spreadsheets/forms/lists can be used as an interface between TT and models (BIMs/DTs) for data integration. Table 1 provides a comparison of digital tools for entering and sharing data. Brackets indicate the tool fulfils the criteria but with limitations. For example, third-party plugins in Microsoft (MS) *Excel* or *Google Sheets* need to be used to create QR codes for the data or a link to the file.

Table 1: Digital tools for entering and sharing data

+ = Yes (+) = Partial/limited - = No N/A = Not available	MS Excel	Google Sheets	MS Office Forms	Google Forms	MS Lists
Cloud-based	(+)	+	+	+	+
Multiple users	(+)	+	+	+	+
Mobile app	+	+	(+)	(+)	+
Desktop app	+	-	-	-	+
Creates QR codes	(+)	(+)	+	-	-
Share link	(+)	+	+	+	+
Excel export	+	+	+	+	+
Embed as link	(+)	+	+	+	(+)

Forms are useful for preliminary surveys and visual assessment of buildings, and the data can be exported to *Excel*. However, there are limitations when using forms to capture data. *MS Lists* provides a versatile platform to manage and share items. It allows the creation of lists from and to *Excel*, supports several data types, can store photos taken with smartphones, as well as attach other types of files. *MS Lists* can generate formula values for columns and enforce unique values, such as a unique ID of the physical building element.

Tracking technologies

Paper documents can be used to register assets, but this approach can hinder collaboration and sharing which is important to reusing buildings elements. Data can be registered with computers and smartphones, but identification of elements is still manual, time-consuming, and prone to error. For example, any visual label or ID of building components would be manually input/searched in the digital tool to register/retrieve data.

Tracking technologies, on the other hand, enable the automatic identification of objects and some TTs can store additional data such as location, contact information, or a link. Thus, making it possible to connect objects to a shared database for asset tracking. QR codes, RFID, Bluetooth, or NFC can be used. In recent years, BLE technologies for tracking personal items have become available (e.g., *Tile*, *Chipolo* trackers), and products from smartphone producers include *Apple's AirTag* and *Samsung's SmartTag*. Some of these BLE tags can track beyond their normal range by anonymously using the network of peer devices. This relatively new use of TT has the potential to be applied to construction elements. Table 2 provides a comparison of TT and specific BLE tags across criteria relevant to this study.

RFID technology is composed of a tag, antennas, a reader, and application software. Active RFIDs are equipped with a battery. RFID tags can have memory for reading/writing data but are mostly used to identify items, and an external database through software is required for the data management part. The readable range of RFIDs varies depending on the frequency bands, location (tag, reader, and antenna types), and obstacles in the way. NFC is a subset of RFID and is increasingly integrated into smartphones. The range of BLE tags also varies depending on obstructions. AirTags are equipped with an NFC that redirects to a webpage with the tag's serial number and contact information of the owner. Thus, TTs are sometimes combined for multiple reasons such as enhanced capabilities or creating dissimilar redundancy in the tracking system. Except for RFID, all the reviewed technologies can be utilized with smartphones. *AirTags* only work with *Apple* phones, as do SmartTags with Samsung devices. In addition, *AirTags* can also use the network of non-Apple devices. *AirTags* have Ultra-wideband (UWB), a precision location technology that guides towards the tag when nearby. The *SmartTag+* (with UWB) has an AR mobile feature for locating the item. The GPS of reading devices and smartphones helps locate items in the real world, and not only relative to them (for RFID/BLE tags). The next section explains the tested technologies and workflows for reuse of concrete.

Materials and methods

We evaluate various methods of integrating QR codes, NFC, and BLE tags to existing precast concrete elements and linking them to their BIM model. Although prior studies often relied on RFID, it was not employed in this case. The main reason is that RFID requires an investment in equipment such as handheld readers or fixed infrastructure and software applications. In contrast, QR codes can be easily generated within tools given in Table 1, from a web browser such as Chrome, or using Python (Computer Science, 2022). QR codes can be scanned by most smartphones today. NFC capability is available for most new smartphones and there are free apps to use them. Multiple actors with managed access, at different points in time, could read or write multiple types of data to an NFC tag without the need for equipment and software that is required for RFIDs.

Case study description

To explore multiple tracking technologies, and their use in combination, a *digital model* was prepared of an existing building with a prefabricated concrete structure, and a *pilot* (pavilion) made from reused concrete components. Some of the reused concrete elements in the pilot were recovered from the demolition of an apartment building, built in 1967-68, in the *Drottninghög* neighbourhood in Helsingborg, Sweden.

Table 2: Requirements for tracking building elements

Criteria	QR codes	Active RFID	Passive RFID	NFC	BLE-UWB-NFC Apple AirTag	BLE-UWB SmartTag+	BLE Chipolo One	BLE Tile Sticker
Reading range	Low	High < 100 m	Low <10 m	Very low < 5 cm	N/A	< 120 m (outdoors)	Moderate < 60 m	Moderate < 76 m
Out-of-range tracking	-	-	-	-	+	+	+	+
No need for visual access	-	+	+	+	+	+	+	+
Bidirectional data flow	-	(+)	(+)	+	+	+	+	+
Store multiple types of data	-	(+)	(+)	+	(+)	-	-	-
No battery	+	-	+	+	-	-	-	-
Ingress Protection (IP)	(+) e.g., casing	(+) e.g., plastic casing	(+) e.g., plastic casing	(+) e.g., plastic casing	(+) IP67 water at 1 m depth for 30 minutes	(+) IP52 dust and moisture	(+) IPX5 water splash	(+) IP67
Relative cost	Very Low	Very High	Low	Low	Very High	Very High	High	High

The area is undergoing a process of revitalization where some housing blocks of the 1960s have been demolished and some are under review by the planning authorities. Precast elements used in the pavilion came from different donor buildings and factory rejects of hollow core slabs. The elements in *Drottninghög* were originally marked with a metal plate indicating project and element IDs, weight, and production date. Elements used in the pilot may be reused again for new projects. In addition, more precast elements may become available for reuse after decisions are taken for the existing buildings. The investigated methods of tracking may support the reuse of precast concrete elements coming from different buildings in circular design projects.

Asset registration in the database

Due to the aspects described in the *Data Capture* sub-section, *MS List* was selected from the reviewed tools in Table 1, to generate unique IDs and as a database to store the serial number of NFC/BLE tags, QR codes, a photo, and object location. The list can be expanded with more data types and file attachments. To register assets and give them a unique ID, a simple naming convention, hereby called the *Taxonomy ID*, is used as it is can be easily understood and assigned to elements as follows:
TaxonomySystemName_ComponentCategory_TypeCode_InstanceNumber_OptionalPartNumber
Example for a wall panel: Skåne_Wall_V01_1_0

Asset tracking with NFC

NFC is a passive tag that draws power from the device reading it and can store data. Thus, they can be used to potentially host information for multiple life cycles of a building element (existing building, deconstruction, storage, reuse). However, NFC has a very short range of a few centimetres. The 3D model can be used to know the exact placement of the tag on the concrete panel. NFC tags, compliant with ISO 14443 Type-A, are tested for reading capability. NFC can be attached to concrete as (a) embedded inside the material, (b) attached stickers. In both cases, NFC may be hidden from view. In new precast panels, tags can be embedded before concrete pouring. Three core drills are made in a laboratory on C30/37 concrete samples to test NFC tags. The core drills' diameter used is 38 mm (same as the *Chipolo One*) and performed at depths of 6.5 mm (enough for a *Chipolo One*), 8 mm and 15mm. NFC stickers are put in the last two. Then, fine concrete, suitable for thin layers, was poured to embed tags. Tapping to NFC is tested on attached tags and some common interior surfaces, if applied after reassembly in the new structure, such as linoleum, carpets, ceramic tiles, plywood board, or hardwood flooring. The findings are presented in the results.

Asset tracking with BLE tags

Recent BLE tags can track items even when out of range. This is not possible with other TTs. BLE tags allow for near real-time tracking. In addition, BLE apps allow sharing of the tag's location with other users. This can be a novel way to support the availability, database creation, and circulation of *buildings as material banks* (BAMB) (Copeland and Bilec, 2020). Some BLE apps (i.e., *Tile*, *Samsung*) can save the location history, which could be used to track travel distances and calculation of some LCA stages. The current high pricing of such BLE tags, which are not customized to construction, can hinder their adoption. In this paper, this is explored as a potentially novel method for construction. The first core drill is used for a *Chipolo One* BLE tag or an NFC tag, and should be done before the deconstruction. The BLE app can accurately locate the components. Alternatively, only one core drill can be used to attach both the BLE tag and a sticker NFC. Most BLE tags presented in Table 2 have a 1–3-year battery life. However, *Tile Sticker* tags can be attached to almost any surface and have IP67 protection against moisture and a battery duration of 3 years, which may be more than sufficient for a deconstruction and reuse project.

Asset tracking with QR codes

Byers et al. (2022) tested engraved QR codes for reusing wood elements and found this to be a feasible method for a pavilion in a controlled environment with easily accessible and visible tags. However, engraving may not be a practical option for large and heavy precast concrete panels or if elements need to be cut. In such cases, printed stickers or screwed plates can be used for attaching QR codes to panels. The choice between these methods depends on factors such as the environment where elements will be stored/assembled.

When building components are visible, NFC and BLE tags can be attached before deconstruction. However, deconstructed prefabricated concrete walls, are usually stacked side by side, and slabs may be stacked on top of one another. This makes NFC tags placed on the surface of a panel out of range and the identification of each element with BLE more challenging. In the pre-deconstruction audit, assets are registered in the database, where the unique ID is assigned. During storage, QR codes can be generated based on the ID and attached to the readable side of stacked panels. It is worth mentioning that QR codes can be *static* or *dynamic*. Static QR codes cannot update if there are information changes, but printed stickers or plates allow for easy replacement. *Dynamic QR codes* have an encoded address (web link) that redirects to a second one (which can be changed at any time). There are commercial tools that can be used for Dynamic QR codes. In this study, to circumvent the issues of static QR codes (e.g., link to a file/folder), a placeholder webpage can be used instead, with links or directly embedded forms/lists from a shared folder in the cloud. To generate QR codes, the Python package *qrcode 7.3.1* (n.d.) or *QR4Office* app for *MS Office* was used.

Integration of tags in BIM

Two ways of integrating tags into a BIM are (a) to model tags as objects in a BIM, and (b) information on tags as a property of the object (wall, slab etc.). Locating tags on the physical asset may be desired for NFCs, but also for other tags. Therefore, tags are modelled as a face-based family in Revit 2023 (shown in step 1 of Figure 2).

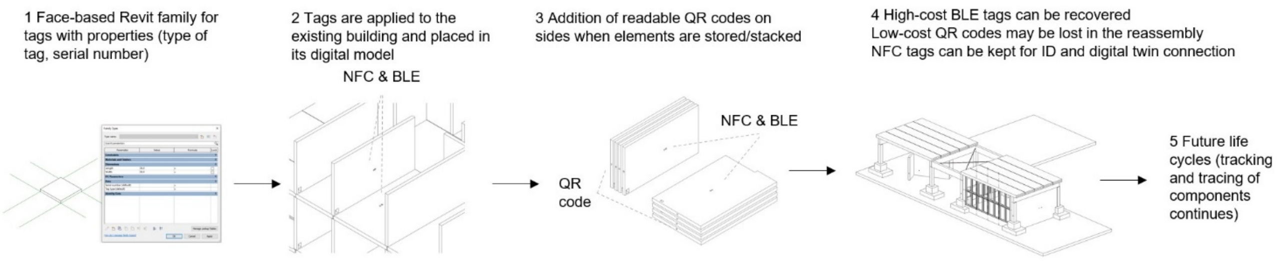

Figure 2: Steps in creating and associating tags to the digital model and physical counterpart (illustrated with model views in Revit)

Information in *MS List* and the BIM can be updated along the steps shown in Figure 2. This study also makes use of the *Speckle platform* for data integration between physical assets and digital models. One compelling feature of Speckle is that models can be sent from many authoring tools to Speckle and received back in the same or another tool. The Speckle model of a building/component can also be viewed on smartphones (on-site) and can be annotated with information on tags, comments, and file attachments.

Results

Given that concrete panels are heavy and moved a few times with machinery, the combination of multiple TTs can be useful in supporting their reuse along the life cycles. This study explores the use of NFC, BLE, and QR codes for tracking prefabricated concrete assets from deconstruction to reuse. NFC and BLE tags are added before deconstruction (step 2 in Fig. 2). The study used MS Lists as a database to store an ID for each element and data of applied tags. Asset data should be registered in the inspection before deconstruction in the database and then copied to the BIM model. Furthermore, to support data capture on-site, the Revit model can be exported to Speckle to assist with the registration through comments in a 3D viewer. Afterwards, such comments can be visualized directly in the authoring tool in their respective view. QR codes are generated based on the Taxonomy ID and added (step 3 in Fig. 2). NFC tags remain attached to elements for identification and linked to the database, and low-cost QR codes may be lost or replaced as needed (step 4 in Fig. 2). After reassembly in a new structure, high-cost BLE tags can be recovered and reused in new projects (steps 4 and 5). Figure 3 shows the data flow and integration process between the physical asset and the digital model.

Digital Twins for precast concrete assets

Pictures of panels are taken on-site and added to MS Lists for documentation. Taxonomy ID is added as a property to each panel instance in the Speckle/Revit model. Since the IFC Global Unique ID (GUID) changes with each export, the Taxonomy ID was used to identify assets in the model. This property should be transferred in model exchanges between tools and file formats.

Modelled tags were attached to digital objects (walls/floors) at the approximate location of the physical tag. Then, the type of tag and its ID is added as properties to the tag's model in Revit. The digital model (panels + tags) can be considered a first step towards *digital twins* of reused building elements, updated when needed with new information. These BIM objects can be used as a library for digital design in reuse projects. The design for reuse scenario is illustrated in steps 4 and 5 of Figure 2, where a pavilion was built from reused elements from several donor buildings in Sweden.

Testing of NFC tags for reused concrete

Laboratory tests were done to verify the effectiveness of NFC for tagging concrete. Five scenarios of data access were tested by using two smartphones, a *Samsung S21* and a *Google Pixel 4a*. NFC tags were placed in the following cases: (1) between two laser-cut acrylic layers (3 mm each) as casing in the 6.5 mm core drill, (2) embedded in concrete at 8 mm depth, (3) embedded at 15 mm depth, (4) attached to the concrete surface, (5) attached to *Chipolo One* (BLE) tag in the 6.5 mm core drill. Figure 4 shows the scenarios. To test the reading capabilities, various common coverings for interior walls and floors were evaluated. The results of these tests are presented in Table 3, with the thickness of each layer recorded.

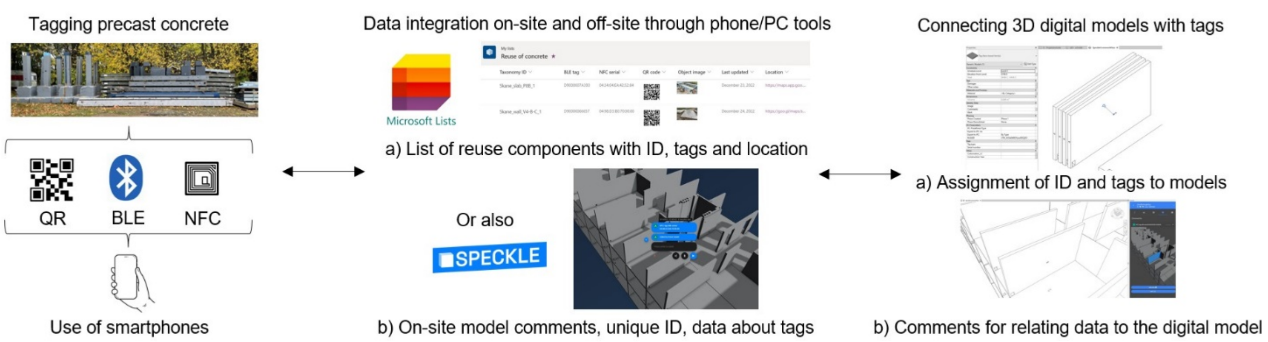

Figure 3: Workflow for cyber-physical integration of prefabricated assets with digital models through tags

Table 3: *Test results for five scenarios of attaching NFC to concrete, and when an interior surface is applied to each scenario*

+ = reading - = no reading	Base depth (mm), test	Linoleum, +2.5 mm	Ceramic Tile, +7.5 mm	Carpet, +7.2 mm	Carpet, +10.7 mm	Plywood board, +12 mm	Hardwood floor, +20 mm
1 NFC in acrylic	3, +	+	+	+	+	+	-
2 NFC in concrete	8, +	+	+	+	+	+	-
3 NFC in concrete	15, +	+	+	+	+	+	-
4 NFC sticker	0, +	+	+	+	+	+	+
5 NFC + BLE	0, +	+	+	+	+	+	+

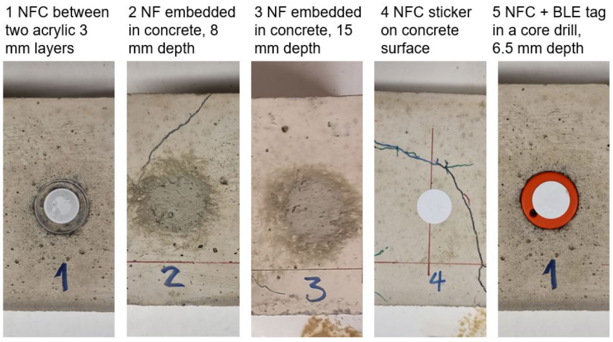

Figure 4: Tested scenarios on concrete (image of base depth)

Discussion

Previous studies have proposed the integration of RFID with BIM for different applications in the construction industry (Motamedi et al., 2016, 2011). Motamedi et al. (2016) proposed extending Industry Foundation Classes (IFC) with definitions for RFID, as it was not part of the IFC schema. In their study, it was argued that the *IfcSensor* entity was unsuitable to model data storage and communication technology such as RFID. The same study provided definitions for entities, relationships, and properties of RFID in the IFC, by manually editing the IFC EXPRESS schema. Motamedi et al. (2016) also developed custom software to access data on tags and use the IFC as a central database. At the time of writing this paper, the latest IFC schema does not include implementations for RFID and other TTs. In this study, we proposed a workflow using different TTs to support the reuse of structural precast concrete, without the need for extending schemas, RFID equipment, or custom software. To register assets and tag data, we used an MS List database, which was integrated with the BIM model, aided by using Speckle's 3D viewer. In future work, we aim to further enhance the interoperability of the workflow by utilizing open standards like the IFC and independent database solutions with open data formats.

As information may change over time, a bidirectional data flow between tags-database-model is an improvement to the one-directional data reading, as it can account for changes of ownership, location of the element, and cutting the elements for reuse.

Advantages of NFC

NFC was developed for secure communications in short ranges and is widely used for transactions with credit cards, smartphones, and wearable technology. When applied to construction products, the risks of data breaches can be eliminated compared to other technologies. NFC can also be programmed to be locked with a password for managing access and made read-only. NFC, a low-cost subset of RFID, was implemented with available apps for smartphones with NFC capabilities. The tested scenarios show that NFC can be a viable solution for tagging building components. This was investigated for concrete and for different attaching methods such as embedding the NFC into reused concrete, onto the concrete surface and coupling the NFC with a BLE tag in one core drill. In addition, there is the potential to use NFC for multiple life cycles as the tags were still readable after some common interior surfaces were applied to the concrete surfaces of the five scenarios. However, real-world tests will be part of future work performed to track elements in *Drottninghög*, including any additional layers in the reassembled structures. Since NFC has a short range, the digital model can be used to find the location of tags attached to physical objects. The NFC Forum introduced last year a *wayfinding mark*, a visual feature to help users know where to tap. This can be a part of the reused product to easily find the tag. The tag can also provide information to occupants regarding sustainability aspects, as well as technical data.

Potential of BLE tags

Rather than using RFID which requires antennas and equipment, this study suggests that BLE and NFC tags can be combined to track reusable building components in a decentralized manner, enabling a network of people to input and access data, through IoT and smartphones. The study tested *Chipolo One* tags which came in four colours. The colour information and an assigned tag name (i.e., Taxonomy ID) were possible to see in the Chipolo app for smartphones. This allowed for easier identification and ringing of tags for finding it. In the scenario that only one core drill is made where NFC is coupled with BLE, the BLE tag can be recovered after reassembly and reused in other projects, thus reducing investment costs. The NFC would be sufficient to identify elements for future reuse.

QR codes for prefabricated concrete

Byers et al. (2022) used a commercial tool to create and manage dynamic QR codes, but the subscription service limited the number of codes produced and usage over time. Their study acknowledges that laser-engraved QR codes require visual access and are a permanent solution. Thus, it can be argued that printed QR stickers or screwed plates are the most suitable for concrete elements. QR tags can be placed where considered suitable, replaced, and updated as needed. In the presented workflow, static QR codes were sufficient to store a short unique ID for each element, which can be generated with open-source or free tools and scanned with a phone. The ID is also understood by users as it is based on a naming convention. If the elements are cut for reuse, new QR codes can be generated with an extension to the naming. The split parts can also be added to the database and reflected in the digital model. This process allows keeping track of any cuts and changes needed in the design for reuse. However, QR codes require visual access, which some other technologies don't. Therefore, multiple TTs are combined to align the potential of each technology to the life cycle applicability for reusing prefabricated concrete structures.

Limitations

Using more than one technology can be instrumental for the reuse of concrete but may also result in additional efforts. During initial inspections, the component type, number of panels selected, and storage capabilities may not require the use of all three technologies. For example, a void of a panel type may allow for easy placement and reading of a tag in the existing condition, storage, and reassembly phases.

The relatively high cost of BLE may be prohibitive in projects with a high number of reused components e.g., timber-frame wood elements. However, the use of BLE technology may still be viable for larger, monolithic, and more expensive concrete elements such as in the presented case study.

An NFC tag may be preferable to a QR code for long-term storage of several data types, less invasive when visible, and hidden behind paints/surfaces. The NFC may, however, be hard to identify if behind other surfaces. In that case, the *wayfinding mark* or the *3D model* can help locate tags in the physical asset.

The study relied on Revit as a BIM tool. Alternative authoring tools to model buildings and digital twins for reuse can be with tools like Archicad or Allplan. The use of IFC is of interest in future work as it would enable greater interoperability between tools and the long-term storage of digital models. Preserving object properties and their IDs is an important consideration for achieving this interoperability. The information included in the model (Taxonomy ID, tags, and data) needs to be preserved when exchanging data between tools and file formats.

Conclusions

Digital technologies are needed to create, manage, and share data for the reuse of buildings, their components, and materials. This study presents a concept of combining three tracking technologies, a database, and digital models to facilitate the reuse of prefabricated concrete structures. Initially, we provide a comparison of digital tools and technologies for registering and tracking assets. QR codes, NFC, and specific BLE tags are proposed in a workflow that supports circular construction projects. Static QR codes can be used to identify elements and come at a low cost. NFCs are useful to store multiple types of data, for a relatively long time, and can prevent unauthorized access or network threats. Laboratory tests based on realistic scenarios indicate the feasibility of NFC tags and will be applied to real-world projects. Emerging BLE tags have the potential to enable the concept of *buildings as material banks*, by sharing between people, and tracking when out of range. BLE tags are placed in a core drill in existing precast concrete and are recoverable after reassembly, and reusable in more projects. Our approach does not require special equipment, or custom software that is not widely available, making our method accessible to a wider range of users.

As part of our future work, we plan to investigate alternative data storage technologies that are independent of proprietary software solutions, as well as develop automation features and API-based data exchange capabilities between various tools. Sharing a digital twin of a building element through a BIM library or digital marketplace can support circular construction practices. In future work, we plan to investigate in greater detail the concept of digital twins for reuse, to store and share the right level of information for the redesign process. We will also develop material passports that are linked to precast concrete elements, enabling the exchange of information for a circular built environment.

By providing a means to identify and track building elements, our approach can help reduce waste and support more sustainable practices. As such, we hope that this study will serve as a starting point for future research and development in this area.

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