2025 European Conference on Computing in Construction

CIB W78 Conference on IT in Construction

Porto, Portugal
July 14-17, 2025

TOWARDS TRACKING CIRCULAR CONSTRUCTION SUPPLY CHAINS: DATA CARRIER PERFORMANCE IN REALISTIC EXPERIMENTS

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Abstract

Due to the need for effective track and trace systems to enable circular construction supply chains (CCSC), this study evaluated the performance of radio-frequency identification (RFID), near-field communication (NFC) chips, quick response (QR) codes and Direct Product Marking (DPM) in identifying and reading material information. Key metrics — detection speed, error rates, and user experience — were assessed and gave consideration to the differential impacts of controlled and uncontrolled experimental conditions. Findings indicate that, relative to DPM, RFID and NFC offered improved usability and reduced reading times, with minimal differences in error rates; results were strongly influenced by usability and experimental context.

Introduction

Circular construction supply chains (CCSCs) aim to mitigate the environmental impact of the construction sector, which generates over one-third of global solid waste and is responsible for approximately 37% of global energy-related CO_2 emissions (United Nations Environment Programme, 2024). The efficient reuse of materials within CCSCs requires advanced tracking and tracing and robust data management solutions. These tools ensure transparency and efficient decision-making across multiple stakeholders and phases (Wijewickrama et al., 2021). Making collected and associated information about materials and components digitally available throughout their life cycle can enable more informed decision-making, support reuse and recycling, and foster transparency and accountability across the construction and demolition processes.

This requires a bridge between the physical and digital realms capable of facilitating seamless interaction, processing, and retrieval of material data. A novel solution is to attach physical data carriers to pieces of material. These data carriers can either store associated information or, more commonly, provide the user reading the carrier with a link to the externally stored data containing information about the material.

Different physical data carriers exist, each with its own advantages and disadvantages. Byers et al. (2024a) compared the usability and efficiency of direct product marking (DPM) codes, quick response (QR) codes, and near-field communication (NFC) chips in the specific context of CCSCs. They conducted an experimental design in a controlled setting to assess speed and error rates between different carriers and collected participant feedback on the experience. Users were instructed to retrieve digital information about the prepared materials by reading the attached data carriers. Users then evaluated the age of the material components according to their readings. Byers et al. (2024a) found that DPM underperformed compared to QR codes and NFC chips. Users reported a slight preference for NFC, which enabled faster information retrieval. The study by Byers et al. (2024a) thus found that increasing digitization of data carriers resulted in faster speed, fewer errors, and better user experience in their experiment. This paper extends the research performed by Byers et al. (2024a) in two directions.

First, since NFC previously performed well, the present study extends the experiment conducted by Byers et al. (2024a) by assessing the performance of radio-frequency identification (RFID). NFC and RFID are both derived from the same underlying technology. High-frequency devices, commonly referred to as NFC, operate at 13.56 MHz with a reading range of up to 5 cm. By contrast, ultra-high-frequency (UHF) systems, commonly referred to as RFID, operate at 850–950 MHz with a potential reading range of up to several meters. Both technologies enable contactless identification, eliminating the need for optical readability, as required by QR codes (Gao et al., 2024). This allows remote access, automated inventory updates, and reduced reliance on manual processes. These features make NFC and RFID suitable for automated tracking and real-time data exchange in CCSCs (Bottani et al., 2024). In comparison to NFC, RFID supports simultaneous readings of multiple tags (Bottani et al., 2024) and is optimized for high-volume tracking, making RFID more scalable in growing CCSCs (Yang et al., 2021). RFID applications in construction usually use passive UHF systems due to their lower cost, longer lifespan, and ability to function without a power source (Vhatkar and Bhole, 2010; Xue et al., 2018). Despite their advantages in range, UHF systems often require specialized handheld readers. Although some studies have suggested the use of RFIDs, to our knowledge there is no study that compares RFIDs with other tracking

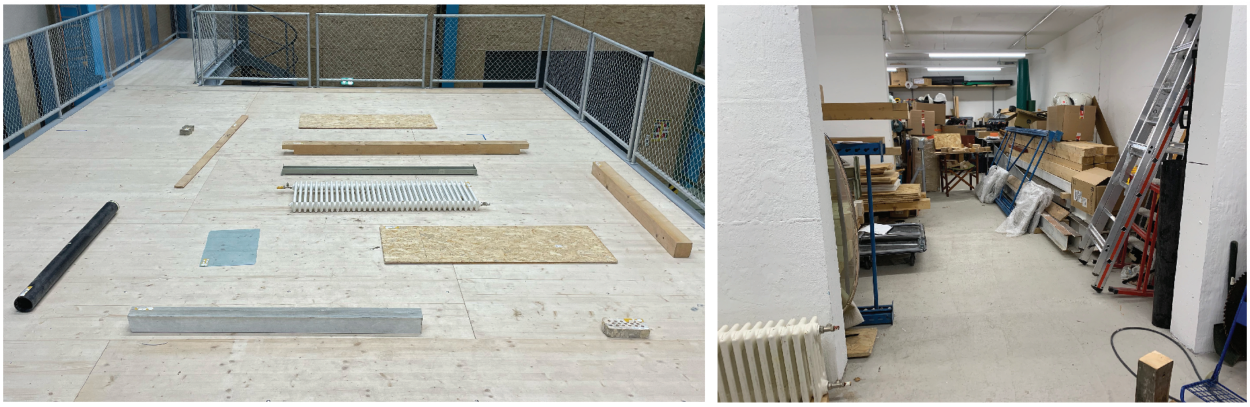

Figure 1: Experimental setups of the former study (left, from B.S. Byers et al., 2024) and the current study (right)

methods in the specific context of CCSCs.

Second, considering variability in uncontrolled scenarios is critical to understanding how systems operate in practical applications for CCSCs and how they can be scaled and adopted (Thirumal et al., 2024). The transition to a circular economy in construction relies on reuse ecosystems, where existing buildings serve as material banks that enable selective deconstruction and recovery of materials for future projects (Çetin et al., 2023). Real-world CCSC scenarios involve selectively deconstructing buildings to recover high-value materials, which are then stored in warehouses or marketplaces until reuse. This process requires robust tracking of each material's properties, history, and condition. To enable effective reuse, digital tools like building information modeling (BIM), material passports, and non-destructive testing help document material integrity and ensure compatibility with new construction projects (Byers et al., 2024b). Uncontrolled environments better reflect real-world field conditions, where component placement and data carrier positioning may not be obvious.

The valuable insights about NFC, QR, and DPM usability in Byers et al. (2024a) are limited by the study's controlled setup. Eliminating environmental variables that could confound the experiment makes the study unrepresentative of practice. In addition, it examines only NFC chips for CCSCs, not RFID tags. Although RFID presents the beneficial abilities to scan multiple tags simultaneously and operate at longer distances, it is unclear whether these advantages translate into improved performance under real-world conditions. Construction environments introduce significant challenges for data carrier performance, including signal interference from metal, electromagnetic noise, and extreme weather conditions, all of which can reduce detection accuracy and reliability (Lemieszewski et al., 2024).

Respectively, two experimental research questions were formulated:

1. Does increasing data carrier digitization (RFID and QR) show better reading efficiency than the traditional approach (DPM)?
2. How does an uncontrolled environment affect the effectiveness of data carriers compared to a controlled environment?

The resulting experiment provided insight into the performance of RFID, QR, and DPM data carriers. It enabled a comparison of their potential relative advantages, particularly regarding the level of digitization. These results also build on the previous findings by Byers et al. (2024a), allowing for a reflection on how different technologies perform under more realistic, uncontrolled conditions. The present findings suggest that the experimental setup in Byers et al. (2024a) affected the test results. These results could inform more context-sensitive recommendations for implementing data carriers in practice.

Research Design

This study is similar to the previous quantitative, participant-based experiment conducted by Byers et al. (2024a). In the former study, NFC chips, QR codes, and DPM codes were investigated. The present study substituted the NFC chips with RFID tags but kept the QR and DPM codes. The materials selected for this experiment were chosen to align with those used in the study by Byers et al. (2024a); beyond that, the specific types and quantities of materials were selected arbitrarily. The materials used in both studies represent the diversity of typical construction components: two masonry bricks, one radiator, one PVC pipe, three wooden beams, one steel beam, one wooden board, two Oriented strand board (OSB) sheets, and one acrylic sheet. In both studies, participants were tasked with using the data carriers to read the material passports and then count the number of components older than 25 years.

Unlike the previous study (Figure 1, left), the present experiment was conducted in an uncontrolled environment: a storage space for reclaimed materials (Figure 1, right). Participants were assigned to use only one data carrier and then required to locate the components with data carriers and complete the assigned inventory task. The experiment was completed individually to eliminate potential biases

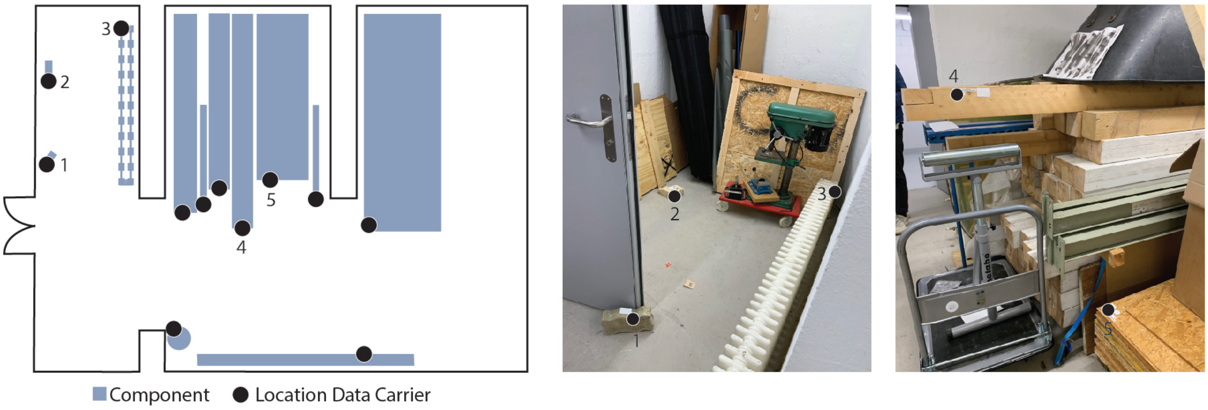

Figure 2: Experimental setups of the former study. Storage plan (left) and data carriers (center, right). The storage plan is symbolic and not to scale.

that could have arisen from participants observing one another. Consequently, each participant completed the experiment only once using one data carrier. Although the data carriers were not consistently placed on the same sides or types of material, they were positioned within the participants' potential line of sight, eliminating the need for material handling or repositioning. Before they began, participants were informed of the total number of tagged components and the types of materials involved (Figure 2).

This setup enabled a practical experimental approach to investigate effective solutions applicable in real-world contexts. Both objective and subjective quantitative data was collected from participants. The study measured three dependent variables: task completion time (continuous), errors (discrete), and system usability scale (SUS), which participants assessed using a Likert scale. To reliably assess the user experience of the track-and-trace stack, the SUS employed a standardized calculation to derive a usability score ranging from 0 to 100 (Brooke, 1995). Data was analyzed through exploratory and statistical methods using Python. More details about the procedure, data carrier, and data analysis are provided in the following sections.

Procedure

As in the former study, participants, recruited via convenience sampling, comprised graduate students and researchers in civil engineering and architecture from ETH Zurich. This nonrepresentative sample may reflect future users of similar systems. Ethical approval was obtained from the ETH Zurich Ethics Commission (Project 2024-N-28).

Each participant was timed as they completed the task. A facilitator was responsible for timing the experiment and recording the final answer. After each task, participants completed the SUS survey. All data was recorded in Google Sheets.

Data Carriers

All three data carrier types were arranged in a cluster on each component. Each data carrier was linked to a distinct material passport system. The UHF RFID tag (BIS01AU) was accessed with a specific reader (BIS01H2) that shown material information. The QR code directed participants to a Google Sheet containing the material passport. The DPM contained a 15-character product code (ASCII) prompting participants to locate the matching data sheet from a binder of 50 printed material passports. This procedure simulates a typical control scenario in the architecture, engineering, and construction (AEC) industry.

Data Analysis

Exploratory data analysis was conducted to answer the research questions and examine the variability and distribution of the data for the three systems. Statistical analysis focused on performance comparisons within this study and against the former study. Prior to analysis, minor individual data points were excluded during data cleaning to ensure the reliability of the analysis. Metrics were reported as mean values per participant to ensure comparability across systems and studies with differing sample sizes. Distributions of individual results were also visualized to support interpretation.

The results of the experiment are reported in Table 1, Table 2, and Figure 3. The previous study conducted by Byers et al. (2024a) is referred to as Study 1 and the present experiment as Study 2. Study 1 contains a sample size of n_{DPM}=35, n_{QR}=39, n_{NFC}=39, while Study 2 has a sample size of n_{DPM}=4, n_{QR}=4, n_{RFID}=8. The next two subsections elaborate on the results relevant to reading efficiency (research question 1) and usability comparison (research question 2).

Data Carrier Reading Efficiency

Table 1 shows mean system performance based on two metrics: task time (seconds) and error rate (count) across the two studies. It is structured into two major sections, one for each study. Each section is divided into two sub-

Table 1: Comparison of mean system performance (time and error rates) for Study 1 by Byers et al. (2024a) (n_{DPM}=35, n_{QR}=39, n_{NFC}=39) and Study 2 as described in this paper (n_{DPM}=4, n_{QR}=4, n_{RFID}=8). Measured values are shown alongside the relative performance advantage of QR, NFC, or RFID over the DPM baseline.

	Study 1 (Byers et al., 2024a)		**Study 2**	
System	Average Time (seconds)	Advantage over DPM (seconds)	Average Time (seconds)	Advantage over DPM (seconds)
DPM	447	0 (0%)	905	0 (0%)
QR	237	-210 (-47%)	509	-396 (-44%)
NFC	203	-244 (-55%)	-	-
RFID	-	-	566	-339 (-37%)
System	Average Errors (count)	Advantage over DPM (count)	Average Errors (count)	Advantage over DPM (count)
DPM	0.09	0	0	0
QR	0.23	-0.14	0	0
NFC	0.03	+0.06	-	-
RFID	-	-	0.38	-0.38

Table 2: Comparison of mean usability (SUS score) across studies for Study 1 (n_{DPM} =35, n_{QR}=39, n_{NFC}=39) in a controlled environment and Study 2 (n_{DPM}=4, n_{QR}=4, n_{RFID}=8) in an uncontrolled environment.

	Study 1 (Byers et al., 2024a)	**Study 2**
System	Absolute	Absolute
DPM	45	49
QR	80	76
NFC	85	-
RFID	-	70

sections: The first presents the average time (seconds) and the advantage over DPM, which reflects system speed. The second presents the average number of errors and the advantage over DPM. Figure 3 visualizes the distribution of time and error rates for Study 2. The leftmost violin plot illustrates the spread of task-completion times, and the middle violin plot depicts the error-count distribution.

The time-performance results show that DPM recorded an average time of 447 seconds in Study 1 and 905 seconds in Study 2. QR had an average time of 237 seconds (-210s, -47%) in Study 1 and 509 seconds (-396s, -44%) in Study 2. NFC, tested only in Study 1, had an average time of 203 seconds (-244s, -55%). RFID, tested only in Study 2, had an average time of 566 seconds (-339s, -37%). The leftmost violin plot in Figure 3 shows the distribution of time performance for Study 2, with DPM values concentrated around 900–1000 seconds; QR and RFID with lower values; and RFID exhibiting higher variability.

The error-performance results show that DPM had an average error rate of 0.09 in Study 1 and 0 in Study 2. QR had an average error rate of 0.23 (-0.14 errors than DPM) in Study 1 and 0 errors in Study 2, resulting in the empty violin plot for the error rate of QR in Figure 3. NFC, tested only in Study 1, had an average advantage of +0.06. RFID, tested only in Study 2, had an average error rate of 0.38 (-0.38 errors than DPM). The middle violin plot in Figure 3 shows the error distribution in Study 2, with DPM showing a wider spread, including positive values; QR showing no distribution; and RFID having a broad spread, mostly negative.

Comparison of Usability

Table 2 presents the mean SUS scores for systems tested across Study 1 and Study 2. The SUS scores in Table 2 are presented for each system. In Study 1, DPM had a SUS score of 45, QR had 80, and NFC had 85, indicating the digital systems have higher perceived usability. In Study 2, DPM's usability score was 49, QR had 76, and RFID, which was not present in Study 1, recorded a SUS score of 70.

Figure 3 visualizes the distribution of SUS scores across systems in Study 2. The rightmost violin plot shows that QR had the highest concentration of scores around 60–80, while RFID displayed a wider distribution with a lower tail, suggesting greater variability in perceived usability. DPM exhibited a narrower spread with lower overall scores, aligning with its SUS value in Table 2.

Discussion

The following subsections first evaluate the impact of higher data carrier digitization (i.e., RFID and QR over DPM) on reading efficiency (as defined by speed and error count), and then compare the usability of data carriers

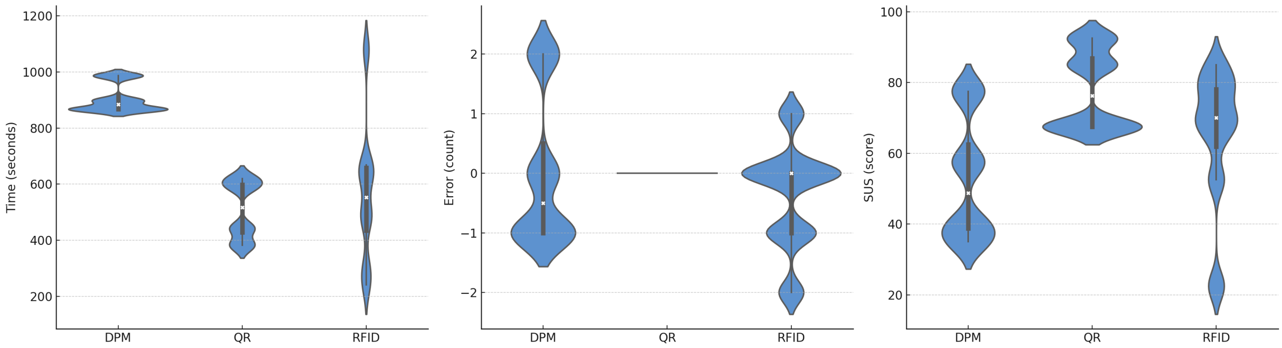

Figure 3: Violin plots of time (seconds), error rates (count), and SUS (score) for absolute values of Study 2 (n_{DPM}=4, n_{QR}=4, n_{RFID}=8).

in an uncontrolled environment versus a controlled setting.

The Impact of Data Carrier Digitization

The results indicate that higher digitization of data carriers improves reading efficiency, but the relationship is not consistent across studies. In Study 1, performance followed a clear hierarchy based on digitization, with DPM < QR < NFC, where NFC had the greatest time advantage (-55%) over DPM, followed by QR (-47%). In Study 2, however, the order shifted to DPM < RFID < QR, with RFID performing better than DPM by -37%, which is less than the QR code relative performance gain of -44% over DPM. While QR exhibited a similar advantage in both studies, the RFID in Study 2 resulted in a smaller relative improvement compared to NFC chips in Study 1.

These results also highlight a discrepancy between expected and observed performance for RFID. From a technical standpoint, RFID supports longer read ranges then NFC, multi-tag scanning, and automated data retrieval (Bottani et al., 2024). However, in Study 2, RFID did not surpass QR codes in reading efficiency and showed higher time variability, as seen in Figure 3. Although RFID had the lowest error count in Study 2, making it the most accurate system, its time performance suggests that practical usability factors influenced the results. This suggests that while higher digitization levels might improve tracking efficiency, usability remains a key factor in real-world applications, a topic further explored in the next subsection on SUS scores and user experience.

The Impact of an Uncontrolled Environment

The second research question examines how uncontrolled conditions affect the usability of data carriers in CCSCs. Study 1 by Byers et al. (2024a) tested DPM, QR, and NFC in a controlled environment, while the current Study 2 investigated DPM, QR, and RFID in an uncontrolled environment.

The SUS results show that in both studies, participants reported consistently high usability for QR. RFID was rated lower relative to QR in Study 2 than NFC was relative to QR in Study 1. DPM remained the least usable, with slightly higher score in Study 2. There are two possible explanations for this outcome. First, QR codes may indeed be better suited to uncontrolled environments due to their intuitive visual representation, which allows participants to quickly locate and scan the codes without additional equipment. In contrast, while RFID offers contactless identification, fast data-reading and multi-tag scanning, it requires a specific handheld reader. Secondly, as the storage space in the experiment was located in a basement, RFID reading may have been disrupted by surrounding material interference (Lemieszewski et al., 2024), further impacting its efficiency. External factors may have also influenced QR performance. In both studies, QR code reading times depended on the user's internet connection, since scanning directed to an online material passport. Variations in network availability and loading times could have introduced additional delays that were not inherently linked to the QR technology itself. Overall, these results confirm that uncontrolled conditions, which better simulate real-world CCSC scenarios, present additional challenges for the performance of data carriers (Thirumal et al., 2024). The observed differences in efficiency and SUS scores may not be solely attributable to the technology itself, but rather a combination of environmental and contextual factors affecting performance, all of which indicates the need for further in-depth studies.

Limitations and Future Research

One key limitation of this study is the small sample size due to the study's exploratory nature. This limits the robustness of the findings and increases susceptibility to outliers, necessitating cautious interpretation of the results. To strengthen the reliability and generalizability of the findings, future research should incorporate larger datasets. Additionally, further experiments should be conducted across diverse real-world settings to better capture variability in CCSC applications.

Marginal discrepancies between NFC performance in controlled environments and RFID performance in uncontrolled environments highlight the need for further studies to compare RFID and NFC under the same conditions, whether in a controlled, uncontrolled, or both environments.

Furthermore, the involvement of key stakeholders across Circular Construction Supply Chains (CCSCs) is critical for validating the practical applicability of these technologies. Conducting field studies in collaboration with industry actors — such as demolition contractors, material resellers, and reuse-focused designers — will provide valuable insights into real-world challenges, enabling the optimization of data carriers for broader implementation and long-term reliability.

Conclusions

Following the previous study conducted by Byers et al. (2024a) under controlled conditions, this study investigated the usability, time, and errors of RFID, QR, and DPM data carriers in a quasi-realistic CCSC setting. It explored two core research questions: (1) whether increasing data carrier digitization (RFID and QR) improves reading efficiency compared to DPM, and (2) how performance differs under uncontrolled, real-world-like conditions.

The findings show that higher data carrier digitization led to improved reading efficiency. In this study, RFID did not outperform QR. This result was likely due to usability challenges and environmental factors, in addition to uncontrolled conditions that influenced system performance. RFID in Study 2 showed lower performance than NFC in Study 1, which highlights the need for further research comparing both technologies under matched conditions and evaluating real-world CCSC applicability. These results point to the promising potential of digital data carriers, while also underscoring the importance of context-aware implementation.

As an exploratory study, this work provides an important first step toward understanding the real-world performance of RFID in CCSCs. While the sample size and differing experimental designs limit direct statistical comparisons between studies, the observed trends offer valuable early insights that can inform larger-scale investigations. While the two studies used different experimental designs — with the study by Byers et al. (2024a) conducted under controlled conditions — direct comparison of absolute values is limited; however, their relative performance differences remain indicative. To our knowledge, this is the first experimental evaluation of RFID in a quasi-realistic CCSC context. The observed performance patterns suggest that assumptions about RFID's efficiency must be tested against its intended use in practical environments, reinforcing the need for further validation of its operational potential.

The contribution of this study lies in its empirical comparison of RFID, QR, and DPM in a quasi-realistic CCSC setting and the practical considerations for future implementations that resulted. More broadly, the study underscores the necessity of testing track-and-trace solutions in environments that reflect their intended applications. This step ensures that deployment decisions are informed by real-world constraints. Although the current findings are preliminary, they provide a strong foundation for advancing data carrier technologies in circular construction. Building upon these results can enable broader adoption and support the scalability of data-driven reuse within the architecture, engineering, and construction industry.

To fully explore the potential of RFID and other technologies in CCSCs, future research should pursue larger-scale studies, direct comparisons between RFID and NFC, trials in varied CCSC environments, and iterative testing over time. These early findings highlight a promising path forward for identifying effective, scalable solutions for material tracking and tracing in circular construction practices.

Acknowledgments

The authors would like to thank the students of the course Digital Transformation for Circular Construction and members of the Chair for Circular Engineering for Architecture at ETH Zurich for their participation. In addition, the authors would like to thank Dr. Jennifer Bartmess and Dr. Roxanne Goldberg for their invaluable contributions to this work in editing and content refinement. Lastly, the authors are appreciative to the representatives from Balluf, Switzerland for their engagement, interest, and provided materials for the research.

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

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

References

Bottani, E., Correale, S., Rizzi, A., Stefanini, R., and Vezzani, L. (2024). How RFID technology enables the supply chain and retail 4.0: A survey with Italian stakeholders. International Journal of RF Technologies: Research and Applications, 14(2):125–150.

Brooke, J. (1995). SUS: A quick and dirty usability scale. Usability Eval. Ind., 189.

Byers, B., Stengele, K., and De Wolf, C. (2024a). Data Carriers for Product Data in Circular Construction Supply Chains: A Quantitative Analysis.

Byers, B. S., Raghu, D., Olumo, A., De Wolf, C., and Haas, C. (2024b). From research to practice: A review on technologies for addressing the information gap for building material reuse in circular construction. Sustainable Production and Consumption, 45:177–191.

Gao, M. Y., Han, J., Yang, Y., Tiong, R. L. K., Zhao, C., and Han, C. (2024). BIM-Based and IoT-Driven Smart Tracking for Precast Construction Dynamic Scheduling. Journal of Construction Engineering and Management, 150(9):04024117.

Lemieszewski, ., Baraniecki, J., and Prochacki, S. (2024). Optimization of RFID Attack Detection using a Received Signal Strength Indication Comparison Method. Procedia Computer Science, 246:4142–4151.

Thirumal, S., Udawatta, N., Karunasena, G., and Al-Ameri, R. (2024). Barriers to Adopting Digital Technologies to Implement Circular Economy Practices in the Construction Industry: A Systematic Literature Review. Sustainability, 16(8):3185. Number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

United Nations Environment Programme (2024). 2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector. United Nations Environment Programme.

Vhatkar, K. N. and Bhole, G. P. (2010). Internal Location Based System for Mobile Devices Using Passive RFID. arXiv:1009.3448 [cs].

Wijewickrama, M., Rameezdeen, R., and Chileshe, N. (2021). Information brokerage for circular economy in the construction industry: A systematic literature review. Journal of Cleaner Production, 313:127938.

Xue, F., Chen, K., Lu, W., Niu, Y., and Huang, G. Q. (2018). Linking radio-frequency identification to Building Information Modeling: Status quo, development trajectory and guidelines for practitioners. Automation in Construction, 93:241–251.

Yang, S.-S., Jang, Y.-H., Park, M.-H., Park, S.-C., and Kim, H.-J. (2021). Design and Implementation of Active Access Control System by Using NFC-based EAP-AKA Protocol. Wireless Personal Communications, 118(4):2487–2503.

Çetin, S., Raghu, D., Honic, M., Straub, A., and Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. Sustainable Production and Consumption, 40:422–437.