INTERNATIONAL JOURNAL OF SUSTAINABLE ENERGY
2024, VOL. 43, NO. 1, 2421281
https://doi.org/10.1080/14786451.2024.2421281

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Patterns and trends in the use of RFID within the construction industry and Digital Twin architecture: a Latent Semantic Analysis

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ABSTRACT
RFID technology is becoming increasingly popular in various industries due to its simplicity, affordability, and adaptability. However, its integration into the construction industry, particularly within the Digital Twin framework, remains limited. This study reviews current research and case studies on RFID in construction, focusing on its potential combination with Digital Twins. It examines the integration of RFID with BIM, sensors and other techniques to monitor building conditions. Using Latent Semantic Analysis, the study identifies key trends and patterns in the literature, revealing a predominant focus on the standalone use of RFID for localisation and tracking, with limited integration into other technologies. The findings highlight persistent barriers to wider adoption and underscore the need for further research to overcome these challenges.

ARTICLE HISTORY
Received 3 August 2024
Accepted 21 October 2024

KEYWORDS
RFID; Construction industry; Digital Twin; Building Information Modeling; Latent Semantic Analysis

1. Introduction

The construction industry attracts more new technologies each year. Although the level of digitalisation is still lower than in other industries, significant progress has been made with the widespread use of Building Information Modeling (BIM) and Digital Twins of buildings, as well as related technologies to support them (Anumba, Baugh, and Khalfan 2002; Asgari and Rahimian 2017). Considering that the Digital Twin architecture actively uses IoT and data collection devices to ensure a sufficient level of synchronisation between physical and digital environments, more research is devoted to exploring different combinations of sensors, Radio Frequency Identification technology (RFID) and blockchain to achieve a higher level of automation in construction tasks (Bakhshi et al. 2024; Jiang et al. 2023; Khan, Biplob, and Nemai 2024).

According to the report 'Future of Construction' (Robinson, Leonard, and Whittington 2021), the construction sector is the engine of global economic growth and in the coming decades, the growth rate of the construction industry will be higher than that of manufacturing or services, driven by the population, emigration and increasing working age. In this context, it is crucial to explore existing technologies that can accelerate the process of digitisation and automation in construction while being compatible with the technologies currently in use. RFID is not a new technology and has been around for decades, but it remains a promising area of research as new application scenarios continue to emerge. Although RFID is partially used for some tasks in construction, the technology is still not widely adopted in the industry, and its potential application to a broader range of tasks has not been sufficiently explored.

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According to the Eurostat report ‘Use of the Internet of Things in enterprises’, less than 30% of companies in the construction sector have adopted IoT, including RFID, in their processes. Moreover, it is mostly used by large companies (36%) and only 15% and 24% by small and medium-sized enterprises, respectively (Use of Internet of Things in Enterprises 2022). Many studies continue to highlight existing barriers to RFID adoption (Kineber et al. 2023; Thirumal et al. 2024; Waqar et al. 2023). For example, Waqar et al. (2023) identified key barriers to RFID implementation in small construction projects, including technical, cultural, privacy and resource challenges. The study emphasised the need for additional training, operational support, and compatibility of RFID systems. Nevertheless, the studies acknowledge the strong potential of RFID, particularly in its passive configuration, to be applied across a range of construction tasks and project scales.

Marketing reports (RFID market size, share, growth, trends 2023; RFID market size, share, statistic, and industry growth analysis 2023) predict that the RFID market will grow at a CAGR of 11.68% over the period 2024–2029. The Asia-Pacific region is expected to be the fastest-growing market. In terms of industry distribution, logistics, and transportation remain major areas of RFID implementation, particularly in the retail segment. Key companies operating in the RFID market include Zebra Technologies Corp. (USA), Alien Technology (USA), Avery Dennison Corporation (USA), Invengo Technology Pte Ltd. (China), and CAEN RFID S.r.L (Italy). The reports also highlight the potential for RFID utilisation in the construction industry, suggesting that the growth rate of the technology will lead to significant advances and extend the variety of applications.

Although using RFID in construction has been extensively studied in academic publications, most research focuses on localisation, tracking and supply chain management. Only a limited number of studies address the integration of RFID into the Digital Twin architecture. Given the importance of Digital Twin maintenance and technologies that ensure geometrical model accuracy, such as laser scanning and photogrammetry, there is a clear need for further research to bridge this gap. Therefore, the primary research question to be addressed is how RFID technology can be integrated into the Digital Twin architecture, considering the existing theoretical and experimental knowledge in the domain. Given the limitations of RFID in terms of measurement accuracy, which affects the range of tasks it can perform, a deeper analysis of current publications and case studies is needed. Despite the challenges in implementing RFID, its ease of use and rapid advancement across various industries make it a strong candidate for wider adoption in construction and a promising solution for enhancing existing technologies.

This study aims to provide a comprehensive review, identifying patterns and trends in the use of RFID based on existing literature, particularly when RFID is combined with the most advanced technologies that are becoming more widely used in construction. Simultaneously, we aim to identify opportunities for broader adoption by exploring relevant case studies and how the use of RFID for specific tasks can be scaled up, highlighting the uniqueness and novelty of our research.

The paper is structured as follows: the background section provides the main principles and characteristics of RFID technology. The materials and methods section introduces the Latent Semantic Analysis (LSA) methodology, outlining the dataset preparation and feature extraction for textual data. The results and discussion section presents the LSA outcomes, content analysis of the dataset and identifies the central ideas in the publications. Finally, the study concludes with a discussion of critical issues, implementational barriers, and suggestions for future research.

2. Background

RFID technology has a rich history rooted in the fundamental works of Faraday, Maxwell and Hertz on electromagnetic energy. The concept of RFID began to form during the Second World War with advances in radio frequency communications and radar. A landmark paper by Harry Stockman entitled ‘Communications by Means of Reflected Power’ (published in 1948) is often considered a key moment in the development of RFID technology. For nearly two decades after Stockman’s work, the precursors of RFID were actively explored by researchers. Significant progress was made in the 1970s, culminating in the introduction of the first commercially available RFID systems in the 1980s. The 1990s marked a turning point as RFID technology began to enter mainstream business and technology sectors. Notable developments during this period included Texas Instruments' TIRIS system and the involvement of major companies such as Philips and Bosch. Advances in materials and semiconductor technology from companies such as IBM and Intel helped make low-cost RFID tags possible. By the early 2000s, RFID technology was increasingly adopted by major retailers and supply chain companies, including Wal-Mart. In 2006, RFID was formally regulated by the International Organization for Standardization (ISO), further supporting its expansion across industries (Michálek and Juraj 2008). According to a study by Duan and Cao (2020), the initial idea of using RFID in construction was first proposed in 1995, followed by the first implementation attempt in 2003. Studies on the subject have been ongoing for almost twenty years, but significant progress has been made since 2010, particularly with the integration of RFID and regular sensors.

A standard RFID system consists of three main key components: an RFID tag (transponder), a reader (interrogator), and the back-end system to support data transmission and communication between the reader and tags (Duan and Cao 2020; Xue et al. 2018). The reader communicates with the tags via an antenna using electromagnetic waves. In a passive configuration, the reader provides the energy necessary to activate the tag. This passive configuration allows systems to be designed with minimal maintenance requirements and operate for long periods without the risk of power loss or depletion. Considering the dynamically changing nature of the construction environment, this feature of RFID makes it particularly attractive, especially in hazardous or remote locations where the maintenance of regular sensors can be a challenge. The battery-powered RFID systems, commonly referred to as active systems, can be used in building maintenance or construction applications, such as Structural Health Monitoring (SHM), damage detection, or indoor environmental assessment as they operate similarly to regular sensors (Lisowski et al. 2016). The main components RFID system, operating ranges, and detection mechanisms are illustrated in Figure 1.

An RFID tag carries a distinctive identifier (ID) and other relevant information about the object of interest such as classification, material composition, physical dimensions, storage location, manufacturing source, delivery timestamp, and other details. Tags are designed to use energy from a battery (active tags) or electromagnetic induction (passive tags). Passive tags are generally smaller and less expensive, but they have a shorter communication range. Semi-passive or battery-assisted

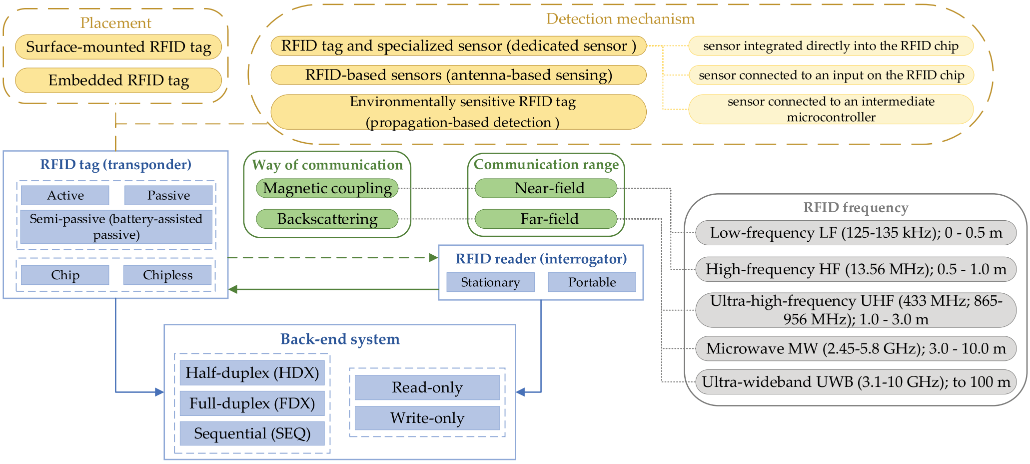

Figure 1. Main components of the RFID system.

tags are essentially passive tags that receive additional power from an external battery that increases the tag's capabilities and extends its reading range. For information storage, conventional RFID tags rely on microelectronic chips. Meanwhile, the chipless tags encode information directly onto the tag material eliminating the need for the chip (Le Breton et al. 2022). In terms of tag data carriers, RFID tags fall into two main categories: read-only and read-write. The read-only tag transmits its predefined information (e.g. tag ID), typically encoded during tag manufacture. On the other hand, the read-write tags support writable memory, allowing data to be recorded (Duan and Cao 2020).

A reader is a two-way radio transceiver that plays a critical role in the RFID system. Its primary function is to decode the signals emitted by tags (Duan and Cao 2020). Information stored on tags can be collected using stationary or portable readers. Stationary readers are capable of continuously interrogating tags located within their designated reading range. However, the use of fixed readers requires the installation and maintenance of a permanent infrastructure. Additionally, each stationary reader can only effectively cover a limited area. Portable readers, on the other hand, offer greater flexibility. These types of readers can be moved as required to scan large areas. This mobility can be achieved by manual handling or by attaching the reader to a vehicle, robot, or Unmanned Aerial Vehicle (UAV) (Le Breton et al. 2022).

The back-end system serves as a hub for storing and processing information. RFID systems can be classified into three types according to the method of information transmission: half-duplex (HDX), full-duplex (FDX), and sequential (SEQ). An RFID system can operate over a range of bandwidths, from narrowband to ultra-wideband UWB. Early RFID systems consisted mainly of short-range devices that relied on magnetic coupling between the reader and transponder. The evolution of technology led to the creation of long-range systems, driving the adoption of UHF RFID as the most often used solution. Currently, passive UHF RFID tags allow reading ranges of up to 10 metres while retaining the benefits of battery-free solutions. However, the powering of more long-range systems remains a challenge (Le Breton et al. 2022; Lisowski et al. 2016). Based on the defined communication range, RFID technology can be divided into two main types: near-field and far-field. The near-field RFID systems work based on magnetic induction. The far-field RFID uses electromagnetic waves to establish communication by using the backscatter technique. In this approach, the dipole antenna on the tag is configured to absorb specific frequency electromagnetic waves emitted by the reader. When the antenna impedance is high the tag can reflect and scatter the electromagnetic waves back to the reader (Duan and Cao 2020).

In summary, RFID technology can offer many benefits, including hands-free operation and resistance to harsh environments. RFID tags are compact, corrosion-resistant and flexible, making them a good solution for a variety of applications. Depending on the configuration, they have a read range that is acceptable for a broad range of construction tasks. In addition, multiple RFID tags can be read simultaneously, increasing the number of possible uses.

3. Materials and methods

A manual review of publications within a specific domain is a well-established approach. However, it has limitations, including reviewing a limited number of articles, a tendency to focus on more cited papers, subjectivity in the interpretation of results, and potential gaps in fully representing patterns in the field. To address these drawbacks, the frequency and occurrence of themes can be effectively assessed by semantically grouping keywords using techniques such as Latent Semantic Analysis (LSA). LSA is a mathematical and statistical technique used to identify latent concepts within textual data at a semantic level. It uses a set of algorithms to transform unstructured text into structured data objects and analyses these data objects to identify underlying patterns. It operates as an unsupervised text mining approach, using Singular Value Decomposition (SVD) to create a low-dimensional space to discover relationships, reveal topics, and compare terms and documents (Sehra, Singh, and Rai 2017; Wagire, Rathore, and Jain 2019; Yalcinkaya and Singh 2015). To reduce subjectivity and avoid duplication or overlap with existing studies, LSA was chosen as the main method of dataset analysis. The dataset was prepared using the PRISMA methodology to ensure traceability and replicability of results. The step-by-step formation of the dataset is shown in Figure 2.

The first stage in preparing the dataset is to select the publications to be analyzed. The procedure for publication selection is described below:

- Inclusion criteria
  - Peer-reviewed articles published between 2013–2023 years.
  - Articles that explicitly discuss RFID technology and use cases of application RFID in construction, Building Information Modelling, and Digital Twins.
  - Studies that provide insights into the application of RFID in combination with laser scanning, photogrammetry, and sensors.
- Exclusion criteria
  - Non-peer-reviewed publications, grey literature, and pre-published works.
  - Articles not written in English.
  - Studies that do not directly address the use of RFID in the construction industry or focus on other applications.
- Rationale for database selection
  - Scopus is a well-known database with wide coverage of scientific literature, including engineering and technical sciences relevant to the aim of this paper. The database consists of peer-reviewed studies, ensuring that the literature used is credible and of high quality. The Scopus subject areas of engineering, computer science, physics, mathematics, energy, and environmental sciences were used for this study.
  - Web of Science covers a wide range of high-impact journals and peer-reviewed publications. For this research, the following Web of Science categories were used: Civil Engineering, Building Construction, Earth Sciences, and Multidisciplinary.

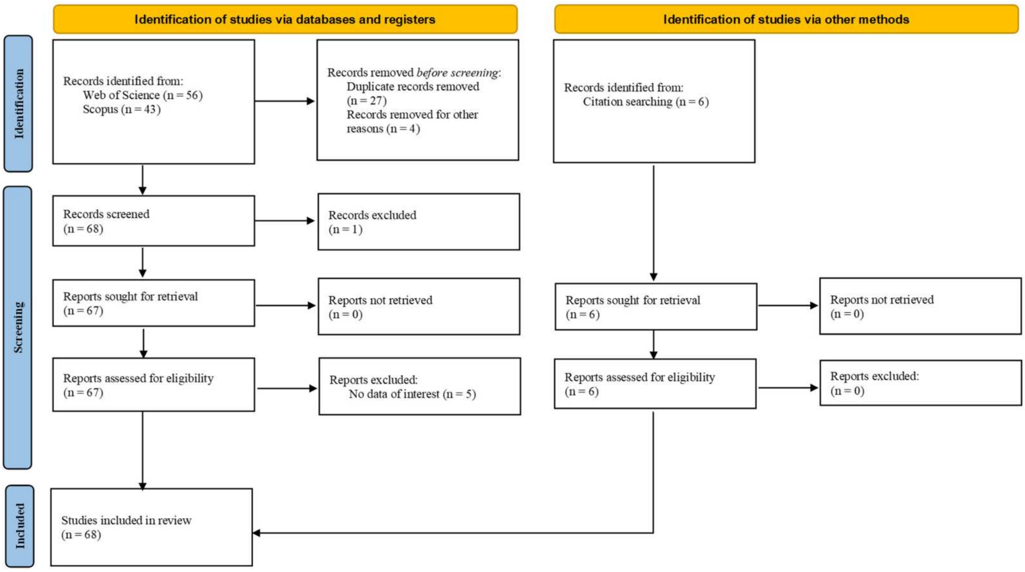

Figure 2. PRISMA flow chart for preparing the dataset.

The keywords used to identify and collect relevant publications covering RFID, construction, and Digital Twin are shown in Table 1. At the final stage, a sample of 68 articles was formed to analyze publication content in detail.

In the next stage, abstracts and keywords were extracted from the dataset. Co-occurrence keyword analysis was applied and the 118 terms most frequently occurring were used to build a co-occurrence keyword network as shown in Figure 3. In the science mapping approach, the node or link size reflects the term's importance or influence. Therefore, the larger the node, the greater the influence or significance of the keyword (Nwaogu et al. 2023). The keyword co-occurrence network also shows that there is no direct link between the keywords 'RFID' and 'Digital Twin' and that 'BIM' is used as a proxy to link the concepts. Nevertheless, there is a strong link between 'Digital Twin' and 'IoT', which also often includes RFID technology.

Further, the following steps and parameters of the text-mining procedures were utilised. The first step was to apply the feature extraction procedure to the dataset. The derived features, often referred to as tokens, are commonly used in document classification methods. In this case, terms with a frequency of less than 5% in all abstracts and terms appearing less than 5 times in all abstracts are removed and not present in the generated document-term matrix. The word cloud represents the frequency of tokens present in all abstracts as shown in Figure 4. As a result, a document-term correlation matrix was created, and 340 tokens were extracted from the dataset. The feature extraction parameters that have been applied are as follows:

- abstracts were tokenised using the bag-of-words representation model;
- tokens were converted to lowercase letters;
- minimum frequency of the term – 5;
- sparsity threshold – 0,95;
- punctuation, numbers, and English stopwords were removed.

At the next stage, the generated document-term matrix 68 × 340, describing the occurrence of a group of terms in documents, was used as input to the LSA. The following parameters were set for analysis:

- the number of topics was reduced to 3;
- to perform the classification in the newly created semantic space, we applied hard clustering, where each term element (token) can belong to only one topic to represent a class;
- the number of terms in a topic was estimated to be 15;
- the number of closest terms was estimated to be 5.

The results of the LSA are presented in Tables 2–4. Table 2 provides an overview of the total number of terms and documents categorised by topic. Table 3 focuses on the eigenvalues, mathematical entities that correspond to the importance of each topic. To assess the quality of the dimensional reduction from the original N dimensions (initially 340 terms in the dataset) to a reduced set of dimensions (specifically 15 dimensions in our analysis), we measure the cumulative percentage of variance. The cumulative variance provides information on the relevance of the identified themes. A higher cumulative variance indicates a better approximation achieved by the truncated SVD. In our case, the total cumulative variance was approximately 40% of the original matrix

Table 1. Keywords used to identify and collect relevant publications.

RFID	(AND) Construction	(AND) Digital Twin
'Radio Frequency Identification', 'RFID Technology'	'Building Information Model', 'Building Information Modelling', 'BIM', 'Construct*', 'Construction industry', 'AEC'	'Digital Twin*', 'Twinning'

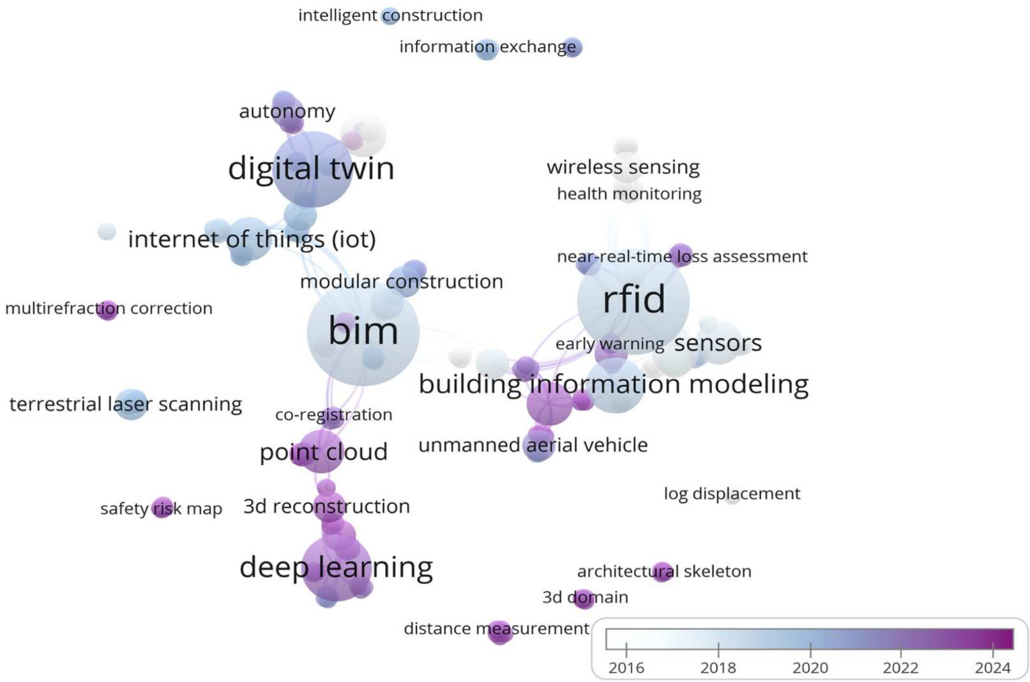

Figure 3. Keyword co-occurrence network.

which can be attributed to the limited data sample within the dataset, as well as the fragmentation and weak links between the analyzed articles. Table 4 compiles lists of the main terms associated with each of the identified themes. These terms are arranged in descending order of importance within their respective themes. To visually represent the strength of the associations between pairs of terms, we use a correlation graph or a term-to-term correlation matrix as shown in Figure 5. This type of representation allows for the assessment of similarity, measured by cosine similarity, within the newly constructed semantic space. Cosine similarity facilitates the comparison of terms with different frequencies of use, producing similarity values between 0 and 1, where 1 represents perfect similarity. The terms are presented in the order corresponding to the identified topic classes or clusters.

Furthermore, based on the analysis of the keywords and their clusters, as well as the results of the LSA, three main thematic categories within the dataset, along with corresponding subtopics, have been identified and designated for subsequent detailed analysis as shown in Table 5.

To sum up this section, it is important to acknowledge the limitations of the chosen approach:

(1) Limited database search: our search was limited to only two databases, which may have resulted in missing relevant publications.
(2) Methodological variability: different search methods and eligibility criteria could produce different results for the final dataset of publications.
(3) Keyword selection: despite efforts to select relevant articles, some keywords may not have been included in the literature search or may not have met the eligibility criteria.
(4) Use of abstracts only: we relied only on the abstracts of the publications, which could be considered a limitation as it excludes the richness of information found in the full texts. However, it should be noted that the entities derived from the full text of the articles could add noise and irrelevant data, making computational analysis more difficult (Yalcinkaya and Singh 2015).

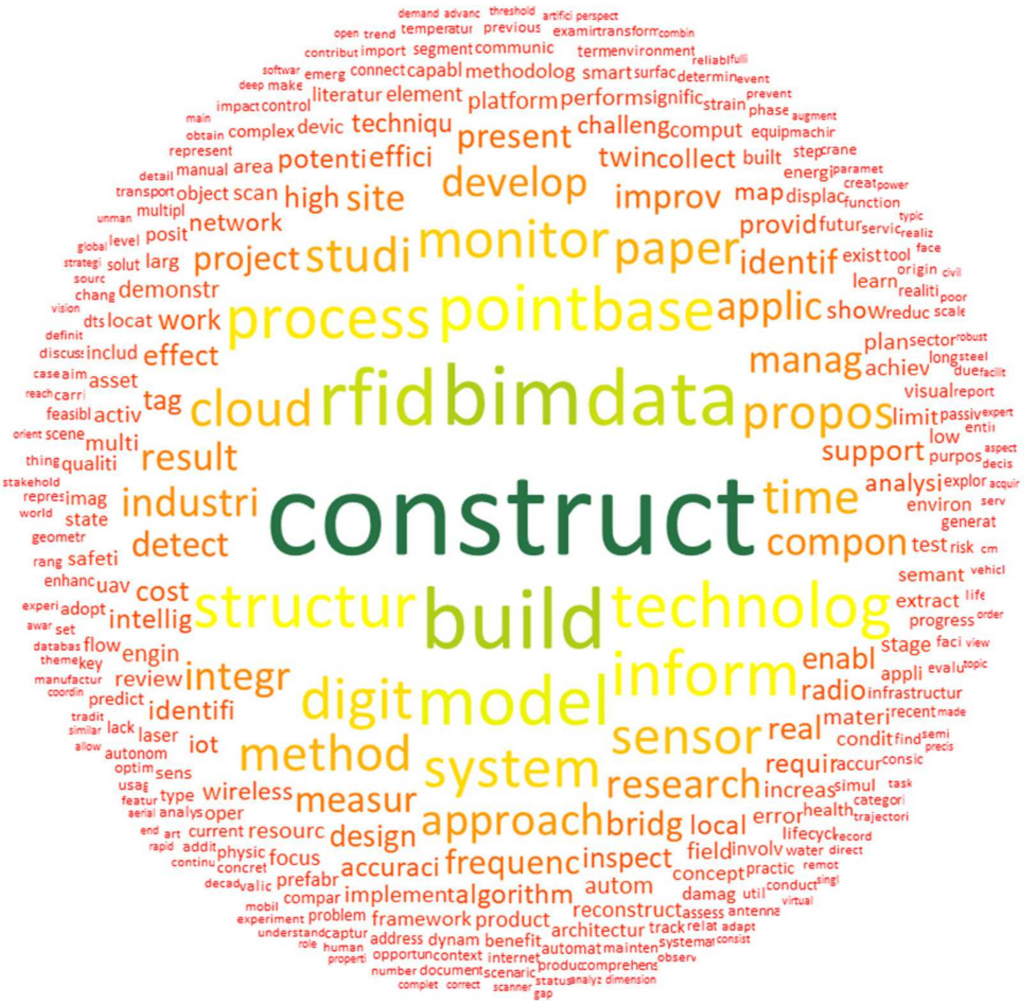

Figure 4. Word cloud of tokens in the dataset.

Table 2. Summary table of LSA results.

	Topic1	Topic2	Topic3
Number of terms/topics	269	49	22
Number of documents/topics	59	3	6

Table 3. Eigenvalues.

Parameter	Topic1	Topic2	Topic3
Eigenvalue	55.900	31.279	27.534
Variability (%)	22.539	7.057	5.468
Cumulative %	22.539	29.596	35.064

Table 4. Three topic-based loading tokens.

Topic No	Terms (tokens)
T3.1	construct, build, bim, data, technolog, process, rfid, inform, model, base, digit, structur, system, time, approach
T3.2	bridg, measur, smart, detect, sector, accuraci, algorithm, techniqu, map, scan, local, imag, condit, reconstruct, uav
T3.3	point, cloud, method, tag, represent, captur, geometr, displac, segment, automat, sens, status, passiv, trend, expert

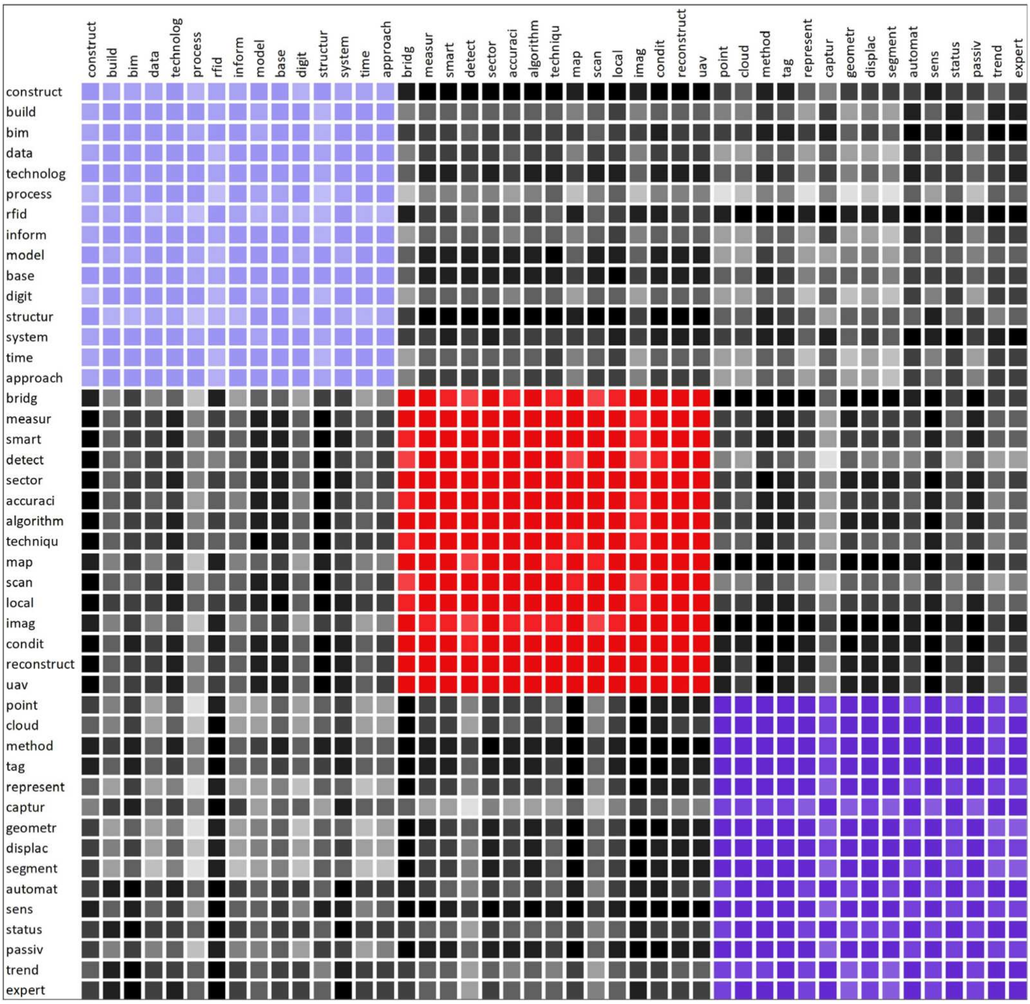

Figure 5. Term-term correlation matrix.

Table 5. LSA-based topic labels.

Topic No	Topic name	Subtopic No	Subtopic name
T3.1	Application of RFID for construction processes at different stages of the building life cycle	T3.1.1	Construction progress monitoring and quality inspection
		T3.1.2	The information management of prefabricated building components and construction materials
		T3.1.3	Safety management in construction
T3.2	Application of RFID for processes related to the monitoring of structures or buildings	T.3.2.1	RFID for Structural Health Monitoring
		T.3.2.2	RFID application for buildings in seismically active zones
		T.3.2.3	RFID application for crack detection and propagation
T3.3	Linking RFID and key digital technologies and equipment in construction	T3.3.1	RFID and Digital Twin/BIM
		T3.3.2	RFID and Laser scanning
		T3.3.3	RFID and Unmanned aerial vehicles (UAVs)
		T.3.3.4	RFID and sensors

4. Results and discussion

4.1. Application of RFID to construction processes at different stages of the building life cycle (T3.1)

4.1.1. Construction progress monitoring and quality inspection (T3.1.1.)

Traditionally, construction progress monitoring involves manual data collection through visual inspections. However, this method is error-prone and expensive due to the labour-intensive and time-consuming nature of recording field data. RFID can serve as a solution to this problem by making it easier to track and locate various resources such as machinery, equipment, and materials on a construction site. The study by Guven and Ergen (2021) proposes the use of RFID to monitor masonry works by tracking the movements of the hoist used to remove empty pallets of material from the installation floor. This tracking determines the start and end of the task, as well as the number of clean-up operations, to assess the progress of the construction activity.

The term ‘construction quality’ encompasses the criteria to ensure that construction projects are safe, profitable, environmentally friendly, and compliant with regulations, technical standards, and design documentation. To improve the construction quality inspection, RFID can be used to address issues related to localisation of building components, duplication of data, and inadequate feedback during rework and maintenance. An effective way of sharing construction quality information across multiple participants is through BIM-RFID integration, which will be discussed in more detail in the following sections. For example, Huo et al. (2023) proposed a system to improve construction quality through intelligent positional inspection. The system uses BIM software to facilitate real-time interaction between the BIM model and quality issue data linked to building components via RFID tags. Project members can use handheld RFID readers to identify and track problematic components, perform necessary maintenance, and provide visual information and feedback.

4.1.2. The information management of prefabricated building components and construction materials (T3.1.2.)

Managing prefabricated building components can be a challenging task, with aspects such as component properties, location, and use often overlooked or difficult to track. In this context, the combination of BIM and RFID can be used to provide visual representations of information about components, such as component description according to the IFC schema derived from the BIM model, and details such as type, manufacturer, location, and physical characteristics linked to the RFID tag. Ma, Jiang, and Shang (2019) developed a framework for the management of prefabricated concrete components using BIM-RFID integration. This approach consists of two phases. In the design phase, a new RFID family was created within the IFC schema. In the application phase, RFID devices connected to a PC terminal collect data from tags on the components. This data is then transferred to the BIM model, enabling the integration and visualisation of the component’s status information. Li et al. (2018) developed a platform that integrates BIM, RFID, and IoT sensors to support the assembly process of prefabricated construction. RFID readers collect component localisation data, which is then uploaded to the cloud for near real-time processing and analysis. For data visualisation, BIM and virtual reality technologies were used in this study.

The study by Iacovidou et al. (2021) proposed using a combination of BIM and RFID to create ‘component passports’ and promote the reuse of modular components. RFID technology facilitates the storage of and access to data on building elements throughout their lifecycle. The ‘component passports’ enable the evaluation of component properties and quality over time by storing data throughout the element lifecycle, including load history, physical condition, and any damage or refurbishment events. This information helps to track the performance of modular elements, enabling the reuse of high-quality components in new designs.

The creation of component and material passports is a promising strategy to promote circularity in construction. The European framework for sustainable buildings, known as Level(s), identifies resource-efficient and circular material life cycles as one of its six macro-objectives. This objective includes designing buildings for adaptability and renovation, as well as for deconstruction, reuse, and recycling, to facilitate the reuse of building materials and components in new construction projects and minimise construction waste. Implementing RFID technology to identify building components and materials might improve accountability for reusable materials and building elements, driving the digital transformation of the industry towards sustainability goals (Dodd, Donatello, and Cordella 2021). Similarly, the study by Tao et al. (2018) applied RFID to estimate carbon and greenhouse gas emissions of prefabricated components. Passive tags were used as identifiers for prefabricated building elements and were further linked to material usage ('material passport') to calculate greenhouse gas emissions.

4.1.3. Safety management in construction (T3.1.3.)

The construction industry is a high-risk sector with a large number of accidents and fatalities. Most construction site incidents can be attributed to deficiencies in worker training, work experience, knowledge, and safety awareness (Zhang et al. 2019). To improve the safety management for the construction site, Jin et al. (2020) propose a real-time intrusion monitoring system. The system utilises smart hardhats equipped with RFID tags, portable and stationary RFID readers, and a cloud-based management platform. This system enables safety managers to monitor workers in real-time and block their access to dangerous areas according to preestablished permission rules.

Another application of RFID in safety management involves the identification of hazardous zones within a construction site. Traditionally, two categories of methods have been used for this purpose: sensor-based and vision-based. Sensor-based methods encompass a range of technologies, including GPS, radars, RFID, UWB, Bluetooth, and others. These methods are characterised by their high penetration capabilities and compatibility with BIM and Digital Twins. Nonetheless, they do have certain limitations. For instance, sensors may require configuration adjustments based on the specific characteristics of the hazardous area, as they must withstand harsh environmental conditions such as high temperature, humidity, or vibrations. In addition, their performance is typically better suited for monitoring hazardous zones than identifying them. On the contrary, vision-based methods excel in identifying dangerous areas within a construction site by utilising image acquisition devices. However, employing a hybrid approach that combines vision-based methods with the dynamic data from IoT can significantly enhance the overall system performance (Lu et al. 2023).

Besides the primary applications mentioned above, content analysis of the dataset indicates that RFID has several additional uses in the construction industry:

- Inventory and labour management, building components supply chain, and scheduling risks. By installing RFID tags and readers on machinery, tools, and equipment, their movement can be monitored at predetermined locations. This can save time and costs on large construction projects, as assets can be remotely controlled, and alerts can be raised if deviations from the schedule are detected (Chen et al. 2020).
- Digitally enabled heritage conservation and building relocation process. RFID can provide a digital bridge between the physical elements of the building and the BIM model by enabling effective documentation of individual building elements in a digital environment during the disassembly process (Heesom et al. 2020).
- On-site landslide monitoring. The RFID-based monitoring system can be used on construction sites to ensure the stability of the land mass during excavation and to provide measurement data, with accuracy within a few centimetres (Charléty et al. 2022).

The analysis shows that despite the wide range of tasks RFID is used for, its primary functions remain identification and tracking. While there is a growing trend to integrate RFID with BIM models, the technology primarily serves as a bridge between the digital model and the physical environment. Therefore, the establishment of a general standard for the use of RFID technology in a BIM environment is crucial to encourage wider adoption.

4.2. Application of RFID for processes related to the monitoring of structures or buildings (T3.2)

4.2.1. RFID for Structural Health Monitoring (T.3.2.1.)

For structures with critical safety implications, the timely detection of cracks or deformations throughout their service life is important. Extending the useful life of structures depends on ensuring their health and safety before they reach a critical state. Over time, building structures can deteriorate due to fatigue, corrosion, crack propagation, natural and man-made disasters, unaccounted loads, etc. Damage detection involves comparing multiple structural components to detect any changes in material or geometric properties which helps to determine the presence, location, type, and extent of the damage and can be performed at the global or local level of the building (Lu et al. 2020; Wu et al. 2023).

Non-destructive evaluation (NDE) techniques are often used to determine the harshness and type of damage or deformation process. Although NDE has been proven to be effective for SHM, its implementation tends to be expensive (Fils, Jang, and Sherpa 2021). In the context of RFID application for these tasks, two approaches emerge. First, RFID acts as an ‘identifier’ for building structures in the SHM system. The second application is an RFID-based sensor network for structure monitoring, particularly its passive configuration due to easiness of maintenance. According to Duan and Cao (2020), common RFID-based sensors can be classified in terms of detection mechanism as follows:

- Integration of the RFID tag and the specialised sensor. In this approach, a specialised sensor is used to assess the status of a target object. The tag is designed to receive information from the sensor and then transmit signals to the reader. However, due to limitations associated with the power consumption of passive systems, this combination requires an external energy source.
- RFID-based sensors (without the use of specialised sensors). The tag itself acts as a sensor in conjunction with the structure being inspected. For example, sensors for crack detection.
- RFID tags with integrated environmentally sensitive materials. This strategy involves making tags with specific materials that respond to environmental stimuli. For example, sensors for vibration detection.

Based on the placement of the RFID sensor node it can be classified as follows (Duan and Cao 2020):

- RFID tags mounted on the surface of building components which applies to both new and existing structures.
- RFID tags embedded in components during manufacturing. This method allows continuous monitoring of component location and status. However, as most embedded tags are passive, their reading range is reduced.

In addition to potential obstacles in the construction environment and the distance between the RFID tag and reader, the material of the surface to which the tag is attached or integrated also affects its readability. For example, in the bridge’s SHM, water acts as a barrier, disrupting communication between tags and readers. To overcome this, a tag attached to underwater structures requires an antenna above the surface. Similarly, materials such as concrete or metal can interfere with communication, whereas materials such as wood or plastic do not affect the parameters of tags' readability (Duan and Cao 2020).

For strain measurements, the study by Shishir et al. (2017) investigated the creation of smart skin sensors based on passive chipless RFID tags. This has been achieved by using a folded patch antenna, which shifts its resonant frequency when subjected to strain or deformation. The change in frequency is detected and recorded by the reader and is used as a proxy to identify changes in strain. A similar approach was used in the study by Jayawardana, Liyanapathirana, and Zhu (2019), where semi-passive RFID tags were used as part of a wireless multi-sensor system to measure dynamic acceleration and strain in metallic structures.

Besides strain measurements, vibration is another parameter that is often important in SHM systems. Vibration measurements can be used to track the resonant frequency of structures or to identify transient vibrations that exceed a certain limit. Detecting transient vibrations requires continuous monitoring, which raises the issue of power consumption for the sensors used. However, for measuring robust vibrations, RFID-based sensors could be a suitable option. This is particularly relevant in the proximity of strong vibration sources or locations characterised by significant resonance factors (Le Breton et al. 2022).

The longevity of the sensing tags can be a significant challenge when SHM is provided over long periods, especially for tags that rely on battery backup. Currently, battery backup is commonly used to enable tags with advanced features, such as continuous monitoring or extended reading ranges. However, the reliance on batteries becomes problematic in locations where maintenance is difficult. According to Le Breton et al. (2022), one of the potential solutions is energy harvesting which involves converting minute amounts of ambient energy into a usable electrical form, potentially eliminating the need for traditional battery support.

Another aspect to be analyzed is the application of RFID in real-time scenarios. Lisowski et al. (2016) presented a wireless passive sensing platform designed for online damage detection and monitoring. The platform is based on HF RFID, where tags are integrated into the building structure to detect vibration and temperature. The tag data can be read by a handheld reader or, alternatively, by a device equipped with a Near Field Communication protocol. Moreover, the analyzed studies show that data collected from RFID-based sensors can be used as a source for the development of prognostic models for building deformations. For example, in the study by Neerukatti, Fard, and Chattopadhyay (2017), data collected from RFID was used as historical data for creating and calibrating a prognostic model for real-time damage prediction. Similarly, Fils, Jang, and Sherpa (2021) developed an ANN-based model for crack propagation in reinforced concrete structures using RFID-based crack sensors. The data collected included crack width, environmental factors (temperature), and the Received Signal Strength Indicator (RSSI). Using an ANN-based prediction model, the data captured was analyzed to improve the precision and reliability of the forecast.

4.2.2. RFID application for buildings in seismically active zones (T.3.2.2.)

Following natural hazard events, such as earthquakes, the assessment of structural conditions is often based on visual inspection. This process requires a high degree of precision and involves an accurate examination of all damaged structural and nonstructural elements, including assessing the extent of their damage and calculating the overall seismic impact on the building. However, the visual and manual approach is particularly time-consuming, labour-intensive, costly, and may be subjective depending on the inspector's competence. To address these challenges, a more efficient solution involves the use of automated inspection and processing of post-earthquake assessment information. SHM systems play a critical role in this context by providing sensor data that can facilitate real-time updates on structural conditions. When buildings are equipped with accelerometers or other types of sensors it is possible to apply dynamic response reconstruction methods that allow the estimation of unmeasured parameters, thus improving the overall accuracy of the assessment.

Additionally, post-earthquake inspections often require the removal of ornate components to examine building structures. To streamline this process, RFID-based strain sensors that contain a chip for data writing and storage can be used. When the sensor is attached to the surface of the element it can record the strain values under normal operating conditions and during earthquakes. These measurements serve as proxy metrics to determine the level of damage sustained by the component without the need to remove the structure finishings or decorative elements.

A study by Zhang and Bai (2015) presents an RFID-based wireless system for rapid structural health assessment. The system includes a breakage-triggered strain sensor that detects when strain exceeds a predetermined threshold, which is critical for ensuring that structural elements remain within safe strain limits and prevent overload risks. The breakage-triggered sensor uses RFID technology for wireless communication, allowing a portable reader to non-invasively scan structural conditions. Simultaneously, visualisation within the BIM model uses a tag ID for the element identification. A similar methodology for post-earthquake damage assessment was presented by You et al. (2022). Deformation sensors were used to detect strain deviations and passive RFID tags were attached to structural elements to enable structure identification without the need to remove non-structural parts or finishes. In this study, the use of RFID tags in combination with a conventional deformation sensor proved to be a more cost-effective solution than accelerometers with real-time functionality.

4.2.3. RFID application for crack detection and propagation (T.3.2.3.)

Traditionally, crack detection has relied on visual inspection and manual measurement. However, in recent years, there has been a rise in depth measurement techniques that are combined with automatic reconstruction processes. These methods are often supported by point-based or voxel-based representations and use machine learning algorithms to predict crack propagation. They can be broadly categorised into active and passive methods. Active methods include technologies such as infrared cameras, laser, and LiDAR scanners, and produce a point cloud as a result of data collection. On the other hand, passive techniques include methods such as structure from motion (SfM), simultaneous localisation and mapping (SLAM), and multiview stereo (MVS) and essentially provide the data for image-based modelling. However, when it comes to crack localisation and monitoring, sensor-based approaches remain the most robust solution (Wang and Gan 2023; Wang et al. 2020).

The wireless crack detection approach has significant potential for a wide range of applications, including the detection and monitoring of crack propagation in building elements under normal operating conditions or caused by building settlement or damage. RFID-based sensors offer several advantages for this application, including ease of installation, independence from a power source, and affordability, allowing for the deployment of as many nodes as needed. In addition, multiple sensors can be interrogated simultaneously, enabling tag arrays to provide a comprehensive view of crack characteristics and distribution when monitoring complex structures.

Pour-Ghaz et al. (2014) conducted a study focused on the implementation of an RFID-based system to detect and monitor cracks in concrete structures. The underlying principle involves the use of electrically conductive materials on the concrete surface, which allows the detection of cracks by monitoring changes in electrical resistance. Essentially, these conductive surface sensors stretch when the concrete substrate is under strain, and in the event of concrete cracking, the sensors also experience fractures, causing changes in their electrical resistance, which triggers a corresponding change in the response of the RFID tag. Martínez-Castro et al. (2019) introduced an approach to the detection of crack propagation on metallic surfaces using UHF RFID sensors. This method involves a comparison between the results of the backscatter-power-based damage indicator and the physical properties associated with progressive linear elastic fracture. Evaluation of the effectiveness of the sensor was based on two physical characteristics: vertical deformation and crack opening with single and multiple sensor setups. It should be noted that the feasibility of using sensor clusters, despite possible coupling effects, has been successfully demonstrated in this case study.

While the use of RFID-based SHM systems has shown considerable potential, particularly for crack detection and structural assessment, several challenges remain that limit their practical use. The case studies analyzed show that RFID offers advantages in terms of cost-effectiveness, ease of installation, and independence from power sources. However, the performance of RFID tags, particularly in harsh or complex environments such as seismic zones or underwater structures, often suffers from readability problems caused by interference from materials such as concrete, metal, or water. In addition, RFID systems still face limitations in providing real-time, high-resolution data compared to other sensing technologies such as accelerometers or LiDAR, which offer greater accuracy but at a higher cost. This creates a trade-off between affordability and accuracy that needs to be considered. For example, current applications of RFID in post-earthquake damage assessment demonstrate the potential for faster and more automated inspections but remain less robust than more established methods.

4.3. Linking RFID and key digital technologies and equipment in construction (T3.3)

BIM, Digital Twins, photogrammetry, laser scanning, and sensors are the leading technologies in today's construction landscape. Optimal results in construction projects can only be achieved through the strategic and harmonious integration of these technologies throughout the building's lifespan. For example, Edwards et al. (2023) introduced an automated process for identifying assets within 3D scan data and linking them to an asset management system ('auto-linking process') to improve asset maintenance. The method involves identifying asset locations (based on the attached RFID tag) within the corresponding 3D point cloud obtained by laser scanning and subsequently integrating these data into a Digital Twin-supported management system. In this study, RFID serves as a complementary resource for asset identification and positioning. The effectiveness of the process is further enhanced by the combination of the BIM model and Digital Twins architecture, which ensures the accuracy of the system.

4.3.1. RFID and Digital Twin / BIM (T3.3.1.)

Currently, BIM and Digital Twins are widely used in the construction industry, serving as a common environment for participants involved in construction projects at all stages of the life cycle (Agrawal, Fischer, and Singh 2022; Agrawal, Singh, and Fischer 2022; Boje et al. 2020; Hribernik et al. 2021; Singh 2016; Stark, Fresemann, and Lindow 2019; Wang et al. 2013). However, maintaining an up-to-date BIM model throughout the building's lifetime remains a significant challenge. Typically, this requires laborious manual surveys to collect data on building conditions and identify discrepancies with as-design BIM. The updating of the geometry of the building model currently relies on techniques such as image-based methods and laser scanning to capture point clouds (Yin, Lin, and Yeoh 2023). Changes to the structure can be identified by comparing the point cloud with the existing BIM model (Scan to BIM, Scan vs BIM approaches). However, the characteristics of point clouds, such as sparse and uneven density, unordered distribution, lack of mutual information, and large data volume, pose significant challenges to the interpretation and processing of raw point clouds. To date, tasks such as point cloud classification, object recognition, and geometry modelling still rely heavily on manual intervention, resulting in labour-intensive processes, especially for complex assets. To address this challenge, an increasing number of studies are exploring the application of deep learning methods to these tasks. However, the integration of machine learning for automated feature extraction from point clouds and semantic classification requires a significant amount of training data, which remains a major challenge in the field. Most research efforts aimed at automating the recognition and classification of objects within point clouds have been conducted using limited training datasets or synthetic data. Considering that building components have different structures, shapes, and sizes, even well-trained neural networks face difficulties in this regard (Chuang and Sung 2021; Chuang and Yang 2023).

In an RFID-enabled BIM environment, there is an improved level of identification and traceability of objects. Physical assets or building structures can be identified with up-to-date data and linked to BIM or Digital Twin architecture. According to Xue et al. (2018), considering the integration of BIM and RFID and its application in the built environment, the selection parameters for RFID can be summarised as follows:

- The UHF is the most widely used for this application as it offers acceptable reading ranges and fast data reading rates, meeting the need for timely data collection.
- UWB RFID systems are commonly used in indoor location scenarios. However, in general, its use is less common than that of UHF due to the significantly higher cost and technical maintenance challenges.
- Limited use of HF, LF, and MW systems. The low adoption of MW RFID can be attributed to their high cost, suboptimal readability, and susceptibility to environmental conditions. The lower adoption of the HF and LF systems could be due to their limited reading range and slower reading speed.
- Passive RFID systems are often chosen over active due to their lower cost and smaller size. However, active RFID has a distinct advantage in terms of a larger reading range.

According to a study by Xue et al. (2018), the following steps should be applied in the BIM and RFID integration:

(1) Firstly, to determine the parameters of the RFID (the frequency and type), IFC classes, and information storage architecture (local server or cloud-based) according to the life stage of the construction project.
(2) Secondly, to identify the RFID data encoding scheme and to install RFID hardware in the physical environment. As mentioned above, the installation of RFID tags depends on the target object, as tags can be embedded in building structures or attached to surfaces, as well as identifying the need for fixed or portable readers.
(3) Thirdly, to build an RFID-to-BIM gateway. After receiving data from the tags, the gateway will convert the information into the appropriate format and communicate with BIM to process and store the information collected.

Data plays a central role in Digital Twin systems, where synchronisation between the physical and digital environments requires timely data transfer, typically in real-time or near real-time. However, the simultaneous collection of large amounts of heterogeneous, multi-source data places a significant burden on network and computing resources. One of the key challenges in implementing Digital Twins is balancing the need to create a simplified but high-fidelity digital model while accurately capturing the complex behaviour of a building. A practical solution is to adopt a flexible, modular modelling strategy, which can be achieved through black-box modelling (using only data) or grey-box modelling (combining physical properties with data) (Liu et al. 2021). The integration of real-time sensor data into the Digital Twin architecture remains an area of active research. This challenge goes beyond data models, structures and interoperability to include the management of physical equipment and devices within the system. Given the widespread use of RFID technology in inventory management, there is clear potential for its implementation to support the management and compatibility of IoT devices within Digital Twin.

4.3.2. RFID and laser scanning (T3.3.2.)

To provide context, laser scanning involves a sequence of three essential steps: data acquisition, extraction of geometric information from a point cloud, and object modelling. Technology is categorised into three main types: terrestrial (TLS), mobile (MLS), and airborne laser scanning (ALS). These types are further differentiated by measurement principles, which include time-of-flight

(TOF) and amplitude-modulated continuous wave (AMCW). In a TOF scanner, distance is measured by emitting a pulse of light and then recording the time it takes for the pulse to reach the target and return. Conversely, an AMCW scanner emits a continuous wave with modulated amplitude and measures distance by analyzing the phase difference between the emitted and reflected waves. AMCW scanners offer higher measurement accuracy, making them particularly valuable for maintaining the fidelity of digital building models. To date, TLS is one of the most used survey equipment in the construction industry. Its static nature is well suited to the requirements of building surveys, ensuring high accuracy and suitability for capturing the complexities of building geometry (Han et al. 2023; Masood et al. 2020; Yang, Cheng, and Wang 2020; Yang et al. 2022).

The point cloud generated by laser scanning presents several challenges for subsequent processing, including a lack of structure and internal spatial relationships, inconsistent point density and quality, data redundancy, and noise. In addition, when scanning large, elongated objects using multiple scanner stations or mobile laser scanners, there is the potential for accruing drift error, in other words, systematic shift between scanned scenes (Keitaanniemi et al. 2023). Detecting a drift error is difficult without georeferencing and scaling the point cloud. To overcome this problem, landmarks or other control points with precisely defined coordinates, often provided by tacheometric measurements, are used to control the position of the point cloud. This approach also helps to align the point cloud with the reference BIM model and to define a common coordinate system. In this regard, RFID tags with predefined coordinates can be used as reference points to support the georeferencing and scaling of the point cloud, manage displacement issues when using mobile scanners and SLAM algorithms, and improve object recognition within the point cloud (Fotsing, Menadjou, and Bobda 2021; Grandio et al. 2023; Kim et al. 2023; Luo et al. 2023).

As studies show, the integration of laser scanning and RFID enables faster object recognition during the processing of point-cloud data beyond the limits of structural and non-structural components. For example, Valero, Adán, and Bosché (2016) present a 3D data processing algorithm using a combination of laser scanner and RFID which improves the creation of detailed semantic 3D models of indoor interiors, similar to the auto-link technique proposed by Edwards et al. (2023) for technical systems equipment. By attaching RFID tags to furniture or building elements, and scanning them simultaneously, the algorithm accesses discriminative geometric information in the scanned area. This information is used for object identification within the point cloud, leading to increased speed and accuracy in the modelling process. In general, the proposed approach effectively identifies and helps model the elements of indoor spaces, including openings, as well as typical furniture objects based on predefined links between RFID tags and indoor components where they were placed.

4.3.3. RFID and Unmanned aerial vehicles (T3.3.3.)

UAVs have become an integral part of the construction. Primarily, drones have been used for image data collection with subsequent 3D reconstruction of building models. Using commonly available digital cameras and SfM workflows, it is possible to create highly detailed 3D representations of buildings with an accuracy of up to a few centimetres. However, when it comes to processing photogrammetric data and image blocks, the challenges are very similar to those associated with laser scanning point clouds. It includes ensuring correct registration and transformation with the reference building model, the need to use control points with known coordinates, and object recognition and classification tasks. An exception is the application of deep learning methods, in particular convolutional neural networks (CNNs). Currently, CNNs offer good performance for object recognition and classification when applied to image data (Kaiser, Clemen, and Maas 2022; Lu et al. 2023).

By equipping a UAV with an RFID reader, a single drone can take on the role of numerous portable interrogators. This efficiency not only reduces operating costs but also facilitates deployment across large construction sites or building assets to manage many RFID tags simultaneously.

However, to ensure consistent readings, the UAV may need to be several metres away from the target which poses a challenge for obstacle avoidance. In general, this combination offers the added benefit of being able to read tags in a variety of environments, including dangerous or inaccessible areas of construction sites or high-risk facilities.

In the context of the integration of UAV and RFID, the use of passive tags offers several advantages such as low cost, compactness, and minimal maintenance requirements, which can ensure the utilisation of the system during all stages of the building life cycle. At the same time, active tags enable a larger reading range and higher power of the signal, which can be particularly useful in a construction site environment where many obstacles exist. As an example, the study by Won, Chi, and Park (2020) presented a platform for resource localisation and tracking by combining reader-equipped UAVs with active tags located on the construction site. Using active UHF tags and UAV placed reader, the platform collects RSSI data along with UAV motion information. Further, by incorporating a deep learning algorithm, the platform processes obtained data sets, resulting in improved accuracy of tag-to-location associations. However, it was shown that despite efforts to minimise interference with on-site activities by operating at different altitudes from 10 to 100 metres, potential obstructions of the construction environment, such as tower cranes, electrical poles, and wires, still affect the effectiveness of the proposed approach.

Other critical considerations are the Coverage Path Planning problem and using UAVs in environments where the GPS signal is weak or unavailable. Traditionally, the UWB used to provide location data to UAVs, along with the SLAM algorithm. However, considering the obstacle-rich nature and the dynamically changing conditions of construction sites, it is imperative to investigate alternative technologies, including RFID, to ensure an optimal and stable drone flight trajectory. Currently, there are both model-based and nonmodel-based approaches to optimising drone flight paths. In the model-based approach, where a known reference model such as BIM is available, RFID can be used as a supplementary tool to detect and locate structural elements or obstacles that obstruct the drone's flight trajectory. For non-model-based approaches, RFID can provide information for path calibration if its predefined coordinates are known (Gao et al. 2023; Ivić et al. 2023).

4.3.4. RFID and sensors (T.3.3.4.)

The construction industry has traditionally relied on various sensors such as strain, barometric, wind, temperature, humidity sensors, accelerometers, etc. (Liu and Bao 2023; Ravazzolo et al. 2015). The active wireless sensor is designed to transmit a sensing signal over a range of up to 100 metres. However, the need for an embedded battery poses a challenge in its maintenance. For simple tasks, such as indoor conditions monitoring, the use of RFID-based sensors provides a solution to this limitation. According to Seyis and Sönmez (2022), passive tags offer considerable advantages over regular sensors in several scenarios:

- more economically effective, especially in scenarios where a significant number of nodes are required.
- monitoring for objects that require small or flexible devices.
- long-term monitoring in difficult-to-access locations.
- green applications with a focus on minimising waste (batteries).
- loss-prone scenarios, as RFID tags are significantly cheaper than conventional sensors.

However, as a drawback, passive RFID-based sensors are limited in reading range, support only a few features, and also lack standardisation in sensing techniques. The studies highlight that reading range and accuracy remain the main concerns when it comes to deploying RFID (Khan, Biplob, and Nemai 2024; Kineber et al. 2023). Evidently, technological advances have steadily improved the drawbacks of passive tag configurations. However, it is crucial to carefully evaluate the use of passive tags for applications requiring high accuracy of data collection.

According to Le Breton et al. (2022), three main categories of RFID tags can be used in wireless sensing systems:

- Dedicated sensors, that can be divided into three groups: sensors integrated directly into the RFID chip, sensors connected to the RFID chip, and sensors connected to an intermediate microcontroller. Examples of dedicated sensors are temperature, displacement, or tilt measurement sensors. This type is often the most accurate but requires an additional power source.
- Antenna-based sensing is another approach to convert RFID tags into wireless sensors. Any change in the tag antenna's shape, substrate properties, or near-field region can change the antenna impedance. As an example, this type can be used for moisture, chemical, and temperature measurements, but is often less accurate than dedicated sensors.
- Propagation-based sensors measure the influence of the environment on the RFID signal to assess changes in the characteristics of the propagation channel. As an example, vibration RFID-based sensors.

When designing the architecture of an RFID sensing system it is important to consider that one or a few readers may communicate with a significant number of tags, also known as the many-to-one communication paradigm. Consequently, there is a potential for both false negative and false positive tag detections. False negative detection occurs when a tag is not detected within the sensing area and false positives when a tag is detected outside the intended sensing area. Factors that can lead to false negative detection include adverse material influences, collisions within the communication protocol, or interconnections. On the other hand, the causes of false positive detection include phenomena such as multipath effects, unrestricted antenna coverage, radiation pattern anomalies, etc. One of the strategies to overcome challenges related to multi-access communication is to use different traffic patterns. For example, tags can engage in periodic reporting based on a predefined schedule or adopt an event-driven reporting approach when the tag remains inactive most of the time and only transmits data during active periods triggered by specific events.

While RFID technology shows promise in construction, especially when integrated with BIM, Digital Twins and other technologies such as laser scanning, UAVs and sensors, the case studies analyzed show some critical limitations. Several case studies, including those by Edwards et al. (2023) and Xue et al. (2018), demonstrate successful small-scale applications of RFID in asset identification and management. However, there are challenges in scaling up these systems to larger projects, such as multi-phased construction sites or complex urban environments. Deploying RFID systems across large construction sites raises logistical issues, as the need for multiple fixed or mobile readers increases both investment and operational costs. The cost of installing RFID hardware, maintaining it and dealing with environmental interference makes it less attractive for large-scale deployment. Although RFID improves object recognition when combined with laser scanning or UAV-based photogrammetry, case studies show mixed results in terms of accuracy. For example, the method proposed by Valero, Adán, and Bosché (2016), which combines RFID and 3D laser scanning, shows promise in controlled indoor environments, but the approach may face difficulties when applied to more complex or dynamic environments, such as large construction sites. Another critical issue is the lack of standardisation of RFID systems, especially in the context of sensor integration. Different RFID technologies (e.g. UHF, HF, LF) have different performance characteristics, and there is no universally adopted workflow for their integration into BIM or Digital Twins, which creates significant interoperability issues.

4.4. Results of the content analysis of the dataset and limitations of the study

Based on the content analysis of publications, Table 6 summarises the main applications of RFID according to the distribution of subtopics and highly relevant papers in the theme.

Table 6. The main applications of RFID in topics.

Topic No	Topic name	Subtopic No	Subtopic name	Application of RFID	Highly relevant papers
T3.1	Application of RFID for construction processes at different stages of the building life cycle	T3.1.1	Construction progress monitoring and quality inspection	Localisation and positioning of building components, machinery, and equipment BIM and RFID integration	Guven and Ergen 2021; Huo et al. 2023
		T3.1.2	The information management of prefabricated building components and construction materials	Localisation and positioning of prefabricated components BIM and RFID integration Building component passport Building material passport	Ma, Jiang, and Shang 2019; Li et al. 2018; Iacovidou et al. 2021
		T3.1.3	Safety management in construction	Smart hardhats Monitoring of dangerous zones	Jin et al. 2020; Huo et al. 2023
T3.2	Application of RFID for processes related to the monitoring of structures or buildings	T.3.2.1	RFID for Structural Health Monitoring	RFID-based strain sensors RFID-based vibration sensors RFID-based temperature sensors	Shishir et al. 2017; Jayawardana, Liyanapathirana, and Zhu 2019; Le Breton et al. 2022; Lisowski et al. 2016
		T.3.2.2	RFID application for buildings in seismically active zones	RFID-based breakage-triggered strain sensor Localisation and positioning of structural elements	Zhang and Bai 2015; You et al. 2022
		T.3.2.3	RFID application for crack detection and propagation	RFID-based conductive surface sensors for concrete and metal structures	Pour-Ghaz et al. 2014; Martínez-Castro et al. 2019
T3.3	Linking RFID and key digital technologies and equipment in construction	T3.3.1	RFID and Digital Twin/ BIM	Object recognition in point cloud Localisation and positioning of building elements regarding the BIM model	Edwards et al. 2023; Xue et al. 2018
		T3.3.2	RFID and Laser scanning	Object recognition in point cloud	Valero, Adán, and Bosché 2016
		T3.3.3	RFID and Unmanned aerial vehicles (UAVs)	Resource localisation and tracking by reader-equipped UAV UAV's flight path calibration	Won, Chi, and Park 2020; Gao et al. 2023; Ivić et al. 2023
		T.3.3.4	RFID and sensors	Dedicated, antenna-based, and propagation-based RFID sensors	Charléty et al. 2022

Additionally, an analysis of the application of RFID in construction and Digital Twin architecture was carried out to identify strengths, weaknesses, and opportunities for further development as shown in Tables 7 and 8.

Table 7. An analysis of RFID application in the construction industry.

	Strengths	Weakness	Opportunities
Construction progress monitoring and quality inspection	Higher level of automation compared to visual or manual inspection Resource tracking RFID-BIM/Digital Twin integration Potential use of cloud technologies	Large number of RFID tags Reading range Loss of RFID tags Influence of environment on the stability of RFID Semi-automated data collection process	Extended system longevity through all building life cycle stages Improving construction project management and scheduling Workforce management
The management of building components and materials	Track the status and location of building components through all life cycle stages (from manufacture to demolition or reuse) Minimal maintenance requirements of the RFID system Potential use of cloud technologies	The complexity of the back-end system Loss of information Power consumption Interoperability issues Many-to-one communication issues	Supply chain management and logistics Building sustainability Inventory management
Safety management	Intelligent hard hats Preventing work in hazardous locations Automated authorised access to hazardous locations Hazardous equipment monitoring	Influence of construction environment on the stability of the RFID system Data privacy, confidentiality, and security issues	Improving safety management Workers' training and safety awareness
Structural health monitoring	Identification of RFID-tagged building components Monitoring of building components with RFID-based sensors Longevity and ease of maintenance of RFID-based SHM systems Real-time scenario applications	Sensitivity to structural material and environment Reading range The complexity of the system Information loss Power consumption Interoperability issues Data processing and accuracy	Post-Disaster Monitoring Crack detection and monitoring Structural simulation and prediction AI-based predictive models

To address the research question of how RFID technology can be integrated into the Digital Twin framework, it is evident that RFID has significant potential to be an integral part of the Digital Twin architecture. Currently, the primary applications of RFID in construction are focused on localisation and tracking, but our analysis shows that the integration of RFID with laser scanning and photogrammetry can enhance object recognition and modelling processes. Furthermore, RFID-based sensors can provide an alternative in scenarios where the deployment of traditional sensor networks is either technically or economically infeasible.

4.4.1. Barriers to the adoption of RFID

A certain limitation restricts the wider use of RFID technology in the construction industry. The predominant use of RFID remains in tracking, localisation and object identification, often as a stand-alone technology with minimal integration into other systems. Current applications are mainly seen in the field of materials and equipment management, supply chain logistics and worker safety. Even when RFID is integrated with other technologies, its application tends to remain narrow. For example, in BIM-RFID integration, RFID is primarily used for object identification, acting as a link between physical building elements and their digital counterparts. Similarly, RFID tags serve the same purpose when integrated with laser scanning. In the case of UAV and RFID integration, RFID plays a less prominent role in improving the data collection process. Instead, drones offer more sophisticated solutions that eliminate the need for manual handheld readers.

Several barriers contribute to RFID's limited integration with other technologies. According to Kineber et al. (2023), expert consultations highlight key challenges, including:

Table 8. An analysis of RFID application in the Digital Twin system architecture.

	Strengths	Weakness	Opportunities
RFID and BIM	Real-time visualisation and traceability Identification of building structures Potential use of cloud technologies RFID tags – IFC family's connection Flexibility of system	The complexity of the system architecture Multisource data Linking processes Loss of information Interoperability issues Data accuracy and storage Power consumption	Improve the flow of information through all stages of the building lifecycle Improve communication between stakeholders in the construction project Building's 'component passport' High-fidelity virtual model
RFID and laser scanning	Object identification and recognition within point cloud data	Large number of RFID tags Loss of RFID tags/loss of information	Accelerate point cloud data processing and object modelling
RFID and UAV	Covering large construction sites or built environment One UAV instead of many readers Work in dangerous or hard-to-reach locations	Reading range and the missing signal from tags Data accuracy Pre-developed database of modelled objects Interoperability issues Influence of the environment Undetected tags / false positive/false negative detection Many-to-one communication issues Drift error and need for control points Power consumption Privacy and security issues	Accelerate data collection and processing Optimising raw data volumes Coverage Path Planning Problem UAV Localization
RFID and sensors	Cost-effectiveness Battery less Small and flexible Long life and low maintenance Real-time scenario applications	Reading range Sensitivity to structural material and environment A limited number of features Data processing and accuracy Loss of information Interoperability issues	Wide range of applications (temperature, humidity, vibration, etc.) and measurements

- Infrastructure barriers: significant investment is required to deploy and maintain RFID infrastructure, which is often unattractive to stakeholders involved only in the early phases of construction projects.
- Technological immaturity: while the technology itself is mature, many stakeholders are not familiar enough with RFID, leading to lower adoption rates.
- Privacy concerns: in construction safety applications, workers may be hesitant to be monitored or tracked.
- Security issues: advanced security measures are needed to protect against risks such as cloning and unauthorised access.

In addition to these barriers, we would also emphasise:

- Organisational resistance: companies may be reluctant to change established processes, as RFID implementation often requires personnel training and could reduce productivity during the transition phase.
- Regulatory and standardisation challenges: a lack of uniform regulations and standards.
- Data interoperability issues: when RFID is used alongside other technologies, ensuring seamless data transmission and processing is a challenge.
- Construction site conditions: RFID performs better in controlled environments, whereas construction sites with numerous obstacles, including metals, can interfere with signal reliability.

Considering the resource barriers to RFID adoption highlighted in studies by Kineber et al. (2023), Thirumal et al. (2024) and Waqar et al. (2023), including the need for significant capital and operational expenses, it is evident that RFID implementation varies significantly between small and large-scale construction projects. Large construction projects with higher budgets and greater complexity can use RFID to enhance process automation and improve operational efficiency across multiple project phases, such as inventory management, workforce tracking and safety monitoring. For example, in a case study from Hong Kong (Zhong et al. 2017), a large-scale RFID deployment was used to automate the monitoring of prefabricated components in a public housing project. Embedding RFID tags in prefabricated units provided real-time tracking from production to installation, reducing delays and improving overall logistics. The study also shows that RFID improved data collection processes and reduced paperwork by up to 48%, improved delivery by 25% and improved assembly by around 7%. However, signal disruption and tag damage or loss were highlighted as limitations in the study. In addition, large construction projects may require tag customisation and adjustment to cope with the diversity of the construction site environment. In contrast, small projects often operate in a more controlled setting with fewer resources, where RFID can be used more selectively to monitor only critical tasks. However, recent research into the use of passive configuration RFID in small construction projects in Malaysia (Waqar et al. 2023) has shown that the use of RFID is still limited, with barriers such as knowledge of the technology and its feasibility, financial issues and lack of collaboration still not overcome.

4.4.2. Barriers to the adoption of RFID in Digital Twin architecture

In the context of using RFID as part of a Digital Twin architecture, it is worth highlighting the issue of measurement accuracy. Our analysis shows that the main challenges that need to be addressed are reading range and reading accuracy, which is consistent with the findings of previous studies, such as Khan, Biplob, and Nemai (2024), that have identified similar issues, although focusing only on localisation tasks. Depending on the application, the measurement accuracy can be quite sufficient (up to 1 cm for localisation) when using active tags and a well-designed system architecture. Considering RFID as an additional source of information for the Digital Twin, which can be used in conjunction with sensors, laser scanning, or photogrammetry, it is important to acknowledge that active tags show better results in terms of accuracy of measurements due to their longer reading range and higher sensitivity. At the same time, the active type of RFID is similar to conventional sensors used for these tasks, whose performance in various conditions has already been well studied, unlike the performance of RFID in these applications. However, active RFID can potentially be a cheaper and more flexible solution compared to traditional WLN, especially in multinode scenarios.

Another factor to consider is the reading range of RFID-based systems. One of the key characteristics of tags is their responsiveness to radio frequency signals, which determines the minimum power required to activate the tag and facilitate communication with the reader. Today's passive tags require less than 22 dBm to initiate activation, resulting in a reading range of 25 metres which might be sufficient for many tasks. According to Le Breton et al. (2022), as technology evolves, the sensitivity of both tags and readers tends to decrease, leading to increases in reading range. Although RFID technology is advancing, as evidenced by improvements in reading range and accuracy, further research is required to provide more practical examples for different types of construction tasks.

In addition, the integration of RFID into the Digital Twin architecture raises significant challenges in terms of data interoperability. Ensuring interoperability is crucial from a technological perspective, especially given the wide variety of IoT devices and equipment that can be deployed at the physical layer. While this issue affects all IoT devices, particular attention must be paid to the compatibility of interfaces, data exchange protocols and access to data through standardised APIs.

4.4.3. Study limitations and future research directions

While this study has made useful contributions to the field, it is important to acknowledge its limitations. Firstly, the publication's search was limited to only two databases, Scopus and Web of Science. Although these databases are known for their comprehensiveness, particularly in the field of engineering and technical sciences, other relevant publications may have been overlooked. Secondly, to narrow the data set and minimise bias, we used only articles, excluding conference papers, books, and other sources. This choice was made in the belief that articles provide more focused and accurate information. Thirdly, different results could be obtained by using a combination of different parameters in LSA and full-text analysis rather than abstracts. Therefore, we acknowledge that the research results may not cover the full range of publications, especially given the fast development of RFID technology and the ongoing development of deep learning methods for data processing.

Our analysis reveals that despite growing interest in RFID technology in both academia and industry, there are still challenges to its wider adoption. At present, RFID is mainly used as a stand-alone solution and its integration with other technologies remains limited. To address this, future research will focus on more detail exploring how RFID can be integrated with point clouds and image processing to support synchronisation in a Digital Twin environment. Moreover, exploring how RFID data can be interoperable with data from other sources is essential to fully realise its potential in Digital Twin systems. Another promising direction for future research is the use of RFID to support component and material passports, an area that is gaining traction due to its potential to contribute to sustainability in construction.

5. Conclusions

The construction industry is growing rapidly and becoming a key economic driver for many countries and the global economy in general. However, the industry faces challenges such as low levels of process automation and significant environmental impacts from the extraction, production, and transportation of building materials, as well as concerns about energy efficiency and sustainability of buildings. To address these challenges, it is important to explore and adopt technologies commonly used in other industries, especially those that are easy to integrate, sustainable, flexible, and cost-effective. This article provides a comprehensive review of existing research on the use of RFID, not only within the construction industry but also in relation to the Digital Twin framework. The Latent Semantic Analysis results and subsequent content analysis of the dataset showed how RFID can be used in synergy with technologies such as BIM, laser scanning, UAVs, and various types of sensors.

The content analysis results highlight the potential of RFID technology in the construction industry, particularly when integrated into Digital Twin architectures. RFID applications cover different stages of the building lifecycle, from construction progress monitoring to structural health management, demonstrating its flexibility. However, the analysis also reveals key barriers to the wider adoption of RFID technology. Challenges such as signal interference, limited reading range, infrastructure costs and data interoperability issues need to be addressed to realise RFID's potential. In addition, privacy and security concerns, as well as organisational resistance, hinder the integration of RFID into construction workflows. In Digital Twin architectures, the accuracy of RFID-based measurements and the seamless exchange of data between different IoT devices remain significant barriers. In terms of future research, there is a clear need to investigate how RFID can be better integrated with emerging technologies such as IoT, point clouds and image processing to create more robust workflows. In addition, the development of RFID-enabled material and component passports could significantly contribute to sustainability efforts in construction by improving lifecycle tracking and component reuse.

In summary, the success of adopting new technologies depends on the effective combination of various approaches, methods and equipment. RFID-using systems appear to be a promising solution, bringing benefits such as simplified installation, reduced maintenance, and remote access. Passive and active configurations of RFID offer distinct advantages, but both types can offer long-term functionality, making them suitable for harsh construction environments. Technology can be integrated with BIM and Digital Twin frameworks, providing up-to-date information on the condition of a building throughout its lifespan. The synergy of RFID with other technologies and equipment, such as laser scanning and digital imaging, offers significant potential to improve building information management and asset maintenance. Despite the benefits, careful consideration must be given to the power consumption of active RFID configuration and the accuracy of measured data. Thus, the adoption of RFID in the construction industry presents both opportunities and challenges.

In conclusion, the integration of RFID has the potential to be widespread in construction applications and help transform the effectiveness of the construction industry in general. With further research, development, and practical implementation, RFID can offer a multipurpose and cost-effective solution to meet the diverse challenges and requirements across the sector.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work is part of the dissemination activities of the research project ‘Boosting Research for a Smart and Carbon Neutral Built Environment with Digital Twins (SmartWins)’ (Grant ID Number 101078997), funded under the Horizon Europe call HORIZON-WIDERA-2021-ACCESS-03-01.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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