RFId for Construction Sector. Technological Innovation in Circular Economy Perspective

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Abstract The transition towards the Circular Economy (CE) sets new challenges in the construction sector. In addition to reduction of resource consumption and "closing the loop" concept, CE requires the dematerialization of services and products. Building processes and products need to be rethought to ensure sustainable and circular management of the asset. In this context, the progress in the field of Industry 4.0 technologies, such as Internet of Things (IoT) and Radio Frequency Identification (RFId), promises interesting scenarios in fostering circular transition. Indeed, information technologies can assume a critical role in achieve the Sustainable Development Goals 9 and 12. For about fifteen years, RFIds are used by several industries to automate process, optimize cost, and manage asset information through data-driven approach. This paper aims to investigate the feature of RFId technologies and its application in construction sector. In the perspective of promoting CE principles, such technologies can play an enabling role. Thorough the analysis of scientific literature review and experiences in the market, 20 of the most innovative case studies are presented. A clustering analysis of the case studied presented clarifies the most investigated fields and those where research should focus in the future.

Keywords RFId · IoT · Industry 4.0 · Construction industry · Circular economy

United Nations' Sustainable Development Goals 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 12. Ensure sustainable consumption and production patterns

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1 Introduction

The environmental and economic limits of the current linear development model highlight the need for a rapid ecological and circular transition. As required by the European Union [1], moving towards Circular Economy (CE) means renewing products and processes by overcoming models that are no longer sufficient and crystallized in a habitual vision of the present [2]. In this perspective, the progress in the field of Information and Communication Technologies (ICT) can be identified as a driving force for change, as an exogenous phenomenon that points the way for economic and social transformation [3]. Indeed, digitalization and dematerialization of products and processes are considered key factors to support CE and one of the "Six Transformations to Achieve the Sustainable Development Goals" (SDGs) [4]. More precisely, such approach, identified in the pervasive use of Industry 4.0 technology such as Internet of Things (IoT), Big Data, cloud computing, is now essential in fostering fair, responsible, and sustainable innovation (SDG 9: target 9.4, 9.b) to raise resource-use efficiency (SDG 12: target 12.2, 12.5) [5]. The strategic role of data in the ecological and circular transition is confirmed by several scholars [6, 7] and verified by many sectors (e.g. automotive, aerospace, retail, etc.).

Such approach opens extremely interesting scenarios in the construction sector. Still considered among the main sector exerting the strongest pressure on the environment [8] and accounting for almost 9% of European GDP [9], the construction sector plays a crucial role in circular transition, and it has high scope for digitization. In this perspective, the Industry 4.0 technologies represent, on the one hand, the most recent phase of industrial activities digitization, and on the other, a constantly evolving paradigm [10] that stimulates building product innovation through new dematerialized value. Integrated, connected, and collaborative cyber-physical systems, identified on the IoT, can thus facilitate circular transition and restructuring of industries' capital profitability.

An emblematic case concerns Radio Frequency Identification (RFId) technologies. Greater transparency and efficiency in asset management has pushed RFId technology into various sectors such as manufacturing, retails, and logistics. The ability to create, share, and transform data into information along value chains is the key to creating a circular approach using resources in a more efficient way [11]. With a view to stimulating the introduction of circular approaches, this paper aims to clarify the application potential of RFId technologies in the construction sector. A collection of 20 case studies in the last 15 years are presented to map the state-of-the-art. The clustering analysis of such experiences shows the most investigated fields and those where research should focus in the future.

2 Radio Frequency Identification

2.1 RFId Technology

RFId sensors are considered the new paradigm of the IoT [12]. Although the first applications of the technology date back to World War II for "friend or foe" recognition of anti-aircraft [11], recent progress in chip miniaturization and industrial process production have allowed a drastic reduction in price making the technology extremely versatile for many applications [13]. In the last twenty years, interest in this technology has been discontinuous. After a period of great interest between 2004 and 2007, the trend grew again after 2016 driven by an increased focus on IoT technologies. This trend is confirmed by Google Trend, too. Although to be considered from a qualitative point of view, the Fig. 1 showing the interest in Google searches for the terms 'RFId' or 'Radio Frequency Identification' in the last 18 years, compared to 'IoT' [14].

Used in logistics, automatic payment, access control or the identification of components or animals, RFId systems are already mature technologies that have found widespread application in many market sectors. Basically, it is a technology that allows the remote recognition of an object by using radio communication. The system architecture consists of two main elements: a reader with a data processing module and an antenna to generate the electromagnetic field, and a tag, a device placed on the object to be identified, consisting of an antenna, an integrated circuit (IC), and a substrate. Once entered in the radio signal range, the reader queries the tag, reads data, and organizes it in databases and/or shares it over the network. Several types of RFId technologies exists and different classifications can be made according to.

The presence/absence of a battery in the tag. RFId systems can be divided into passive, active, and semi-passive/semi-active. Passive tags are the most popular type, they do not have a battery and receive their power from the RFId reader. Active tags have an on-tag power supply such as a battery, which emits a constant signal containing identification information [15].

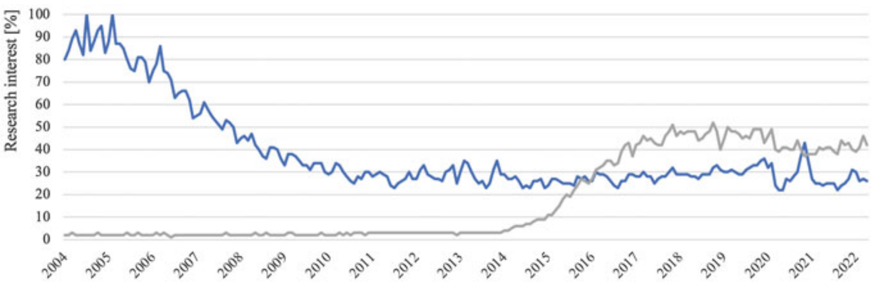

Fig. 1 Search trend on Google [19]: "RFId" (blue) and "IoT" (grey)

Table 1 RFId technology classification

Type	Frequency	Range	Active/Passive	Cost	Main applications
LF	125–134 kHz	1–10 cm	Passive	Very low	Access control, car anti-theft systems, etc.
HF	13.56 MHz	10 cm–1 m	Passive	Low	Labels for retail, safety, etc.
UHF	433 MHz 866–868 MHz (EU) 902–928 MHz (USA)	1–100 m 1–12 m	Active Passive	High	Identification of moving objects, etc.
Mw	2.45–5.8 GHz 3.1–10 GHz (USA)	1–2 m Up to 200 m	Active	High	Alarms, speed gauges, automatic openings, etc.

The frequency of the signal. Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF), and Microwave (Mw) are the main types. Generally, LF systems operate in the 125 kHz to 134 kHz range and have a read range of up to 10 cm. HFs operate in the 13.56 MHz range and provide reading distances of 10 cm to 1 m. UHF systems have a frequency range between 433 and 938 MHz depending on the context, offer read ranges up to 2 m, and have faster data transfer rates. Microwave frequency are less common for RFId technologies [15].

The material tag. The chip and antenna are mounted on a substrate, which can be paper, polyethylene terephthalate (PET) or some other type of plastic. The choice of material depends mainly on the type of transponders and the types of actions to which the asset is subjected. Price and durability of the tag depend strongly on the material used [16].

The memory capacity. In current tags, identified as Gen2 RFId tags, the IC contains four types of memory: Reserved Memory, EP Memory, TID Memory, User Memory. The capacity can vary from 8 bits in the case of passive technologies up to 8kbits. Tags with memory can be of the "read only" or "read/write" type when the data can be modified dynamically [17].

The main features can be summarized in Table 1.

2.2 *Lesson Learnt by Other Sectors*

In recent years, the widespread application of RFId technologies in many product sectors have shown environmental and economic benefits. There are three main experiences that can be stimulating for the construction sector: the auto-identification of assets, geolocation and spatial monitoring of assets, and environmental parameters monitoring. Lessons learnt from other industries can facilitate faster deployment in the construction industry.

Auto-identification. It is one of the main advantages of using RFId systems. Such technology can rapidly raise data collection in supply chains by automatically identifying the assets' features creating new business values by data. The most striking example emerges from the aerospace field [18]. For around 15 years, RFId technologies have been used in the production of airplanes to rationalize production and maintenance time and costs. The Boeing 787 DreamLiner, for example, consists of around 6 million components, provided by around 40 different suppliers. The production cost and maintenance phases require constant monitoring of the status of its components. To improve the control of supply chains, contain costs, and reduce time for inventory, 1.750 RFId tags are used to track aircraft components. Moreover, the digitalization of the inventory process drastically reduces human errors ensuring a greater quality [11]. The civil sector is also moving in this direction, too. Consolis, a world leader in the production of prefabricated tunnel segments and rail sleepers, uses tags embedded in each tunnel segment to identify assets during construction phase, manage information during assets life-cycle, and ensuring greater control and process transparency over the supply chain [19].

Geolocalization monitoring. Real-time geospatial sensing of assets is one of the main scope for RFId technology. Monitoring position of assets in a space could result in greater efficiency in controlling supply chains and governing the timing of a process more accurately. Delivery data, shipment tracking and material stock management are extremely useful actions for logistics and efficient management of complex processes. In many productive companies, doors such as readers monitor the entry and exit of goods and/or people to control matter flows, occupancy, and increase safety in the workplace [20]. In addition to this, position sensors, GPS, accelerometers, and vibration, sensors can be used with RFId systems for performance monitoring of an asset. For some years, structural monitoring is an extreme topic in the academia research, several researchers over the years have tested RFId based solutions. RFId systems have been studied for the structural monitoring of bridges, viaducts, roads and infrastructure works [21]. The ability to track statical position and fluctuations allows operators providing operation and maintenance to intervene in advance, thus reducing the cost of corrective maintenance and the risk of failure. Vizinex, a leading RFId systems company, has developed a passive UHF sensor for automatic maintenance schedule management [22]. In Missouri, the Center for Transportation Infrastructure and Safety has carried out a research project on the implementation of RFId sensors for bridge monitoring [23]. To monitor the corrosion status of a physical element and evaluate its load stress history, a passive RFId sensor was developed.

Environmental parameters monitoring. A further field of application is the use of RFID systems to monitor environmental parameters. Joint use with wireless sensor (WSN) network provides to RFId systems a greater versatility. The typical hardware platform of a WSN node consists of a sensor, a microcontroller, a radio frequency transceiver and a power source. Each node is equipped with a sensor to detect parameters such as temperature, humidity, light, sound, pressure or other physical parameters. Power consumption, chip size and computing power, as well as on-chip memory are very important features to define in an integrated RFId system. A crucial feature of a sensor node is the power source and battery management, especially in WSNs, where the battery can't be replaced [15]. In this context, significant experiences come from pharmaceutical and food chain fields. The cold chain control ensures that products, drugs or food can reach the final consumer in the best condition. Changing in temperature during production and distribution process could lead to alteration of the chemical features of the good with possible damage to the health of the user. In 2016, European MC Donald's and other leaders in the food industry funded the testing of an RFId temperature loggers that could track the food product temperature throughout the supply chain [24]. This ensures high quality in the product sold to the consumer and offers new tools to regulate the relationship with suppliers. A similar example is provided by PostNL's (Belgium). The delivery company has developed together with SenseAnywhere a device for detecting internal conditions in vehicles used for the delivery of pharmaceutical materials [25].

3 Materials and Method

Defining the maturity level and the state-of-the-art of a technology that is difficult to place in a specific context is a tricky issue. Indeed, depending on the application field the maturity level of RFId technology can be drastically change. In recent years, technology development has been taking place more within companies than in academia. This sometimes leads to real difficulties in finding technology-specific information. As confirmed by Costa et al. [15] it emerges that by 2015 the number of patents registered using RFId technology was far higher than the number of scientific papers. This justifies a degree of maturity of the technology that can be widely used in the market. In Europe, more than 16,000 patents have been filed using RFId technology [15]. For these reasons, the collection of case studies used a hybrid approach integrating scientific literature review with experiences from the market.

From the literature review on SCOPUS and ResearchGate databases, of the total 43.000 articles that can be traced through the keywords "RFId" or "Radio Frequency Identification", about 1.283 (about 3%) also integrate the term "construction". An initial analysis of the metadata obtained shows how the distribution of scientific research between 1995 and 2022 (April) follows the trend of Google research show in Fig. 2. The shift of the peak in 2013 is probably due to the research and publication time. Since 2015, the number of papers per year has been constant with around 70 papers per year. Computer Sciences, Automation in Construction and Applied Mechanics and Materials are the three journal papers that include the largest number of articles.

Screening the most innovative cases led to the selection of 20 case studies. Applied research and market application from 2006 to 2022 are presented. The case studies analysis and clustering according to the purpose of the technology provides an overview of the RFId system and highlight new emerging trends for future research.

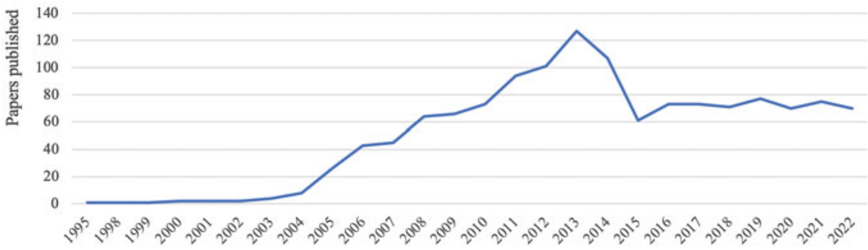

Fig. 2 Number of papers published per year containing "RFId" or "Radio Frequency Identification" AND "Construction" in title, abstract or keywords

4 RFId in Construction Industry

Table 2 shows the case studies with a brief description of the purpose of the technology. Information regarding the year, location, and companies involved helps to clarify the evolutionary process. The case studies are listed in chronological order.

5 Discussion

Form the case studies presented emerges a very wide context. The RFId experiences, as shown in Fig. 3, show a still heterogeneous degree of maturity, proving that it can be considered a recent technology in the construction sector. The market pervasiveness of the cited technology are strongly dependent on national regulatory barriers, the economic value of data provided by technology, and technical issues related to digital and physical integration. Access control for site management or restricted zone in the building represents the most mature and popular in the market. In this case, a lower integration level of tags facilitates the use of cards and keys RFId-based. An emerging and interesting application field is production and supply chain management. Although still used to optimize and control material and component flows within the same company or between a few stakeholders, the creation of a digitized supply chain opens up interesting scenarios for construction sector. A current barrier is the functional and technological unity of the building component, where to install the tag. The promotion of prefabricated systems and dry construction, which facilitates the idea of a building organized by parts that can be replaced over time, may allow a greater application of such tracking systems. The issue becomes more complicated, and the degree of technological maturity and market application declines, when the typical challenges of facility management and computerized asset management arise. Although the advantages from a rational use of resources point of view are obvious, the time dimension, the physical integration, the number and role of stakeholders becomes an obstacle. On the one hand, the technological obsolescence of RFId technology does not (yet) allow its use for components with a long

Table 2 RFId in construction sector case studies

Name, main info	Goal and technology description
RFID-Based Facilities Maintenance. 2006, Frankfurt Airport (DE)	All fire shutters are equipped with RFId tags that store maintenance related information. The technicians identify themselves by scanning their badge and the tag attached to the fire shutter. After performing the checking or the maintenance, the tag is scanned a second time to record updated information. The transponders are designed to be attached to metal. The reading range is only 3 cm and frequency is 13.56 MHz [26]
Intelligent Concrete. 2006, Tilst (DK). Dalton, Aarhus Innovation Lab	An integrated microchips for controlling production and supply chain and optimizing facilities activities for concrete panels. Concrete panel data are shared via internet and organized in specific database. By means of a personal digital assistant with a special reader mounted on the back, the men at the construction site can find all information about the panel immediately (e.g. measurements, weight, serial number, production history, exact mounting instruction and maintenance instructions) [27]
New Meadowlands Stadium. 2010. New jersey (USA). Skanska USA	In 2010, Skanska USA used RFId tag to track over 3.200 pre-cast concrete panels and visualizes it on BIM model for the New Meadowlands Stadium project. Each concrete panel, which weighed around 20 tons, was fitted with a RFId tag to allow it to monitor supply chain information in real-time. The RFId technology allowed to identify and solve problem early in the process, reducing in this way the construction period by 10 days and saving US$ 1 million [28]
Service-Oriented Integrated Information Framework. 2011, Seoul (KR). Sungkyunkwan Univ., Doalltech Co	This research aims to develop a seamlessly integrated information management framework that can share logistics information to project stakeholders. To provide "just in time" delivery for construction sector, the research group have developed an integrated framework to digitalize component and building material flows. The pilot test showed that it can improve time efficiency by about 32% compared to the traditional supply chain management. The result of this research is expected to be utilized effectively as a basic framework to manage information in RFId/WSN based construction supply chain management environments [29]
Door Control System (DCS). 2012, Bielefeld (DE). Schüco	The DCS control system provides access control using RFId technology. A passive RFId card tag for operators is the digital key to access a specific room. Integrated into the door, a RFId reader recognizes the operators and enables them to pass through. Such application is interesting for security and access control to private areas such as hospital, bank, offices etc. [30]

(continued)

Table 2 (continued)

Name, main info	Goal and technology description
Precast Concrete. 2014, North Carolina (USA). Cherry Precast and Concrete Pipe & Precast. HUF RFId	To aid the state North Carolina Department of Transportation's inspections, some American companies' suppliers have integrated an RFId tag embedded in each precast concrete panel to keep track of manufacture data. The RFId led to a fast evolution of the control process. An online database (HiCAMS), accessible to all suppliers by password, allows them to view project data, orders, and delivered products [31]
HardTrack. 2014, San Francisco (USA). Shimmick Construction Co., Wake, Inc. HUF RFId	HardTrack technology consists in active RFId (UHF) tags with integrated sensors to monitor the temperature and humidity of the concrete. In San Francisco, it was used by Shimmick Construction for the concrete foundation of building project. 16 concrete slabs integrated RFId tag and sensors. Each slab must be fully cured before the next one can be poured, to prevent it from cracking due to any stresses from the next slab. HardTrack provides real-time data on the concrete temperature and a software determines the curing date of the poured concrete. This approach has proven direct benefits on construction site timing [32]
Redpoint. 2015, Boston (USA). Redpoint Positioning Corp., Skanska USA	The Redpoint technology helps the company to know when staff members go into an area of a construction site. The system also provides historical data so that management can identify workers who repeatedly enter an unauthorized area and provide them with additional training to prevent such mistakes from happening again. The development of such devices can find rapid application in buildings with restricted access areas [33]
Cluster based RFId. 2015, Montreal (CA). Concordia University	In this research, a localization method based on RFId systems which does not need infrastructure is proposed. The developed of an active RFID technology for the localization of movable objects is proposed. Building components, and equipment with an integrated RFId tag using handheld readers. By extending a Cluster-based Movable Tag Localization technique, a k-Nearest Neighbor algorithm is used [34]
Smart Construction Object. 2016, Hong Kong (CN). The University of Hong Kong	An integrated smart building component was tested and demonstrated in a real-life case in a prefabricated construction in Hong Kong. In this case, an RFId-enabled BIM system was required to track the status of prefabricated façades from off-shore manufacturing, cross-border logistics, through to on-site assembly. The tags for supply chain control included data regarding prefabrication factory, transportation routes, and a construction site [35]

(continued)

Table 2 (continued)

Name, main info	Goal and technology description
IFC-RFId. 2016, Montreal (CA). Concordia University	The mechanical room of the Genomics Centre at Concordia University is chosen for the case study. The building is modeled in BIM and the mechanical elements are added to the model. RFId tags are attached to a selected set of elements to host their related BIM information. Active and passive RFId tags are modeled in Revit under the electrical equipment category and added to the BIM model of the building [36]
The Spot-r worker safety system. 2017, East Harlem, New York (USA). Lettire Construction, Triax tech	The system developed aims to ensure the safety of workers on the construction site. When workers arrive on site, building project manager can use the real-time data to view the total number of workers per floor and zone and organize the work. Furthermore, such solution allows managers to verify if potential incident occurs. For example, the RFId system can detect sudden falls. The software's algorithms can also determine if the data is indicative of a fall or if the worker may simply have dropped the device [37]
Elbphilarmonie façade. 2017, Hamburg (DE). Permasteelisa Group	Permasteelisa, world leader in building façade technology, used an RFId tag to optimize production and construction phase in complex project. To manage a large number of different façade elements, each façade panel was tagged with an RFId that, thanks to a specific ID number, could remotly identify each individual element. In Elbphilarmonie project, such system facilitated and sped up the panel delivery to construction site that was particularly challenging, given its unique urban location and space constraints. This data will also be used for maintenance purpose [38]
MULTIfid project. 2018–2021, Università degli Studi dell'Aquila. (DICEAA), 2bite S.r.l, Pack System S.r.l	The main objective of the MULTIFId project is to create an innovative product consisting of an intelligent, low-cost, and low-emission panel, made from waste from the industrial processing of paper and cardboard. An RFId system is integrated into the panel to monitor the position of workers in risk areas, thermal performance, and monitoring humidity conditions. The academia project tested and verified RFId signal transmission through different campaign monitoring [39]
RFIBricks. 2018, National Taiwan University, Taipei. HUF RFId	RFIBricks is an academia project carried out in Taiwan University. Hsieh et al. [40] present an interactive brick system based on ultra-high frequency RFID sensing. The researchers present a system that enables geometry resolution and geolocation of the asset in a space. Although the state of research is in prototype form, the development of a dynamic user interface opens up interesting scenarios in the field of tracking and tracing components in a space

(continued)

Table 2 (continued)

Name, main info	Goal and technology description
Checked OK. 2018, Cork (IE). Anderco Liftging, CoreRFId. HF RFId	Anderco Lifting, one of Ireland's largest lift companies, is employing an HF RFId solution to improve the efficiency of inspections of the lift equipment that its customers use at construction sites. The system was developed in 2018, and the data collected is being accessed by utilities and several other customers to which Anderco provides six-month cycle inspections [41]
Flexible thermal monitoring. 2018, Turin, (IT). Polytechnic of Turin, DAUIN Department	Giusto et al. [42] investigate RFId technology for indoor climate control. Benefits of a dense deployment of pervasive temperature sensors are presented. The analysis takes into account many features, such as technology simplicity and time of development, flexibility, wired/wireless range, battery life, reliability and cost. A case study with field test shows that the RFId network is nowadays suitable for thermal monitoring
The SensX Extreme. 2019, Cupertino (USA). Smartrac and SensThys. HUF RFId	The SensX Extreme is primarily focused on the smart building and construction market. The aim is to develop technology for leak detection and concrete curing. RFId tags, which can be embedded in the roof section, can detect the presence of water, and the drying phase of concrete during paving, thus enabling higher quality and speed on site. The tags can be used in common building materials, such as gypsum board, insulation, roofing, flooring, and concrete [43]
IFC-RFID system. 2020, Theran (IR). Islamic Azad Univ., Shahid Beheshti Univ., East Carolina University	This research presents a computerized system that integrates the BIM objects in IFC and radio-frequency identification to improve building maintenance performance. The computerized system is successfully applied to the building of a soccer stadium in Theran via the proposed research methodology using a qualitative and practical approach. The research indicates how a slight effort on the implementation of the proposed system could allow a significant improvement of overall maintenance performance [44]
WoodSense. 2021, Gävle (SE). Woodsense, ByggDialog Dalarna	WoodSense provides moisture measurement using passive sensors in the form of tags that can be attached to the wood building façade, wood slab panel, and or others building components. These sensors measure the moisture on the surface and have to be scanned on site with an RFId reader. The application of such solutions is particularly effective in facilities for wooden building that require more attention to environmental phenomena [45]

service life such as building components. The service life of a tag can be as long as 15–20 year but is still shorter than that of building components. On the other hand, technological integration and the need for a battery may represent a limitation for large-scale application. Furthermore, it is evident that one of the main gap is the time limited responsibility of stakeholders in the management of an asset during its useful life. Transferring responsibility for an asset to the user once it has been sold (or the

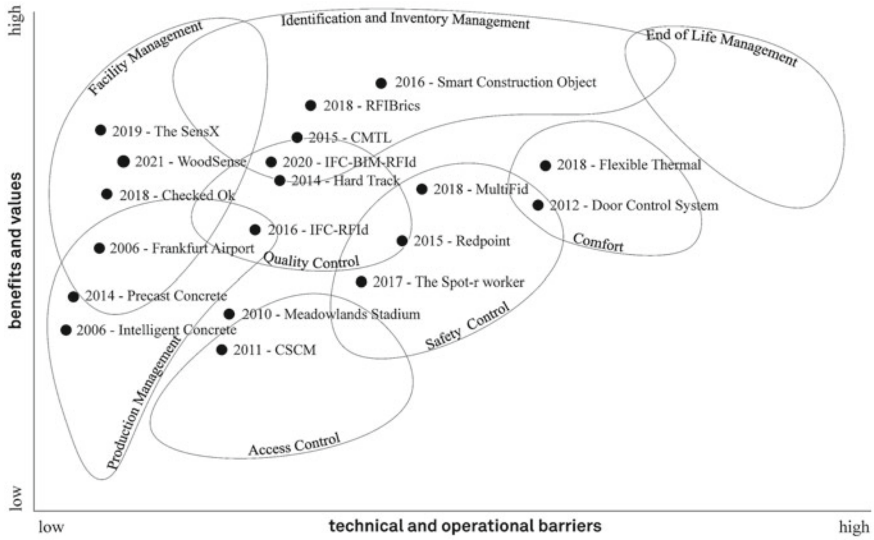

Fig. 3 Thematic areas and case studies for RFId technology in construction sector

warranty has expired) severely limits the interest of manufacturers in such technologies. However, the transition to circular approaches aimed at enhancing the value of the material and extending services (e.g. leasing, Product As a Service, Pay per Use, etc.) over time could change the current paradigm. In that case, circular solutions for inventory, management and end-of-life of an asset could require a much larger amount of information. A separate issue is the use of technology for comfort and thermo-hygrometric regulation of indoor environments. The increased attention to this topic could thus favor the application of RFId solutions for the built environment and offer new services and advantages to the user. The graph below clusters the experiences reported according to macro-topics emerged. A qualitatively identifying areas that have already been widely tested (e.g. access control) and potential areas (e.g. deconstruction) for future development in RFId is proposed. The deconstruction phase and end of life management could represent an emerging areas for RFId application. Although the technical and operational barriers makes the issue more complex, benefits and values in CE perspective could be relevant.

6 Conclusion and Future Development

More than 15 years later the first experiences of RFId in construction sector some considerations can be made. Advantages in a more rational use of resources, automation of processes, and the introduction of new dematerialized services promise new scenarios for construction sector. Industry 4.0 offers new technological tools and approaches to redesign production processes and create new opportunities for economic and environmental value generation. The digitization of the construction sector requires therefore a radical upgrade of the industrial infrastructure boosting product and process innovation (SDG 9). This objective is necessary to the achievement of SDG 12, which aims to promote more resource-efficient models. However, the impact that such technologies and the creation of big data from an environmental point of view must be considered. The most recent estimates indicate that the amount of digital data will grow from 33 zettabytes in 2018 to 175 by 2025. In this perspective, RFId and IoT technologies will contribute considerably to data creation generating an impact on the environment. Future developments in technology and data processing should thus aim to reduce their environmental impact in terms of materials consumed (e.g. to build tags and sensors) and climate-changing gas emissions (e.g. big data management). Although the challenge is complex and extremely interdisciplinary, the circular transition in the construction sector can be strongly enabled by new Industry 4.0 technologies.

References

1. European Union: Closing the loop—An EU action plan for the Circular Economy A (2015). https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF. Last Accessed 23 April 2022
2. Vittoria, E.: Progetto, cultura, tecnica, in Controspazio. Gangemi Editore, Roma (1983)
3. Masino, G.: Industria 4.0 tra passato e future. In: Salento, A. (eds.) Industria 4.0: Oltre il determinismo tecnologico, pp. 23–40. TAO Digital Library, Bologna (2018). https://doi.org/10.6092/unibo/amsacta/604
4. Sachs, J.D., Schmidt-Traub, G., Mazzuccato, M., Messner, D., Nakicenovic, N., Rockstrom, J.: Six transformations to achieve the sustainable developments goals. Nat. Sustain. (2019). https://doi.org/10.1038/s41893-019-0352-9
5. Sustainable Development Goals. https://sdgs.un.org/goals. Last Accessed 23 April 2022
6. Nobre, G.C., Tavares, E.: Assessing the role of big data and the internet of things on the transition to circular economy: Part I. Johnson Matthey Technol. Rev. **64**(1), 19–31 (2020). https://doi.org/10.1595/205651319x15643932870488
7. Ingemarsdotter, E., Jamsin, E., Balkenende, R.: Opportunities and challenges in IoT-enabled circular business model implementation—A case study. Resour. Conserv. Recycl. **162**, 105047 (2020). https://doi.org/10.1016/j.resconrec.2020.105047
8. United Nations Environment Program. 2020 Global status report or buildings and construction (2020). https://wedocs.unep.org/bitstream/handle/20.500.11822/34572/GSR_ES.pdf. Last Accessed 21 March 2022
9. European Commission. https://ec.europa.eu/growth/sectors/construction_en. Last Accessed 21 March 2022
10. Ranta, V., Aarikka-Stenroos, L., Väisänen, J.M.: Digital technologies catalyzing business model innovation for circular economy—Multiple case study. Resour. Conserv. Recycl. **164** (2021). https://doi.org/10.1016/j.resconrec.2020.105155
11. Erabuild. Review of the current stat of Radio Frequency Identification (RFId) Technology, its use and potential future use in Construction, Final Report (2006). https://www.teknologisk.dk/_/media/23536_Report%20RFID%20in%20Construction%20-%20Final%20report%20EBST%20(3).pdf. Last Accessed 21 April 2022

12. Costa, F., Genovesi, S., Borgese, M., Michel, A., Dicandia, F.A., Manara, G.: A review of RFID sensors, the new frontier of Internet of Things. Sensors **21**, 3138 (2021). https://doi.org/10.3390/s21093138
13. Lu, W., Ting, L., Johan, S., Gang, W.: Design of chipless RFID tag by using miniaturized open-loop resonators. IEEE Trans. Antennas Propag. **66**(2), 618–626 (2018). https://doi.org/10.1109/TAP.2017.2782262
14. Google Trends. https://trends.google.com/trends/
15. Klaus, F.: RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and near-Field Communication. Wiley, United Kingdom (2010). https://doi.org/10.1002/9780470665121
16. Want, R.: An introduction to RFID technology. IEEE Pervasive Comput. **5**(1), 25–33 (2006). https://doi.org/10.1109/MPRV.2006.2
17. Marrocco, G.: The Art of UHF RFID antenna design: impedance matching and size-reduction techniques. IEEE Antennas Propag. Mag. **50**(1), 66–79 (2008)
18. Ron, W.: RFID: a technical overview and its application to the enterprise. IT Prof. **7**(3), 27–33 (2005)
19. Consolis. https://www.consolis.com/sustainability/#projects
20. Musa, A., Dabo, A.A.: A review of RFID in supply chain management: 2000–2015. Glob. J. Flex. Syst. Manag. **17**(2), 189–2281 (2016). https://doi.org/10.1007/s40171-016-0136-2
21. Zhang, J., Tian, G.Y., Zhao, A.B.: Passive RFID sensor systems for crack detection & characterization. NDT E Int. **86**, 89–991 (2017)
22. Vizinex RFId. https://www.vizinexrfid.com. Last Accessed 15 April 2022
23. Meyers, J.J., Hernandez, E.S.: Implementation of Radio Frequency Identification (RFID) Sensors for Monitoring of Bridge Deck Corrosion in Missouri. Center for transportation infrastructure and safety. Missouri University of Science & Technology Department of Civil, Architectural & Environmental Engineering (2014). https://doi.org/10.13140/RG.2.1.2528.5843
24. Swedberg, C.: McDonald's, other companies test TAG sensors' RFID temperature loggers. RFId J. (2016). https://www.rfidjournal.com/mcdonalds-other-companies-test-tag-sensors-rfid-temperature-loggers. Last Accessed 12 April 2022
25. SenseAnywhere. https://www.senseanywhere.com. Last Accessed 15 April 2022
26. Legner, C., Thiesse, F.: RFID-based facility maintenance at Frankfurt airport. IEEE Pervasive Comput. **5**(1), 34–39 (2016). https://doi.org/10.1109/MPRV.2006.14
27. Daly, D., Melia, T., Baldwin, G.: Concrete embedded RFID for way-point positioning. In: International Conference on Indoor Positioning and Indoor Navigation, pp. 15–17 (2010)
28. SKANSKA: New home for Jets and Giants. Worldwide. https://group.skanska.com/4a0579/siteassets/media/worldwide-magazine/2010/worldwide-no-2-2010.pdf. Last Accessed 21 April 2022
29. Shin, T.H., Chin, S., Yoon, S.W., Kwon, S.W.: A service-oriented integrated information framework for RFID/WSN-based intelligent construction supply chain management. Autom. Constr. **20**(6), 706–715 (2011). https://doi.org/10.1016/j.autcon.2010.12.002
30. Schüco. https://sepam-serramenti.it/pdf/progettisti/porte/door_control_system_it_en.pdf. Last Accessed 21 April 2022
31. Swedberg, C.: North Carolina transportation Dept. tracks precast concrete and samples. RFID J. (2014). https://www.rfidjournal.com/north-carolina-transportation-dept-tracks-precast-concrete-and-samples. Last Accessed 21 April 2022
32. Swedberg, C.: RFID Is the cure for San Francisco construction project. RFID J. (204). https://www.wakeinc.com/wp-content/uploads/2017/12/Reprint-RFID-Is-the-Cure-for-San-Francisco-Construction-Project-RFID-Journal.pdf. Last Accessed 21 April 2022
33. Redpoint. https://www.redpointpositioning.com. Last Accessed 30 April 2022
34. Soltani, M.M., Motamedi, A., Hammad, A.: Enhancing cluster-based RFID tag localization using artificial neural networks and virtual reference tags. Autom. Constr. **54**, 93–105 (2015). https://doi.org/10.1016/j.autcon.2015.03.009

35. Xue, F., Chen, K., Lu, W., Niu, Y., Huang, G.Q.: Linking radio-frequency identification to building information modeling: status quo, development trajectory, and guidelines for practitioners. Autom. Constr. **93**, 241–251 (2018). https://doi.org/10.1016/j.autcon.2018.05.023
36. Motamedi, A., Soltani, M.M., Setayeshgar, S., Hammad, A.: Extending IFC to incorporate information of RFID tags attached to building elements. Adv. Eng. Inform. **30**, 39–53 (2016). https://doi.org/10.1016/j.aei.2015.11.004
37. Triaxtec. https://www.triaxtec.com/wp-content/uploads/2020/04/LettireConstruction-CaseStudy.pdf. Last Accessed 12 April 2022
38. Permasteelisa Group. https://www.permasteelisagroup.com/project-detail?project=1841. Last Accessed 21 April 2022
39. Pantoli,L., Gabriele,T., Donati, F.F., Mastrodicasa, L., Berardinis, P.D., Rotilio, M., Cucchiella, F., Leoni, A., Stornelli, V.: Sensorial multifunctional panels for smart factory applications. Electronics **10**, 1495 (2021). https://doi.org/10.3390/electronics10121495
40. Hsieh, M.J., Liang, R.H., Huang, D.Y., Ke, J.Y., Chen, B.Y.: RFIBricks: interactive building blocks based on RFID. In: CHI '18: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (2018). https://doi.org/10.1145/3173574.3173763
41. CoreRFId. https://www.corerfid.com/casestudies/anderco-lifting/. Last Accessed 21 April 2022
42. Giusto, E., Gandino, F., Greco, M.L., Rebaudengo, M., Montrucchio, B.: A dense RFID network for flexible thermal monitoring. In: 6th International EURASIP Workshop on RFID Technology (2018). https://doi.org/10.1109/EURFID.2018.8611649
43. SensThys. https://www.sensthys.com/sensx-extreme/. Last Accessed 30 April 2022
44. Kameli, M., Hosseinalipour, M., Sordoud, J.M., Ahmed, S.M., Behruyan, M.: Improving maintenance performance by developing an IFC BIM/RFID-based computer system. J. Ambient. Intell. Humaniz. Comput. **12**, 3055–3074 (2021). https://doi.org/10.1007/s12652-020-02464-3
45. WoodSense. https://en.woodsense.dk. Last Accessed 30 April 2022