Smart technologies: Enablers of construction components reuse?

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ABSTRACT

Purpose: The exploitation of smart technologies such as, Radio Frequency Identification (RFID) and Building Information Modelling (BIM) for tracking and archiving the properties of structural components, is an innovative disruption in the construction sector. It could stimulate reuse of construction components, rather than their wastage addressing a serious pressing problem.

Methods: This study explores the potential of smart technologies to facilitate construction components reuse, and develops a guidance list for promoting their redistribution back to the supply chain. A preliminary assessment of the strengths, weaknesses, opportunities and threats of the RFID technology is presented in order to depict its current and future potential in promoting construction components' sustainable lifecycle management, and in capturing and creating value.

Results: For both RFID and BIM technologies to operate successfully, the right amount and flow of information at each stage of the design-construction-deconstruction-reuse-disposal process is a prerequisite. Although a number of limitations related to the technical operability and recycling of RFID tags currently withhold its roll-out, technological innovation may provide solutions for the future, enabling it to become mainstream.

Conclusions: the use of RFID in the construction sector can create the right conditions for the development of new business models based on the reuse and lifecycle management of components, unlocking multiple technical, environmental, economic, and social benefits. With technological innovation enhancing the capabilities of RFID, and with policy interventions controlling and managing its uptake at all stages of the supply chain, its use as a construction components reuse enabler might soon become realised.

KEYWORDS: Construction and demolition waste (CDW); construction components; reuse; RFID; information flow; lifecycle valuation

INTRODUCTION

Construction and demolition waste (CDW) generated from the construction, renovation and partial or total demolition of buildings and/or civil infrastructure, as well as from the road building and refurbishment activities [1-4], represents one third of the total solid waste generated in Europe, accounting for over 800m tonnes per year [5]. To promote sustainable handling of solid waste, including CDW, generated across the EU and achieve a high level of resource efficiency the revised Waste Framework Directive (rWFD) (2008/98/EC) came into force. In regards to CDW specifically, the rWFD mandates EU member states to implement measures in such a way as to recover, reuse and recycle a minimum of 70% of non-hazardous CDW by the year 2020 [6, 7]. Notwithstanding the potential of the rWFD to achieve resource efficiency, the fate of CDW in Europe remains largely unknown. Its high potential for reuse and recycling however, has urged the European Commission to categorise CDW as a priority waste stream [8, 9]. This categorisation has put the construction sector in the spotlight, and sustainable practices have become increasingly popular as a response to growing concerns regarding the efficient use of raw resources and environmental impacts (e.g. carbon emissions) associated with the production of various construction components (e.g. fabricated pipes, structural steel members, precast concrete blocks, etc.), and their end of life (EoL) fate [10].

Although recycling of CDW is possible, the recovery of construction components for reuse is recognised by the European Commission as a better practice in the construction sector, with a high recovery of value [9]. A number of interventions that can stimulate the reuse of construction components has being widely documented in the global literature and recently reviewed [10]. These interventions - adaptive reuse, deconstruction, design for deconstruction (DfD), design for reuse (DfR) and design for manufacture and assembly (DfMA) - have many benefits to offer, but currently short-term economic and organisational factors, as well as technical constraints associated with the identification, recovery and handling of construction components impede their benefits from being realised [10]. Adding greater consistency and automation to the task of identifying, characterising and tracking construction components could lead to their better documentation and recovery during construction and deconstruction activities, prolonging as such their lifetime through reuse. This practice not only can reduce the amount of virgin materials used in the construction sector, but can also minimise the amount of CDW generated and associated commercial, environmental and social costs.

During the last decades, a number of advanced “smart” technologies have emerged including, radio frequency identification (RFID), optical character recognition, 3D scanning laser, building information modelling (BIM), 3D computer-aided design (CAD), etc., becoming an important tool in the construction sector [11, 12]. Among these technologies RFID, a wireless sensor technology operating based on the detection of electromagnetic signals at radio frequencies [13, 14], has been identified as one of the greatest contributing technologies of the 21st century because of its automatic data collection, information storage capability, ease of handling, and affordability [15]. Given its ability to identify and track objects, RFID has been increasingly used to reduce construction management costs via monitoring the location of resources, such as construction materials and components, equipment and workforce [16-23]. An additional advantage that has made RFID attractive is its ability to be integrated with a range of different technologies, maximising its potential to capture, transmit and collect data. Depending on the task at hand, RFID can be integrated with geographic information system (GIS) and global positioning system (GPS) or ultrasound technologies (e.g. for locating materials and estimating their position in the construction site), personal digital assistant (PDA) technologies (e.g. for monitoring information such as material/component inventories and building drawings and other documentation and safety management), and BIM technologies (e.g. for storing and retrieving component lifecycle data and integrating those into new designs), maximising its potential to capture, transmit and collect data, providing business benefits and return on investments [24, 25]. The latter has gained increased importance due to BIM's ability to digitally represent the physical and functional characteristics of a structure and its capability to retrieve data from a database, forming a reliable basis for decision-making [16, 26]. A unique RFID tag assigned to a construction component can be linked to a BIM database, enabling the recovery and organisation of information during all building project phases incorporated into a 3D information model. In that way reclaimed construction components can find their way in being used into new structures in much easier, cost-efficient and accurate ways [15, 16].

Exploitation of the potential of RFID and BIM for tagging, tracking, recovering and archiving structural components, can be an innovative disruption in the construction sector for stimulating the recovery and reuse of construction components at their EoL stage [10, 26]. Therefore, this study aims to explore the prospect of using RFID and BIM for facilitating construction components reuse, providing the means to the construction sector to make the shift from a massive waste generator to a resource recovery implementer, streamlining the delivery of multiple benefits to the environment, economy and society. Given the early-stage of RFID-BIM integration, emphasis is set on describing the role of RFID in storing, managing and supporting information flow through the construction components lifecycle, promoting their redistribution back to the supply chain. A preliminary assessment of the strengths, weaknesses, opportunities and threats of the RFID technology is also presented in order to depict its current and future potential in sustainable construction components lifecycle management, and in capturing and creating value.

A GLIMPSE INTO THE BASICS

The use of RFID technology

RFID tags first appeared in the 1940's, and since then they have gained a competitive advantage over the use of bar codes due to their potential to provide real-time information traceability and visibility, and their ability to be embedded in a component and product, without any adverse effects on the information held [22, 25, 27]. RFID tags are not restricted by size (e.g. are found in different patterns and sizes), have a strong resistance to contamination (e.g. water, oil, chemicals, etc.), can be read for as many times needed without disruptions or failures, and have a large information capacity (up to several megabytes) [22, 23, 28, 29].

The basic elements of an RFID system are the transponder[1] (i.e. the tag, where the information is stored), the interrogator or transceiver (also called the reader/antenna), and the RFID application software system as shown in **Figure 1** [17, 22, 25, 27, 30]. The working principle of the RFID system is based on the transmission of radio frequency (RF) signals from the reader's antenna to the tag, which induces an electrical current that stimulates

[1] The transponder contains a very small integrated circuit chip (area of less than 2 mm^2) and a small integrated antenna. The circuit chip stores the information, modulates the signal and receives power from the transceiver, whereas the tag's antenna receives and transmits the signal.

the transmission of its data through RF signals back to the reader as a response, without any human intervention [11, 14, 17, 22, 25, 27, 30-32]. The data received by the reader are then transferred to a computer system for processing of the information received [22, 25]. The RFID reader can read multiple tags at the same time, shortening the time of operation, and enhancing the efficiency of the management [17, 22]. In addition to reading data, the reader can modify and/or write data to the RFID tag, which improves the interaction between components, system and stakeholders involved into the various steps of a construction project [21, 33]. However, the distance between the reader and the tags constitutes an important feature of the RFID system [17, 22, 25, 27, 30].

Figure 1 The RFID system components

Depending on the function of RFID, the material of the component/product to which it is attached, the type of environment in which it is expected to function and the source of power that the RFID tag will need to operate, its lifetime and reading distance will differ determining the type of the RFID tag used [29, 34]. There are currently three types of RFID tags available namely, the passive, the semi-passive, and the active RFID tags [22, 25]. Active tags are powered by batteries, which increases the signal strength from the reader to the tag providing an effective reading distance of up to 100m [14]. On the contrary, passive and semi-passive tags, powered from the reader antenna's electromagnetic field and the use of a signal, respectively, have a low signal strength from tag to reader and as such, an effective reading range of up to 15m and 80m, respectively [22, 25]. Active tags have a high memory capacity (32 MB is possible) and a lifetime of up to ten (10) years, but because of their battery system they can be large in size and heavy [22, 23, 25, 27, 35]. Passive tags, can theoretically last for a lifetime and have a small memory capacity (up to 8KB), though large enough to store important information, such as manufacturing batch, production history, product handling instructions, storage or delivery instructions etc. [17, 22, 23, 25, 27, 29]. Tags can also be categorised as read-only and read-write tags, which differ based on the information they can store and whether the information is stored on a database (e.g. using RFID tags to only store a unique ID with the actual data kept in a remote database) or on the tag itself. Read-write tags can store and process information locally, which is particularly useful when dealing with high-volume, complex supply-chain applications. Active tags, due to owning their power source, have a greater read-write range (5-30m) than passive tags (read-write range of less than 2m long), but are more expensive than passive tags due to higher material and manufacturing costs [29, 34]. As such, active tags are usually applied in special areas where the higher costs and higher detail level of information stored are justified such as for locating large assets, whereas passive tags due to their simplicity, adaptability and resistance to harsh environments have a vast number of applications in a variety of industries and sectors [17, 29, 34]. In interactive applications, such as maintenance and component performance tracking, the read and write capability of an RFID tag is a significant advantage [11, 29]. Generally, the reading and writing ranges depend on the operation frequency (i.e. low, high, ultra-high, and microwave) and the tags that operate at ultra-high frequency (UHF) and microwave, typically have longer reading ranges than the tags that operate at lower frequencies [29, 36]. For example, low frequency (LF) RFID is most popular for access control, but also for animal and human ID, whereas high frequency (HF) tags are widely used for smart cards and asset tracking and supply management. The wide frequency ranges offered by UHF makes this technology ideal for tracking large and expensive objects, and for that reason UHF frequency is the most widely used for both passive and active tags [13, 29, 30, 34].

The choice of the tag, reader, and frequency, and their combinations, affect the performance of the RFID tags and as such the requirements they fulfil vary greatly [20, 29]. This enables users to customise the RFID system they use according to their needs [13, 29, 34]. Although selection is sometimes limited by some of the characteristics of the RFID tags (e.g. size/weight, cost, etc.), technological advances in the field showcase the potential for the next generation of RFID tags to overcome these limitations by the production of a fully printed tag including both antenna and circuit (e.g., thin-film transistor circuits). Meanwhile, as the price of silver-based inks (used to print the RFID antenna) is rising, the use of alternative materials (e.g. graphene and metal nano-particle inks) is increasingly being considered, and research is currently embarked on to justify this innovation’s full-scale potential [34]. In the meantime, as RFID is an evolving technology, an innovation that is likely to emerge over the coming decades is the combination of fully printable RFID tags with additional components (e.g. printable batteries, sensors, etc.) that can broaden the adaptability of the RFID tags. This new class of RFID tags would have the ability to combine the form and costs of a passive RFID label with some of the functionalities of an active RFID tag (the so-called smart active label or SALs) and is expected to prevail in the future [34].

The use of BIM technology

BIM is characterised by its ability to digitally ‘build’ a structure in a computer-aided programme, which represents the physical and functional characteristics of a structure [37-41]. These virtual structures are constructed using virtual components, the characteristics and properties of which are analogous to the physical components available in the market [38, 39]. The quantities and properties of the building components and materials used in BIM, as well as the building and component/product geometry, spatial relationships, geographic information, functionality etc., are typically embedded in BIM, forming a useful database that is created and updated by designers, owners and contractors [40, 41]. Intrinsically BIM, combining the efforts of people, process and technology, brings together useful datasets and offers an effective way of modelling and managing this information in order to view, analyse and test the behaviour of a structure, while also design changes quickly, effortlessly and reliably [38-40]. The information mapping generated through BIM can then be used to support decision-making and improve the process of construction and management [42, 43].

Originally the use of BIM was purposed to support, design, construct and integrate project delivery of buildings and other infrastructure, but recently, its focus and function has shifted to include the whole service life of structures, from early lifecycle maintenance and refurbishment, to deconstruction and EoL management [37, 40, 44]. This has made BIM a powerful tool for use in construction, and its benefits are manifold including design consistency and visualization over the whole lifecycle of the building, cost estimations, 'as-built' documentation, maintenance of warranty and service information, quality control, assessment and monitoring, energy and space management, emergency management and retrofit planning [37, 41]. Furthermore, advances in the BIM technology are called to enable project managers to reengineer their processes towards applying lean construction principles and enabling an enhanced communication between the various stakeholders involved in modern construction projects, with the overarching aim of improving the performance of the construction industry [39, 41, 45-47].

APPLICATION OF RFID AND BIM IN THE CONSTRUCTION SECTOR

A general perspective

The application of RFID is particularly useful in the construction sector as it makes it possible to track and trace construction materials and components, hence increasing the productivity and cost efficiency of construction projects, while improving scheduling, materials management, and site optimisation [11, 26]. The success of the RFID system lies on its ability to read multiple tags simultaneously and instantaneously, allowing a range of mixed products, containing individual RFID tags to be read without having to physically move any of the components [11]. The applications of the RFID technology in the construction sector have been widely documented in the literature [12, 16-23, 25, 26, 33, 36, 48, 49].

These are categorised as follows:

- Construction cost and time management (e.g. enabling accurate logistics and progress management to reduce material loss and time required for the construction [21, 23, 33, 36, 50, 51]);
- Construction quality inspection and management using sensor coupled tags that facilitate measurement of physical parameters (e.g. monitoring temperature variations of placed concrete or asphalt pavement to provide real-time information regarding strength and maturity, and enabling the determination of curing rates and optimum strength [23, 25, 52]; collecting data for concrete specimen inspection and management [14, 49]; improving maintenance efficiency [22, 53]);
- Construction material/components supply management using GPS sensor coupled tags to track and locate components (e.g. tracking materials and components in the supply chain and construction sites, enabling better cost and material management [13, 14, 22, 23, 25, 33, 36, 50]);
- Construction safety management (e.g. providing information about the type and location of hazardous materials, and improving safety conditions by monitoring and locating workers [22, 33]);
- Construction documentation management (e.g. tagging and locating drawings, and original build specifications and layouts [22, 23, 33]);
- Construction waste management (e.g. identifying and sorting components and materials according to their type for proper management [16, 26, 42]);

- Location of buried services (e.g. locating gas and water pipes and communication cables for incidents control and management [14, 23]).

RFID integrated with sensors and GPS technologies is well placed to provide solutions for inventory control and location management during the construction and maintenance phase of construction projects, contributing to the overall sustainability in the construction sector [23]. For instance, the identification of construction components that have to be replaced, renovated, or maintained supported by the use of RFID may enable a better management of the components at the end of the structure's life [22, 54]; the proper tracking and management of materials and components used during the construction phase may reduce the costs and amount of waste generated; the tracking of drawings and documentations may contribute to the uptake of deconstruction interventions that can enable the recovery of components for reuse [10].

Maintenance and/or deconstruction processes can also be achieved through the use of BIM. The potential of BIM to offer an up-to-date building information can reduce the errors and financial risks associated with deconstruction, while it can increase components recovery and improve the safety conditions for workers [37]. However, the type of structures (e.g. residential, commercial, industrial, etc.) and their age (e.g. new, old, heritage) can affect the application of BIM, mainly due to the absence of important information such as, detailed data on construction components and other equipment (e.g. installation dates, fixtures, location, physical properties and function) that needs to be available for the effective maintenance and/or deconstruction of the structure [37]. This problem becomes apparent in existing buildings where the implementation of BIM is limited due to the incompleteness and uncertainty of data, and the lack of the as-built documentation and other drawings [37, 42].

In new structures, this is not much of a problem. BIM is used to visualise and create the design of the new structure with each construction component represented as specific object in the structure that comes with its own geometry and features (e.g. material properties, profile shape, structural capacities, etc.), thereby allowing the maintenance and/or deconstruction activities to become relatively easy, using the as-built documentation [40, 42]. The detailed representation of construction components in a structure, and the availability of information (e.g. component type, material, size and weight, embodied carbon, recyclability and reusability, etc.) regarding their properties and characteristics that is made available through the use of BIM, is crucial for the determination of their reusability and recyclability potential [40]. For example, in the study of Akbarnezhad et al. (2014) it was shown that the information made available through the BIM database could assist in the assessment and selection of the best deconstruction intervention based on structure design and characteristics, as well as the geographical coordinates of recycling and prefabrication facilities and of the structure, hence enabling informed decision-making based on the travel distance, cost, carbon emissions, etc. [40].

In spite of its huge potential, BIM often fails to take into account or visualise real-time changes made to a construction project in response to emergent issues on site, which may create a number of challenges when it comes to proper maintenance and deconstruction [21]. RFID, with its real-time information, visibility and traceability, can bridge the interface between a BIM and a real project [21]. RFID has the potential to link components information and history with the BIM platform database, further enhancing the ability of BIM to collect actual and detailed (hazardous) material information, components' masses and connections, and other information relevant to maintenance and/or deconstruction planning, improving as such quality control and management [16, 26, 37]. In addition, tagged components salvaged from existing structures, can be added into the BIM database, making it possible for these to be imported into new BIM designs based on their remaining functionality and intended use [26]. Therefore, RFID-BIM has the potential to stimulate a new way of thinking in the construction sector by promoting its use for green building design addressing key sustainability issues [44, 55]. An element of green building design that grows in importance, due to its potential to reduce raw material use, wastage and carbon footprint, is the recovery and reuse of construction components through deconstruction interventions [40, 44, 47, 55].

Managing secondary construction components reuse

For enabling the better management of construction components, the use of the RFID-BIM application seems to be an innovative disruption in the construction sector, which has only been recently highlighted [15, 16, 26]. Connecting RFID tags with BIM enables components to be tracked, located, and imported into designing processes, hence adding new capabilities to the design of new sustainable structures. Information about the suitability of a component to be reused or recycled after the first, second or *n-th* cycle of its service life is important for promoting and enhancing sustainability in the construction sector.

Although the RFID tagging of components would occur at the production stage, the information related to its processing and use has to be updated throughout the lifecycle of the component [56, 57]. This is because a component’s life story evolves from design and production to use and reuse as it is subjected to changes during the construction, use and deconstruction phases that can transform its characteristics and functionality. Therefore, updating the information stored in a component’s RFID tag throughout its lifecycle can improve the way components are recovered and reused, providing confidence to designers and engineers that the suitability of a construction component to be reused in a new structure can be assessed not only on nominal properties, but the evolution of these properties with time [15, 40, 54]. For example, date and place of manufacturer, life span in situ, embodied carbon, loading history, maximum moment and shear capacity, connections and fixtures used, inspection results after deconstruction, etc., are important data that can and must be recorded on a component’s RFID tag, and dynamically updated as attributes of that unique component into the BIM database, to enable its sustainable lifecycle management. The designers can then use the database to use salvaged components in new structures based on their properties and availability, by changing the design and layout of the designed structure without risking its integrity [16, 26, 40]. **Figure 2** presents the different levels of information required for managing the reuse of construction components.

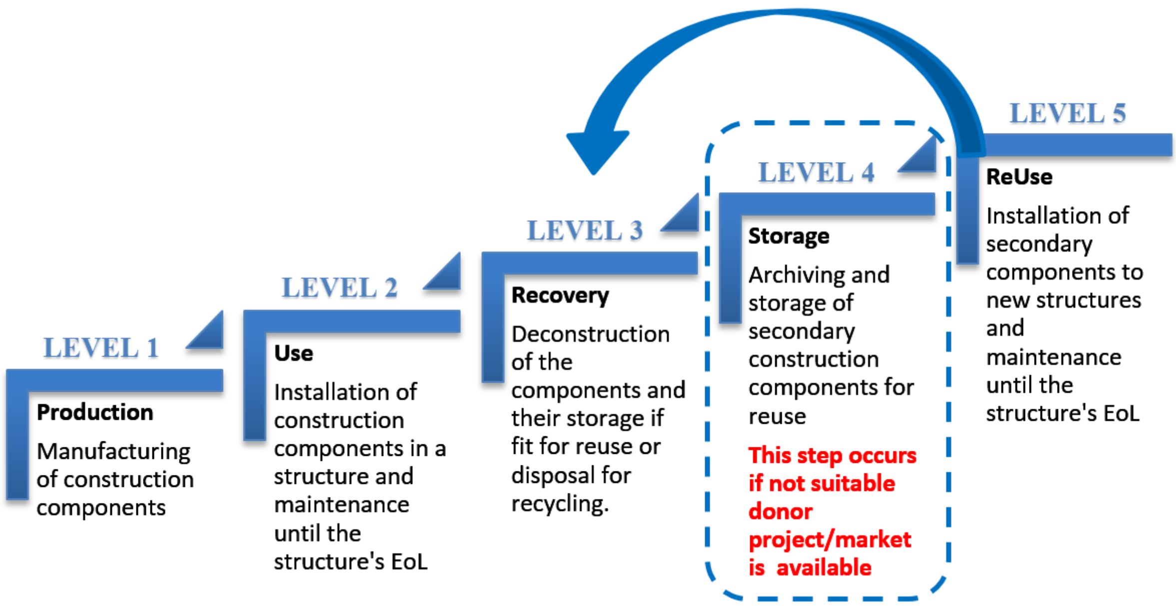

Figure 2 Levels of information flow required for managing construction components reuse

In order that the benefits of RFID tagging are realised for all, it requires the co-operation of various actors along the supply chain to guarantee its functionality and updating during the component's life-cycle [11, 58]. Once all stakeholders consent to the use of RFID, the information stored on the RFID tags through the entire life of the components would play an important role in aiding efficient communication between the stakeholders, and in enabling a vigorous transformation of the currently unsustainable practices into more effective and resourceful ones with reusability at their core. However, the type of information that is to be stored in the RFID tags for promoting construction components' reuse - and sustainability overall - is perhaps one of the most important factors in certifying the successful uptake of this technology. This information can be divided into two categories:

- *Nominal information (static, essential):* this is the information that characterises the component in its as-installed state, analogous to that contained on the 'data sheet' traditionally issued by suppliers and delivered alongside the component; the supplier, the date of manufacture, size and weight etc. Referring to the proposed typology given in Iacovidou and Purnell (2016) and presented in **Table 1**, this would include the action of the component (i.e. its structural and/or functional role as installed), the material from which it is made and grade thereof, the installation method and connection type, and the type of structure in which it was deployed. It might also include inferred residual capacity information (i.e. how the component was expected to degrade with time in service) and information on the previous reuse history, if any. Environmental impact information such as embodied carbon, energy or water should also be included.

- *Service history information (dynamic, desirable):* this is information that evolves in response to the physical and environmental loads the component endures during its service lifetime. Again, referring to the typology of construction components, records of environmental conditions (temperature, humidity, chemical exposure etc.), loading history (stresses, strains, accidental damage), and further information allowing calculation of residual properties (e.g. evidence of corrosion, records from monitoring programs such as acoustic emissions) would allow much greater confidence in the reuse potential of the component, or conversely flag a component as being unfit for reuse and ready for recycling.

Further information would need to be added at the EoL stage. The techniques and procedures used to recover the component, any resultant impairments to components, particularly in regards to the state of the connections, etc. would need to be added, along with general inventory information such as storage location and conditions. It should also be possible for residual capacity measurements to be taken and thus the 'data sheet' for the component can be updated should dynamic service history information not be available. **Table 1** lists the secondary component classifications suggested by Iacovidou and Purnell (2016) for developing a coherent and consistent typology system for secondary components, presented herein alongside the levels of information required for each component classification and its nature (*static* or *dynamic*), as a guidance for capturing all the information relevant to the component for promoting its reuse.

Table 1 Levels of information required for the typology of recovered structural components based on one and more service cycles

Component Classifications*			**Information Level**	**Information classification**
1	**Action**	Physico-mechanical role of the component at deployment.	2, 5	Static
2	**Material**	Grade and quality of materials used (especially for structural components) and recycled content.	1	Static
3	**Deployment**	Structure type in which the component was previously used.	2, 5	Static
4	**Exposure**	Environmental conditions to which the component has been subjected.	2, 4, 5	Dynamic
5	**Loading**	Physico-mechanical fate (e.g. loading history) of the component. For functional components, loadings might be expressed in other terms (e.g. electrical, traffic).	2, 5	Dynamic
6	**Recovery**	Component handling and removal methods from the structure.	3	Static
7	**Residual**	Structural and functional properties of the component remaining (inspection at deconstruction site).	2, 3, 5	Dynamic
8	**Connections**	Capacity of the component to be connected to other structural and/or functional components and artefacts.	1, 5	Static
9	**Availability**	Details of when and where a component is likely to be available, and in what quantity based on generation and demand.	3,4,5	Dynamic

10	**Regeneration**	The number of service cycles of the component through reuse, and its thereafter upcycling, recycling or down-cycling/cascading.	1,2,3,4,5	Static

*Details on proposed components classifications can be found in Iacovidou and Purnell (2016)

The amount of data that can be stored on the tag *(static, essential information)*, the capability to modify the data on the tag after it has been initially programmed (*dynamic, desirable information*), and the lifetime of the tag to ensure its functionality over the components lifecycle, are important aspects that have to be taken into account [14]. *Static information* does not vary with time and as such is best suited to the use of passive RFID tags. On the contrary, *dynamic information* is addendum to the nominal information and as such is better suited to active RFID tags. This dynamic information would be gained from in-situ and/or ex-situ monitoring equipment; in the former case, RFIDs could share a power supply with these systems, but in the latter case, passive or semi-active RFID tags would need to be updated at the same time as the monitoring event takes place. However, with components having different service lifecycles that can range from 10 to over 50 years it is important for the RFID tags attached to them to be able to function for longer periods than are common in other industries. These tags should have long reading ranges and be attached to clearly defined locations in a component so that they can be read. Some common rules and best practices about the location of the tag should be agreed upon to guarantee the readability of tags and ease the reading process [11]. In choosing the attachment method, the reusability of the RFID tags should also be taken into consideration. For instance, if the component is made of metal, the tag needs to be mounted approximately 1 cm from the metal surface to avoid interference [25]. Further details on these topics are explored in the next section.

For new components used in new structures, the longer lifetime of the UHF passive tags, as well as their ability to retain important lifecycle information about component installation, use and maintenance, which is essential for the efficient recovery and management of the component at the end of the structure's life time, makes them a wiser choice over active tags. However, the use of passive tags has the drawback that the RFID reader has to be within a few inches from the tag for proper reading [17]. For components recovered from existing structures where RFID tags have not been previously used, active UHF RFID tags seem to be well-suited especially when components are stored in salvage yards where long reading/detection distances are required in order to make the identification and selection of the desired components for reuse an informed and liable task [36]. However active tags require their internal battery to be replaced approximately every 3-10 years, posing a real challenge when it comes to their selection for tracking and managing the lifecycle information of secondary construction components used in new structures [59]. Consequently, there will be a need for active tags to be replaced by UHF passive tags once the secondary components are going be installed into new structures, in order to ensure their proper tracking, maintenance and recovery at the structure's EoL.

Technological developments in this field have shown that the lifetime of active UHF tags can be significantly improved by using energy harvesting devices that allow a significant reduction in the capacity of the on-board energy storage, while they incorporate additional features such as temperature sensing [60, 61]. However, much research is still needed to assess their suitability for tagging products, including construction components. With improvements in the field of smart active labels (SALs), it is expected in the future that these tags are going to prevail due to their enhanced functionality and superior performance over existing passive labels [34]. Furthermore, advances that will enable sensor coupled RFID tags to monitor the impact of physical values (e.g. temperature, pressure, harmful agents: toxic chemicals, bacterial agents, etc.) on the component's performance, and its transmission to the reader in place of the tag's stored memory contents can be an innovative way to increase confidence in the structural properties of the existing components for reuse in new structures [23, 26]. However, further research is still required in these fields.

OPPORTUNITIES AND CONSTRAINTS IN PROMOTING REUSE THROUGH RFID

At present, the recovery and reuse of construction components at the end of a structure's life is limited. This is largely due to the fact that information about a structure's components and maintenance (e.g. material grade, material strength, properties, construction techniques used and the way components are connected with other components, maintenance cycles) that is required by workers in order to properly recover components and direct them for reuse at the deconstruction stage, is either absent or not easily accessible, rendering deconstruction a time-consuming, labour-intensive and cost-inefficient process [10]. This lowers the level of reliability in the properties and characteristics of construction components, necessitating an inspection process to certify component's quality and suitability for reuse; a procedure that takes time and skilled workforce, creating a gap between deconstruction and reuse phase.

The RFID technology has the potential to bridge this gap and create value by transforming useful information about the components properties, characteristics and performance, into important knowledge during all phases of its lifecycle [15, 36, 57, 58, 62]. This knowledge flow that the RFID technology can provide (as presented in the previous section), not only it can boost the recovery and reuse of construction components, but it can enable the recovery and creation of value [54, 57, 58]. This value can be realised at multiple dimensions, as follows:

- *Technical*: Optimisation of the expected function of the component, improved handling and successful removal/installation of secondary components from/to the right location using the right hardware and connection material after exploiting the embedded data and information (e.g. material data, embodied carbon, production conditions, inspection results, installation, connections and joints used, and repairs conducted) stored in its RFID tag through its lifecycle; data accessibility up until component's EoL phase [16, 26, 36, 58];
- *Economic:* Creation of economic value for the designer and contractor (e.g. green building achievement, lower costs and increased profit), the user (e.g. lower project costs), the salvage yard operators and distributors (e.g. new business opportunities with economic benefits), the component manufacturer (e.g. building reliability and preference, increasing profits through product preference and by repairing/refabricating existing ones, and minimising costs of production due to longer component life), and the waste managers (e.g. improved handling and recycling);
- *Environmental:* Reduction in carbon emissions, toxicity and the use of virgin resources by optimising the functionality of components through proper maintenance and end of their primary life planning [36,

58]; improved waste management when components reach their EoL due to the inclusion of data useful in sustainable waste collection, management and disposal [34];

- *Social:* Confidence over safety for the end user when salvaged components are used; improved welfare through the benefits generated by the reuse of construction components [58]; provision of valuable information about the behaviour of all stakeholders involved in the life story of a construction component (from its production to its final disposal), and waste management performance [34].

As it seems, the uptake of RFID technology can realise the capture and creation of multiple values through improving the lifecycle management of construction components. However, technical limitations can distort this depiction. The material of the component to which the tags are adhered could severely interfere with the operation of RFID [23, 25]. Metals (e.g. steel components), water/humidity and congestion in the environment (e.g. obstructing components) are known to cause radio signal interference that can influence the performance of the RFID by reducing the read range distance to one fifth and one half of the reading distance expected in open air [13, 21, 36, 59]. For example, in the study of Kiziltas et al. (2008) it was shown that for a tagged component placed underneath a ceiling panel and moderately surrounded by metal, the average reading distance was half of the original reading distance, whereas for a component surrounded by metal and partially blocked by a wall, the average reading distance was 20-25% of the original distance [59]. This performance reduction is caused via reflection or absorption of the radio signals by the objects in the environment. To minimize this effect, encapsulated tags are normally used [36, 59]. In addition, in highly metallic and congested environments, multiple antennae can be used to ameliorate performance issues [17, 59]. Furthermore, if there are electromagnetic sources working under a frequency similar to that of the system, special considerations should be made. To address interference limitations, new tags have been designed to be mounted on metallic objects, reaching a similar read range when mounted on metallic surfaces and working in free space [25].

Another limitation of RFID is in regards to the ability of its components (e.g., RFID readers, tags, hardware and software system) to work harmoniously and communicate effectively. Reading multiple times by the same reader in a short time-span (e.g., at entrance or exit gates) can result in a large data flow, that requires a fast system response in processing and filtering the data received, and transferring the necessary information to the related databases and applications such as BIM [59]. Also identifying accurately the position of a component in a structure can sometimes be a challenging task, due to the similarity of components installed at the same space [23, 25]. Moreover, the way components are fixed together in a structure can cause signal diminution which would reduce the tracking ability of a specific component. Tags location in a component and fixture methods used during construction may have to be reconsidered for enabling the use of RFID to become mainstream [23]. The development of common RFID technical standards is currently restricting its development and uptake in the construction sector [29]. The low degree of standardization does not facilitate the proper use of RFID by the various actors in the supply chain withholding much of its potential [21, 22, 29]. The frequency ranges used for RFID in one country are currently incompatible with those used in other countries enlarging the gap between secondary components exchange and development of secondary markets with a global appeal [21, 29].

Despite the aforementioned limitations, which with technological advances and policy development might be addressed in the future, an important factor that has to be taken into account when it comes to the use of RFID is in regards to component recycling when it can no longer be functional. RFID tags and its contained materials might affect the recycling processes and/or the quality of the recyclates, hence creating a problem [34]. RFID tags are complex objects composed of different organic and inorganic materials. The main components of an RFID tag are the antenna made of copper or aluminium (and silver for printed tags), the integrated circuit chip, made of silicon and gold (for bumps) and encapsulation made out of paper and plastic (i.e. polyethylene terephthalate (PET) and polypropylene (PP)), while in the case of active tags nickel batteries are also present [34, 63]. The tags can be between 10 and 40 cm^2 in size and weigh about 12 - 56 g, in the form of a flat square, which can be embedded in a plastic article during moulding, or adhered to its surface using polyurethane or acrylate. At present, there is not a method for separating RFID tags attached to components, and as such they end up in each of the construction components waste stream, significantly increasing the risk of compromising the quality of the recyclate due to contamination [34]. However, removal is possible, using a soluble adhesive and a wash stage before granulation, but it adds additional process complexity and thus not yet considered [63].

The metals (e.g. copper, aluminium, nickel, gold, etc.) and plastic can be the sources of contamination expected from the RFID tags. For example, copper found in RFID tags can contaminate the steel making process and impair the quality of the steel elements. In Europe the limits of copper content in all grades of steel making is less than 0.5%, and although the copper found in the RFID tag can be in the range of 57 and 267 mg (depending on the tag dimensions), which is minimal compared to the tonnes of ferrous metals used in the conversion process, copper's cumulative nature over time may impair the quality of steel in the long-term [34, 64]. As opposed to copper, aluminium is oxidised during the melting process and transferred to the slag phase. Silicon is also transferred to the slag phase, whereas paper and plastic are burnt [34]. Similarly, in aluminium recycling, copper is an accumulating metal and unintentionally become an alloying element in the long-term that cannot be extracted, hence affecting aluminium quality [34]. In wood recycling, the tolerance in copper contamination is 40 mg/kg for recycled wood in panel board manufacture, and 200 mg/kg for recycled wood in both porous and non-porous surface applications [65]. The critical contaminant in wood recycling is plastic, as it cannot be removed affecting the end uses of the wood (e.g. biofuel) [65]. Flame retardants or pigments used in the tag's plastic layers, such as potassium or bromine, may also be carried into the recycling or disposal processes [34, 64]. Although, the amounts might be minimal, these might be critical in the environmental performance of the recycled components and as such, their fate has to be assessed. However, it is not the purpose of this paper to analyse the impact of RFID tags on the quality of the recyclates, but merely to provide an insight into the potential limitations that might occur when tags are introduced into the recycling processes. Impacts on quality can infer impacts on the economy, the environment and the society in general, and as such further research needs to be carried out in order to foresee any threats that might be imposed due to the use of RFID.

Table 2 attempts to summarise the strengths and weaknesses of RFID, and provide an insight into the short-, medium- and long-term opportunities that can be created through its use and potential threats that might hinder this technology from becoming a widespread tool.

Table 2 SWOT statement for the potential of RFID technology in enabling construction components reuse

	STRENGTHS	WEAKNESSES
DIRECT	Identifies, locates and tracks components without human intervention[11, 13, 15-17, 20-23, 25, 26, 29, 31, 34, 36, 47, 49, 53, 56, 58, 59, 66, 67] Stores and retrieves large volume of data at any time [11, 13, 15, 17, 21, 29, 36, 49, 56, 66] Enables non line-of-sight scanning[11, 15, 20, 29, 36, 47, 49, 53] Simultaneous reading of large volumes of data[11, 15, 29, 36, 53] Enhances tracking and forecasting of components performance[11, 20, 21, 36] Increases reliability and accuracy[11, 17, 29, 36] Robust and durable[11, 17, 20, 23, 29, 36, 49, 53] Operates in harsh environments[11, 15, 17, 23, 29, 36] Read-write ability and logging of lifecycle information[11, 15, 20, 21, 29, 36, 49, 53] Reduces logistics in construction-deconstruction and reuse[11, 15, 29] Ability to test the condition of tags and assess their current status and remaining useful life[11] Can be combined with GPS, sensors and BIM technologies[11, 15, 17, 21, 23, 36, 49, 53, 56, 66]	Signal diminution due to interference by metals, obstructing components and water[13, 15, 21-23, 29, 36, 59] Signal collision increasing failure in detecting the position of a component in a structure[15, 21, 23, 25, 29] Reader ability affected by the thickness of substrate material on component surfaces, component material texture and oxidation on the RFID tag[11, 15, 29, 49] Lack of international RFID technical standards[15, 21-23, 29] Lack of standards regarding frequency range[21, 23, 29] Cost restricting the development of RFID technology and its infrastructure[11, 15, 16, 21-23, 25, 29, 31, 36, 49] Tags vulnerability/failure over time[15, 29]
	OPPORTUNITIES	**THREATS**
INDIRECT	Optimises the functionality of construction components[11, 23, 26, 36, 58, 66] Improves handling/removal/installation of components for reuse[11, 26, 36, 58] Enables data storage accessibility up until component's EoL phase[11, 23, 26, 36, 58, 66] Creates economic value for all stakeholders involved in the construction sector[29] Reduces environmental impacts through reduction of components wastage and augmentation of their reuse[15, 36, 58] Empowers proper maintenance and end of primary life planning for construction components[15, 36, 58] Improves the collection and sorting of construction components at their EoL stage[15, 34] Improves economic and social welfare through benefits generated by construction components reuse[58] Provides a great understanding of the behaviour of all stakeholders involved in the life story of a construction component and waste management performance[34, 66] Enables communication between all stakeholders[66]	Lack of training and limited knowledge on the use and capabilities of the technology in the construction sector[11] Unwillingness to invest in RFID due to concerns about investment return[11] Lack of unified standards and best of practice guidance[11, 29, 34, 67] Environmental, economic and technical issues of existing and new tags in the recycling of wasted components[15, 34, 67] Impact of existing and new design considerations on impairing communication between stakeholders and altering the benefits of new business models due to changes in information flow[67]

The SWOT statement presented in the table above indicates that there is a need to address the threats and weaknesses of RFID, for its full potential to be realised. To achieve that we need to gain a better understanding of where innovation and deployment investments in the RFID technology are likely to return the greatest advantages, not only in technical and economic terms, but also in environmental and social, so as to fully capture the value that this technology can provide. Currently, policies that regulate the use and management of RFID tags do not exist. However, removing the tags prior to recycling of construction components is a bifold necessity; first in order to ensure the quality of the materials recovered for recycling, and second to ensure that the RFID uptake for promoting reuse is not compromised by the inability of RFID tags to be detached from the component at its EoL stage. Therefore a protocol for removing RFID tags prior to recycling is needed. Nevertheless, it is important to ensure that the technological advances made in this field (i.e. to deal with RFID's limitations, etc.) are not debilitated by immature legislation enforcement, or specifications development [34].

Finally, awareness is key; stakeholders involved at the various stages of the construction supply chain from RFID designers to waste managers, must be made aware of the potential of RFID in controlling and managing resources at all stages of construction-deconstruction-reuse-disposal and be trained to learn how to properly use this technology in order to ensure full realisation of its benefits. Once RFID and RFID–BIM technologies become established, it should become a prerequisite for all designers and construction companies to learn how to use both of them. This would enable them to properly assess the technical and economic feasibility of new approaches with a focus on sustainability, maximising the multiple benefits that such approaches can offer. Overall, by achieving improved communication between all the stakeholders involved, by maintaining the information flow through the various levels of construction-deconstruction-reuse and by demonstrating commitment to improving awareness and sustainability in the construction sector, potential uptake of the RFID technology is likely to grow. This is especially when technological advances might provide solutions to its current limitations, and sustainability issues become more pressing.

CONCLUSIONS

A prerequisite when dealing with construction components management, is to understand how their characteristics and functionality is transformed at each step of the supply chain. This information if properly recovered and stored can be a valuable tool in promoting their recovery and reuse. RFID is an efficient technology for capturing and retaining this information flow in a sustainable fashion, due to its capacity to store, transfer and access a relatively large number of data. RFID's combination with BIM can be one of the most important technological innovations in the construction sector due to its capability to design new structures by utilising secondary components logged in its database. Notwithstanding its potential, the development and successful application of the RFID-BIM technology, is still a niche. Nonetheless, RFID can be used as a standalone technology aiding not only the reuse and sustainable lifecycle management of construction components, but also the efficient communication between all stakeholders involved in the construction supply chain, from tag designers to CDW managers, refining the performance of both the construction and waste management sectors. Moreover, the widespread uptake of RFID in the construction sector can create the right conditions for new business models to flourish, carrying the potential to unlock multiple technical, environmental, economic, and social benefits. Full utilisation of the capacity of RFID technology is needed in order to capture its real value. With technological advances providing the means to solve RFID's technical limitations and further enhance its abilities by incorporating additional features such as GPS and sensor technologies, and with policy development enabling its control and sustainable management at all stages of the supply chain, its mainstream use as a construction components reuse enabler might soon become realised.

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