Linking radio-frequency identification to Building Information Modeling: Status quo, development trajectory, and guidelines for practitioners

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Abstract

The global construction industry has witnessed the prolific development of radio-frequency identification (RFID), building information modeling (BIM), and most recently, linkage of the two. However, comparatively little attention has been paid to understanding the status quo and development trajectory of such RFID-enabled BIM systems. In view of the proliferation of existing RFID, BIM, and information linkage, practitioners would benefit from a guideline for choosing systems so that their construction engineering and management (CEM) needs can be better met. Accordingly, the study described in this paper has two interconnected research aims: (1) to identify current patterns and development trends in RFID-enabled BIM systems; and (2) to develop a guideline for choosing appropriate solutions for different CEM scenarios. A review of 42 actual cases published in scholarly papers reveals that RFID, used to identify objects and improve real-time information visibility and traceability, is now increasingly linked to BIM as a central information platform. This study provides practitioners with a five-step guideline for linking RFID to BIM for various CEM needs. It also provides researchers with a point of departure for further exploration of approaches to enhancing the value of RFID, BIM, and the integration of one with the other.

Keywords: Radio-frequency identification (RFID); building information modeling (BIM); linking RFID to BIM; systematic review; guideline.

1 Introduction

Building information modeling (BIM) and radio-frequency identification (RFID) have been receiving considerable and increasing attention from researchers and practitioners over the last decade or so. According to the NIBS (National Institute of Building Sciences, 2015), BIM is "a digital representation of physical and functional characteristics of a facility. BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle; defined as existing from earliest conception to demolition". Goedert and Meadati (2008) characterize BIM as an ideal information hub, enabling retrieval and display of essential information in formats consistent with the needs of managers. This information may be geometric, semantic, or topological (Schlueter and Thesseling, 2009; Xue et al., 2018), and to support decision-making throughout the facility's lifecycle it must be continually updated to reflect the facility's as-built condition. The interoperability of BIM can improve communication amongst parties (Arayici et al., 2011; Aram et al., 2013; Alwisy et al., 2018). As a digital platform, BIM can also retain information or knowledge (e.g., the design rationale). Further, it can be used to improve quality control (Chen and Luo, 2014), enhance safety management (Kumar and Bansal, 2018), and help construction waste estimation (Lu et al., 2017).

RFID uses radio waves to read and capture data. The three main components of a typical RFID system are: (1) a RFID tag or transporter carrying ID or other information; (2) a two-way radio transmitter-receiver, known as a reader or interrogator; and (3) a backend system that stores and processes the information for various applications (Finkenzeller, 2010). An RFID system can operate at different bandwidths, from narrow to ultra-wide (UWB). A narrow-band RFID system can be further categorized as low frequency (LF), high frequency (HF), ultra-high frequency (UHF), or microwave (MW). RFID tags can be passive (without batteries) or active (with built-in batteries), depending on the power supply. RFID systems are contactless, independent of line of sight, and robust in harsh conditions (Jaselskis and El-Misalami, 2003). In addition, multiple tags can be read simultaneously. Cost aside, RFID systems have advantages over barcodes, QR codes, and other auto-ID technologies (Flanagan et al., 2014). Chief among these advantages is that RFID systems increase real-time information visibility and traceability (Lu et al., 2011). Consequently, industries such as manufacturing, agriculture, and healthcare are making use of RFID systems for identification, tracking, locating, and recording (Ruiz-Garcia and Lunadei, 2011; Yao et al., 2012; Zhu et al., 2012; Zhong et al., 2013); as is the construction industry (Jaselskis and El-Misalami, 2003; Goodrum, 2006; Wing, 2006; Domdouzis et al., 2007; Wang, 2008; Lu et al., 2011; Grau et al., 2012; Valero et al., 2015).

Increasingly, researchers have been exploring the linking of RFID to BIM in construction for such things as resource management, logistics and supply chain management, process tracking, safety management, and facility management (Chin et al., 2008; Motamedi and Hammad, 2009; Cheng and Chang, 2011; Lu et al., 2011; Fang et al., 2016). In RFID-enabled BIM systems, real-time information visibility and traceability are improved; physical construction objects can be identified with their up-to-date information linked to the “as-built” BIM, which acts as the typical RFID system backend. The physical building process and the cyber BIM - in other words, the “cyber” and “physical” twins - are now connected to form a cyber-physical system (CPS); they can “talk” to each other. The benefits of both BIM and RFID can be better leveraged in combination than in isolation (Chen et al., 2015); this becomes evident in numerous construction engineering and management (CEM) cases that have been reported in academic papers. However, its application so far in actual projects is still largely *ad-hoc* due to practitioners' limited understanding of it (Chen et al., 2015; Pezeshki and Ivari, 2016).

The gaps between industry needs and available academic research have been converted to the following research questions for the purposes of this paper:
(1) What are the current patterns and development trends of research linking RFID to BIM?
(2) How to help practitioners understand the diverse RFID-enabled BIM systems and make appropriate selections to suit real-life CEM needs?

In answering these two questions, an inclusive review of previous literature is conducted to revisit existing RFID-enabled systems from previous studies. This review also sheds light on how to select and deploy RFID-enabled systems according to various CEM needs. The aims of this study are therefore to: (1) identify the current patterns and development trends of linking RFID to BIM; and (2) develop the guideline for understanding and choosing appropriate RFID-enabled BIM systems for CEM activities. The rest of this paper is organized as follows. Section 2 first introduces a conceptual model for linking RFID to BIM to identify its main components, and then presents a thorough literature search to identify actual cases. Data extracted from these cases are analyzed in Section 3 by focusing on their status-quo pattern and development trajectory. Based on the analyzed patterns and evident trends, a five-step guideline is compiled in Section 4, and the implementation of the guideline is demonstrated in a real-life case of RFID-enabled BIM system application. Section 5 presents a conclusion to the study.

2 Research methods

2.1 A conceptual model

To help articulate the research aims and guide the research design, a conceptual model was proposed from the outset (see Figure 1). The three interconnected components of the model, namely, a RFID system, BIM, and the information linkage, should be applicable to real-life

CEM activities. The RFID system senses and identifies the useful properties (e.g., the ID or location) of an object (e.g., a building component or item of equipment) or personnel in various project phases (Lu et al., 2011). BIM, both in 3D and 2D digital representation, can process (with its computation functions) and visualize information (i.e., offering real-time information visibility and traceability) to support decision-making. The model can be imported to a cloud platform for remote access, or it can be used in a standalone manner (Wong et al., 2014). The information linkage component refers to communication of information (i.e., the properties) between the RFID system and BIM, which can be bi-directional. The information collected by the RFID system can be used to update the original information contained in BIM. In the meantime, BIM can provide information to be synchronized in the RFID system.

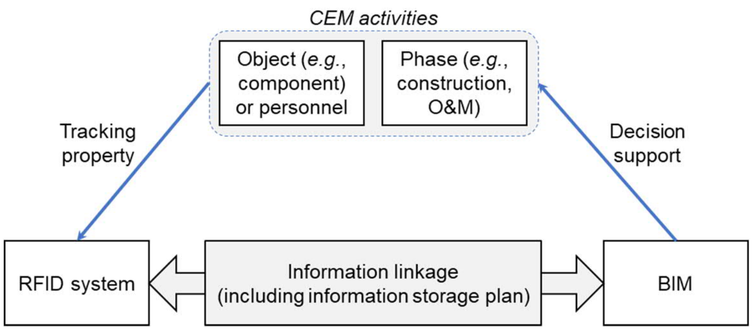


Figure 1. Conceptual model linking RFID to BIM for CEM activities

The options of the RFID system, BIM, and information storage plan are clearly listed in Table 1. What is unclear is how they have been considered in relation to real-life CEM activities (involving various properties of different objects in various phases), and whether they can be developed into a guideline for linking RFID to BIM to support future CEM activities.

Table 1. The three main components linking RFID to BIM

	Possible options		**Explanations**
RFID system	Frequency	LF	125-135 kHz
		HF	13.56 MHz
		UHF	433 MHz; 865-956 MHz
		MW	2.45-5.8 GHz
		UWB	3.1-10 GHz
	Type	active	with built-in batteries in tags
		passive	without built-in batteries
BIM	Digital representation	3D	The model is presented in 3D
		2D	The model is presented in 2D, e.g., floor plan

	Cloud-based	Yes	The model is stored on cloud servers that allow remote access.
		No	The model is stored on a local digital device (e.g., a workstation not allowing remote access).
Information storage plan	In both BIM and RFID tags		The collected information will be used to update both BIM and RFID tags.
	In BIM only		The collected information will be used to update BIM only.
	In RFID tags only		The collected information will be used to update RFID tags only.
	In third-party database		The collected information will be recorded in neither BIM nor RFID tags, but in a third-party database.

2.2 Literature search

Based on the conceptual model and following the PRISMA (preferred reporting items for systematic reviews and meta-analyses) protocols (Moher et al., 2009), a literature search was conducted. It started with Google Scholar on 29 November 2017 using the query combination '(RFID OR UWB OR NFC OR "smart card") (construction OR infrastructure OR building) BIM'. The query means that the target publications must have explicitly mentioned a technical RFID term, a construction term, and the term 'BIM'. Since the term BIM was not widely accepted until the year 2002 (Eastman et al., 2011), this review surveyed literature published between 2002 and 2017. In addition, the search was further restricted to the English literature, excluding patents and law cases.

The search initially produced 2,190 hits including journal and conference papers, books, dissertations, and reports. The titles and abstracts then were screened for suitability. The hits in research areas irrelevant to CEM, e.g., medicine and agriculture, and those not focusing on BIM and RFID, were excluded. The full texts of 264 papers passing the preliminary screening were then downloaded and further refined by the authors based on two criteria: (1) including RFID and BIM in actual CEM applications; and (2) an original contribution (not a review article) with sufficient technical details elaborated in the actual applications. A total of 41 publications, including 22 journal articles, 16 conference papers, 2 theses, and 1 technical report, were finally collected for analyses. The number of hits seems somewhat small in light of widespread promotion of RFID and BIM in the construction industry. However, the selected papers, together with the remaining 264 papers searched, form a very useful information base from which meaningful findings can be derived.

2.3 Data extraction and analyses

Data was manually extracted from the publications. Table 2 is a summary of the information, including the reference, project phase, target object (including personnel), property of the target object, details of the monitored information, radio frequency adopted, involvement of active (battery-powered) tags, information storage plan, and BIM.

Table 2. List of 42 actual cases of linking RFID to BIM

Reference (Author-year)	Phase*	Information to monitor			RFID type+		Information storage plan	BIM#	
		Obj†	Prop‡	Details	Frequency	A?		Type	Cloud?
Hammad and Motamedi (2007)	Const.	C	Sta.	Activity timeline	UHF		BIM	3D-M	
Hämäläinen and Ikonen (2008)	Const.	C	Rec.	Inspection result	HF	√	RFID	3D-M	
Chin et al. (2008)	Const.	M	Sta.	Activity timeline	LF		BIM	3D-M	
Motamedi and Hammad (2009)	Const.	C	Rec.	Progress	UHF		BIM+RFID	3D-M	
	O&M	C	Rec.	Inspection records	UHF		BIM+RFID	3D-M	
Razavi and Haas (2010)	Const.	M	Loc.	Material's location	UHF^		3rd party	2D-FP	
Xie et al. (2010)	Const.	C	Loc.	Steel frame's location	UHF^		3rd party	3D-M	
Azimi et al. (2011)	Const.	C	Sta.	Steel piece's locations over time	UHF^		3rd party	3D-M	
El-Omari and Moselhi (2011)	Const.	C	Sta.	Activity & progress	UHF		BIM	3D-M	
Shahi et al. (2012)	Const.	M	Loc.	Material's location & progress	UWB		BIM	3D-M	
Ding et al. (2013)	Const.	P	Loc.	Worker's location	UHF^		BIM	2D-FP	
Ikonen et al. (2013)	Const.	C	Sta.	Activity timeline	HF & UHF		3rd party	3D-M	√
Shahi et al. (2013)	Const.	C	Loc.	Location-based activity	UWB		3rd party	3D-M	
Guo et al. (2014)	Const.	P	Loc.	Safety of a worker's location	UHF^		3rd party	3D-M	
Sattineni (2014)	Const.	P	Loc.	Indoor location	UHF		BIM	3D-M	√
Costin et al. (2015)	Const.	P	Loc.	Worker's location	UHF		BIM	3D-M	
Zhang and Bai (2015)	Const.	C	Strain	Strain and breakage	UHF		BIM+RFID	3D-M	
Fang et al. (2016)	Const.	P	Loc.	Worker's location	UHF		BIM	3D-M	√
Srewil et al. (2016)	Const.	C	Loc.	Component's location	UHF		BIM	3D-M	√
Niu et al. (2017)	Const.	C	Sta.	Component's status	UHF^		BIM	3D-M	√
Mirzaeifar et al. (2017)	Const.	C	Sta.	Logistic status	HF		3rd party	3D-M	√

Zhong et al. (2017)	Const.	C	Sta.	Status and locations	HF & UHF^		BIM	3D-M	√
Rueppel and Stuebbe (2008)	O&M	P	Loc.	Fire fighter's location	UHF & UWB		3rd party	2D-FP	√
Cong et al. (2010)	O&M	C	Rec.	Repair record, inventory	UHF	√	3rd party	2D-FP	
Krukowski and Arsenijevic (2010)	O&M	P	Loc.	Indoor location	MW	√	3rd party	2D-FP	√
Meadati et al. (2010)	O&M	C	Sta.	Component's status	UHF		BIM	3D-M	
Petrushevski (2012)	O&M	P	Loc.	User's presence for light control	HF		3rd party	2D-FP	
Shen et al. (2012)	O&M	C	Loc.	Asset's location	LF^		BIM	2D-FP	√
Zhang et al. (2013)	O&M	C	Sig.	Visible area of a grid	MW	√	3rd party	3D-M	
Akanmu et al. (2014)	O&M	C	Sta.	Component's status, e.g., failure	UHF^		BIM	3D-M	
Masoudifar et al. (2014)	O&M	C	Loc.	Facility's location	UWB		3rd party	2D-FP	
Montaser and Moselhi (2014)	O&M	P	Loc.	Indoor location	UHF		BIM	3D-M	
Rafiee (2014)	O&M	P	Loc.	locations of authorized persons	UWB		BIM	3D-M	
Costin and Teizer (2015)	O&M	P	Loc.	Indoor location	UHF		3rd party	3D-M	
Tomasi et al. (2015)	O&M	P	Loc.	Indoor location	UWB		3rd party	3D-M	
Chai et al. (2015)	O&M	P	Loc.	Indoor location	UHF	√	3rd party	2D-FP	
Chan et al. (2016)	O&M	C	Loc.	Fault localization	UHF & UWB		3rd party	3D-M	
Motamedi et al. (2016)	O&M	C	Rec.	Record before inspection	UHF	√	BIM+RFID	3D-M	
Jørstad (2016)	O&M	P	Loc.	Indoor location	MW^	√^	BIM	3D-M	√
Park et al. (2016)	O&M	C	Loc.	Indoor location	UWB		3rd party	3D-M	
Hu et al. (2017)	O&M	C	Loc.	Facility's location	UHF^		BIM	3D-M	
Swift et al. (2017)	O&M	C	Loc.	Ownership and location	UHF		BIM+RFID	3D-M	

*: Const. = construction phase, O&M = operation and maintenance phase.

†: C = component, M = material, P = personnel.

‡: Loc. = location, Rec. = records, Sig. = signal strength, Sta. = status.

+: LF = low frequency, HF = high frequency, UHF = ultra-high frequency, MW = microwave, UWB = ultra-wide band; A? = active RFID?

^: Inferred from commercial solution or text, or inquired via private communications

#: 3D-M = 3D model, 2D-FP = 2D floor plan.

3 Analytical results

3.1 Selection patterns of RFID systems, information storage plans and BIM

Based on the extracted data, a Sankey chart was drawn to provide a graphical overview of the studies on linking RFID to BIM for different CEM activities (see Figure 2). In the Sankey chart, the size of a rectangle indicates the numbers of actual cases that mentioned objects and properties targeted for monitoring, RFID system, information storage plan, and BIM specifically. Coincidentally, half of the cases (i.e., 21) covered the construction stage and half the operations and maintenance (O&M) phase. Components (25 out of 42) and personnel (14 out of 42) were the most common targets for monitoring, while only a few cases (4 out of 42) concerned bulk materials (e.g., steel, pipe) in the construction phase. Location was the most popular property to monitor, and all cases in which personnel were monitored aimed for their locations.

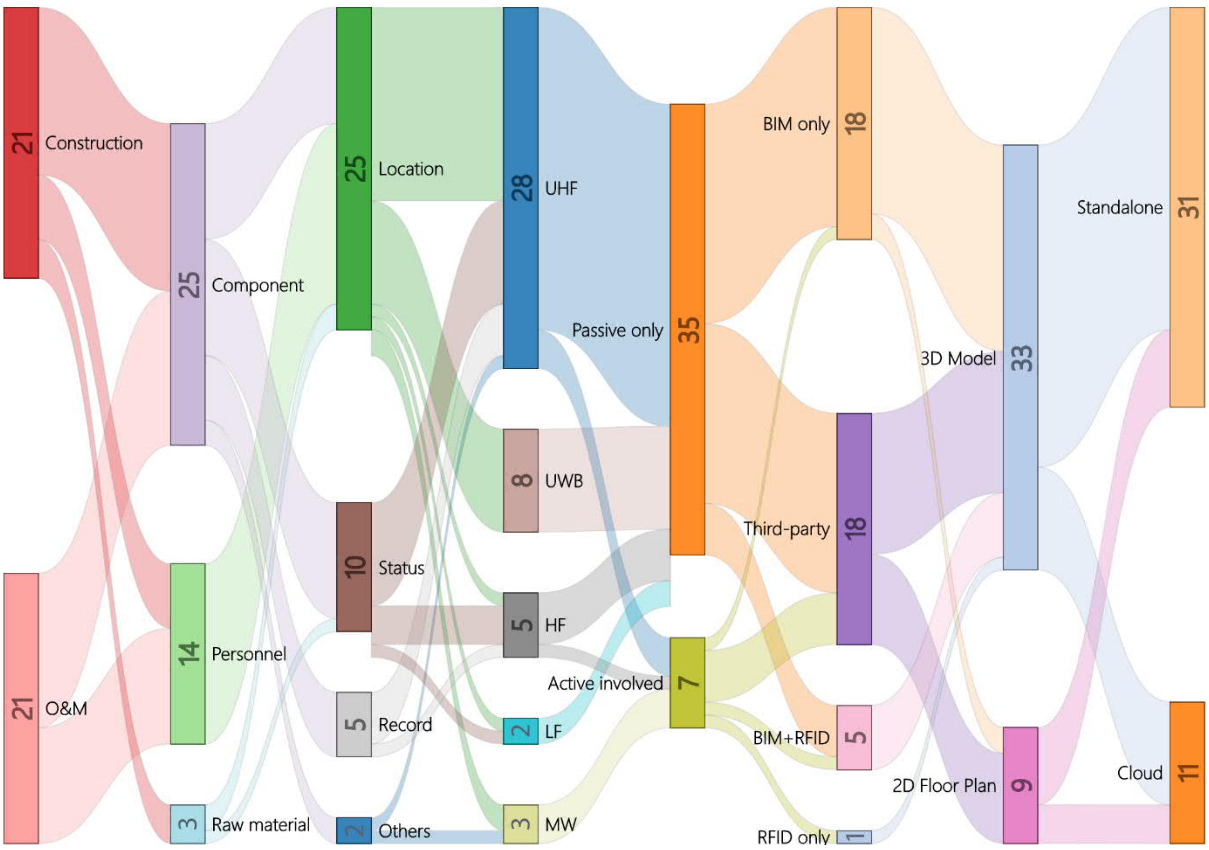


Figure 2. Overview of the reported cases

From Table 2 and Figure 2, the selection pattern of the RFID systems can be summarized as follows:

(1) UHF was the most popular RFID frequency, appearing in over 65% (28 out of 42) of cases. UHF RFID systems were reported to have acceptable reading ranges and fast data read rates (Motamedi and Hammad, 2009; Sattineni, 2014), which can well meet the requirements of in-time data collection raised by fast-changing CEM activities.

(2) UWB RFID systems were adopted in about 20% of cases, mostly for indoor locationing in the O&M phase. The less use of UWB than UHF might be due to two major reasons. First, UWB RFID systems are much more expensive than UHF ones (Fang et al., 2016). In addition, UWB RFID systems require a network of reference points in fixed positions, which are technologically difficult to manage on construction sites due to the changing environment (Masoudifar et al., 2014). Comparatively, UWB RFID systems might fit in with the O&M phase since most facilities in this phase are fixed, making reference points easy to set up.

(3) HF, LF and MW RFID systems were not frequently used in reviewed cases. The rare use of MW RFID systems could be due to the high price, poor readability, and sensitivity to environment (Sørensen et al., 2010). The unpopularity of HF and LF are possibly due to their short reading range and low reading speed. However, considering their abundant supply and relatively cheap price, HF and LF RFID systems could still be preferred in certain contexts (Chin et al., 2008; Hämäläinen and Ikonen, 2008).

(4) Passive RFID systems were preferred to active ones in the revised cases. More explicitly, passive UHF RFID systems were often adopted in the construction phase (e.g., Hammad and Motamedi, 2007; El-Omari and Moselhi, 2011; Zhang and Bai, 2015), and passive UWB RFID systems were generally used in the O&M phase (e.g., Masoudifar et al., 2014; Tomasi et al., 2015). Although active RFID systems are relatively expensive and large in size, they have a much longer reading range than passive ones. Thus, active RFID systems were used for tracking records (Cong et al., 2010) and location of workers and components in the O&M phase (Chai et al., 2015).

In most cases the collected information was stored in BIM only (18 cases) or in a third-party database (18 cases), while in five cases the information was stored in both BIM and RFID, and in one case the information was stored in RFID only. Cases that did not store the information in RFID mentioned that the built-in memory of RFID tag was too small to store all required information (Motamedi and Hammad, 2009). In addition, the 'BIM+RFID' information storage plan was often adopted to track records and other properties (e.g., signal strength) (e.g., Motamedi and Hammad, 2009; Zhang and Bai, 2015). Comparatively, the 'BIM only' information storage plan was often selected for tracking the location and status of components in a 3D model context (e.g., Srewil et al., 2016, Niu et al., 2017). When a 2D floor plan was used for BIM presentation or the target information to be tracked was the location of personnel, the information was often stored in a third-party database (e.g., Cong et al., 2010; Krukowski and Arsenijevic, 2010).

With respect to the selection pattern of BIM, most studies (31 cases) used BIM either presented as a 3D model or a 2D floor plan in a standalone manner. In the remaining eleven cases, most of which focused on the construction phase, RFID systems were linked to cloud BIM. One reason for the less adoption of the cloud BIM might be that in many CEM activities, especially those in the O&M phase, access to Internet was often unavailable. In addition, cloud-computing technologies have not been optimized for BIM until very recently, which also hindered the use of cloud BIM.

3.2 Development trends

Figure 3 shows the number of cases in which location, status, record, and other properties were monitored in the O&M phase by linking RFID to BIM. Before 2014, types of properties targeted for monitoring were more diverse than the situation thereafter. Among those prior-2014 cases, Cong et al. (2010) used RFID to track maintenance records, which were presented to the maintenance crews for their work together with the 2D floor plan retrieved from the BIM model. Meadati et al. (2010) linked RFID to a 3D commercial BIM platform (i.e., Autodesk Revit) to monitor the status of facilities. Akanmu et al. (2014) linked RFID to another 3D commercial BIM platform (i.e., NavisWorks) to monitor the status of light fixtures. Among post-2014 cases, increased attention was paid to tracking the location by linking RFID to BIM. This trend raises the importance of the visibility and traceability of location information.

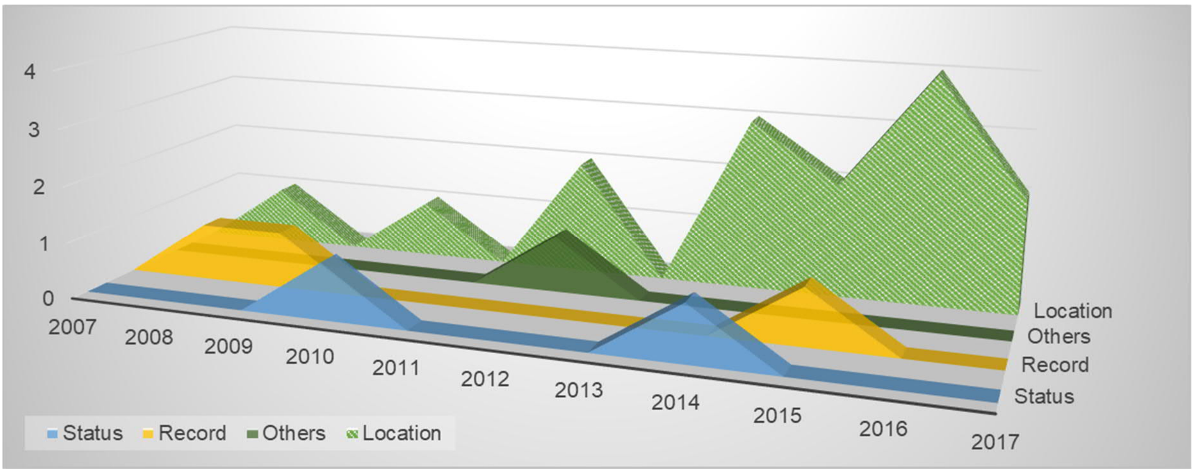


Figure 3. Trend in properties identified in the O&M phase

Another notable trend is that the number of cases using a 3D model has been increasing over time, with some fluctuations (refer to Figure 4). Meanwhile, the number of cases using a BIM-exported 2D floor plan showed a decreasing trend. Early efforts by Rueppel and Stuebbe (2008) and Shen et al. (2012) presented the location of construction personnel and building components in a 2D floor plan with a tailor-made software program. In recent cases, however, presenting the location information in a 3D model is more common (e.g., Chan et al., 2016; Fang et al., 2016; Srewil et al., 2016; Hu et al., 2017). Apart from the use of 3D model or 2D floor plan, Figure 5 shows that more cases of linking RFID to cloud BIM have appeared in the last two years. Niu et al. (2017) developed a system in which the BIM model panel was backed up by WebGL presentations on the webpage. Zhong et al. (2017) adopted a cloud server to hold the BIM model, which received real-time component information traced by RFID systems. The recent increased use of cloud BIM was not by chance, but rather it was led by the fast development of cloud computing technologies and increasing support from professional BIM platforms (e.g., Autodesk BIM 360).

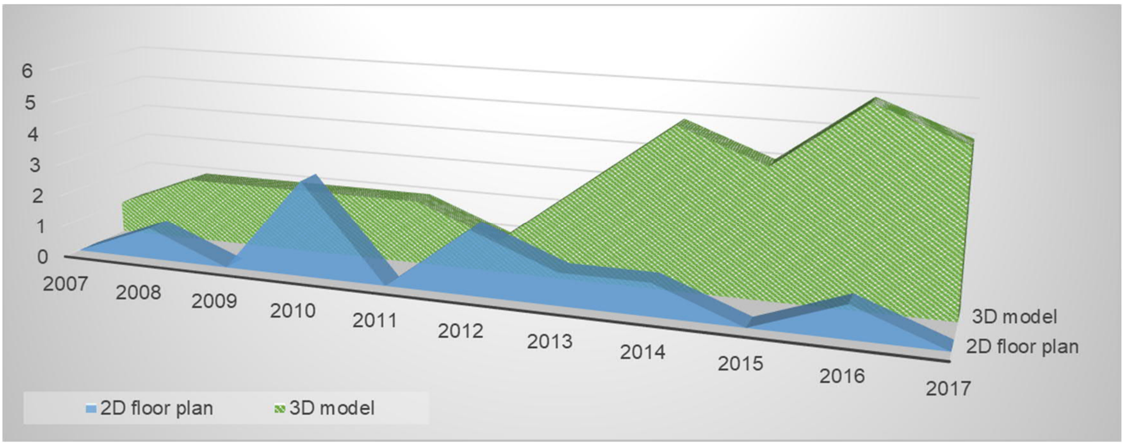


Figure 4. Trend of using 2D floor plan and 3D model

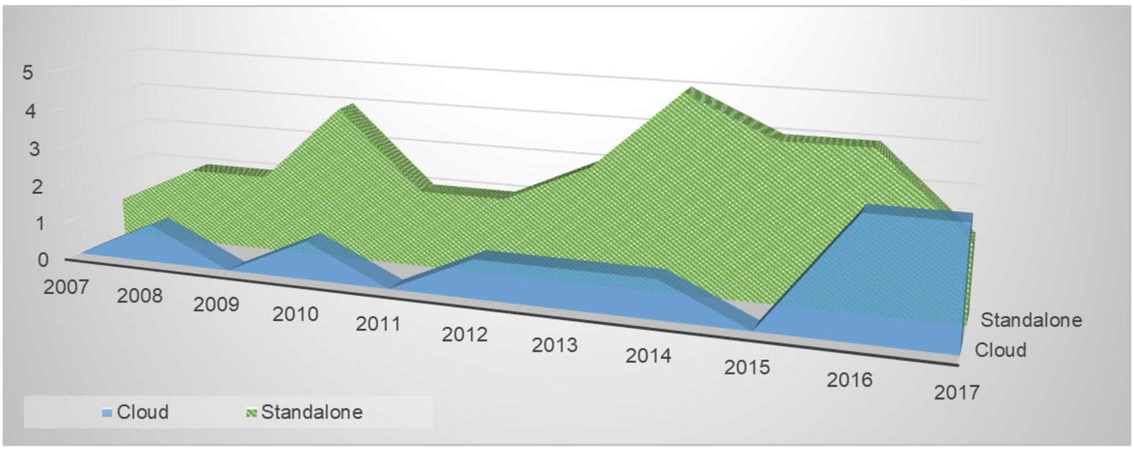


Figure 5. Trend of using cloud or standalone BIM

4 A Guideline for Choosing Appropriate RFID-enabled BIM Systems

4.1 A five-step guideline

Based on the review of 42 actual cases, a five-step guideline for linking RFID to BIM was developed (see Figure 6).

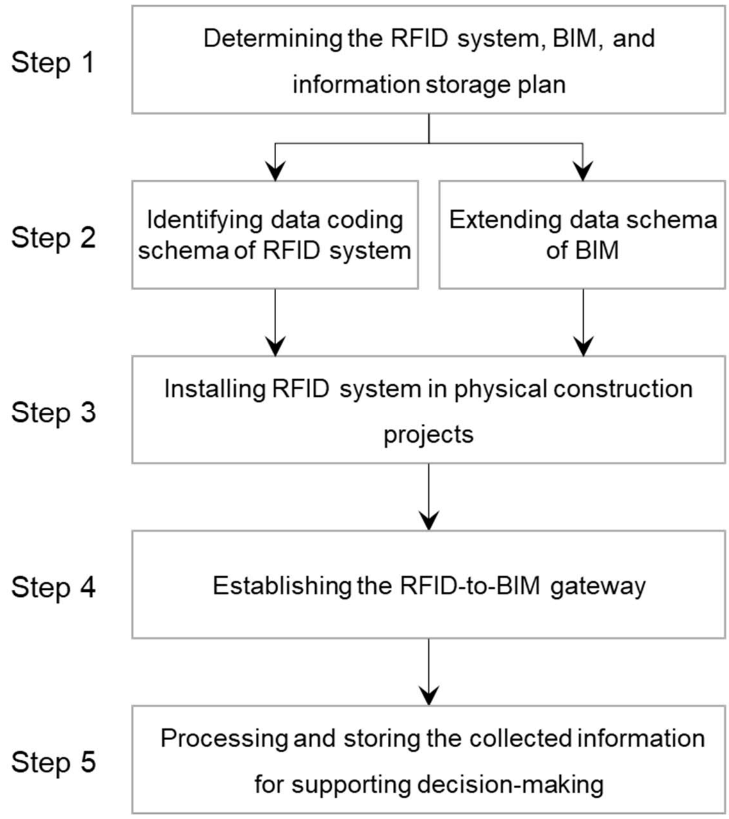


Figure 6. A five-step guideline for choosing appropriate RFID-enabled BIM systems

Step 1: Determining the RFID system, BIM, and information storage plan, there are three key components to be considered. The selection processes are presented in various decision trees as shown below. Decision trees mirror human decision making and are easy to interpret (James et al., 2013). Starting from the square node (called the 'root' node) on the left of a decision tree, one can follow the spitting paths (called 'burst' nodes) by matching conditions until a final decision (called 'leaf' nodes) is met (Quinlan, 1986; Dey, 2002). In this step, three decision trees (shown in Figures 7-9) were developed from an in-depth analysis of the cases. The 'rpart' package (ver. 4.1) was adopted in R (ver. 3.4.2), with the parameters set to 'min bucket = 2, min split = 4,' and others as default to summarize the patterns. Patterns with the identified development trends were then trimmed to exclude unsuitable or out-of-date options.

Figure 7 shows the selection of the RFID system. A UHF RFID system is the solution suggested for most applications in practice (e.g., tracking the status of construction objects or maintenance records). The tags are active if the case requires a long communication distance (> 1m), otherwise passive RFID is adopted. In the O&M phase, a passive UWB RFID system is recommended for monitoring location. However, the reading range of LF and HF RFID systems is relatively short, which is not suitable for many CEM activities requiring a reading range of about 1m (Ergen and Akinci, 2007). The MW RFID system is also unsuitable because it has poor readability and is impossible to scan through fluids and metal (Sørensen et al., 2010). Therefore, the LF, HF, and MW RFID systems are not recommended for CEM uses. In addition, for tasks involving specified requirements such as frequency interruption with assets (e.g. in the case of a hospital), selection of RFID systems should be made with further reference to other studies (e.g., Jaselskis and El-Misalami, 2003; Guven and Ergen, 2013).

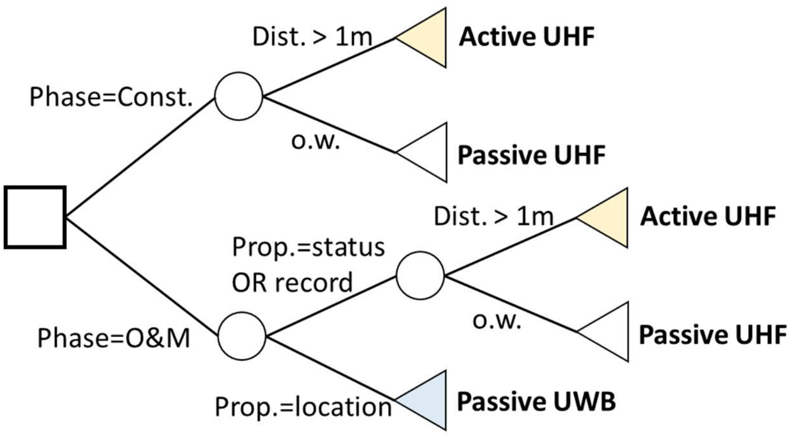


Figure 7. Decision tree for proper RFID system selection

Notes: (1) Prop. = type of property to monitor; (2) Const. = construction phase, O&M = operation and maintenance phase; (3) dist. = distance, o.w. = otherwise.

The decision tree shown in Figure 8 illustrates how to select BIM. Generally, a cloud BIM is preferred in the construction phase where different parties need to remotely access the BIM and information collected by the RFID system. The cloud BIM can be deployed in two ways. The first approach is to use a commercial cloud platform, such as Autodesk BIM 360 or Graphisoft BIM server. However, if these platforms do not provide the necessary protocols to receive the data captured by the RFID system, or more information processing flexibility is required, a second approach is recommended. This approach is to develop a cloud BIM by exporting the BIM data into an open format such as IFC (Industry Foundation Classes), and then rendering the data using interactive online 3D graphics such as WebGL (Web Graphics Library). Standalone BIM is more suitable in two scenarios: when the Internet is not available (e.g., in a confined machine room), or in the O&M phase when information updates in the BIM is made at regular time intervals.

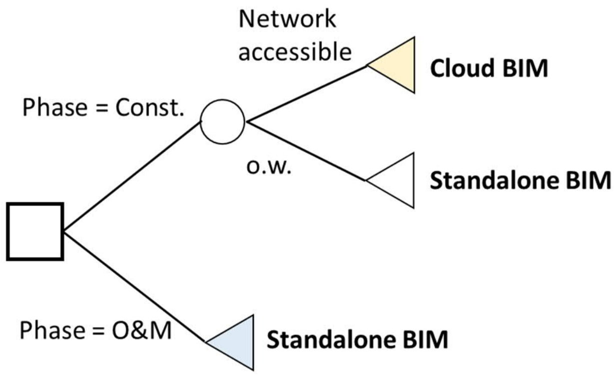


Figure 8. Decision tree for proper BIM selection

Notes: (1) Prop. = type of property to monitor; (2) Const. = construction phase, O&M = operation and maintenance phase; (3) dist. = distance, o.w. = otherwise.

Figure 9 shows how to choose the information storage plan. In several cases studied, information was stored in a third-party database and not directly communicated to the BIM. The decision tree indicates that such information storage plans were mostly adopted when 2D floor plans were used, and their usage has been declining significantly over the years. For future practice, it is expected that information be directly and actively communicated to BIM, and a record (e.g., inspection date and results; see an example in Motamedi et al., 2016) also stored in RFID tags. BIM will become not only the information provider but also the information receiver; that is, providing the as-designed geometric and nongeometric information, and also receiving the tracked information and visualizing it in BIM as a platform (Omar and Nehdi, 2016).

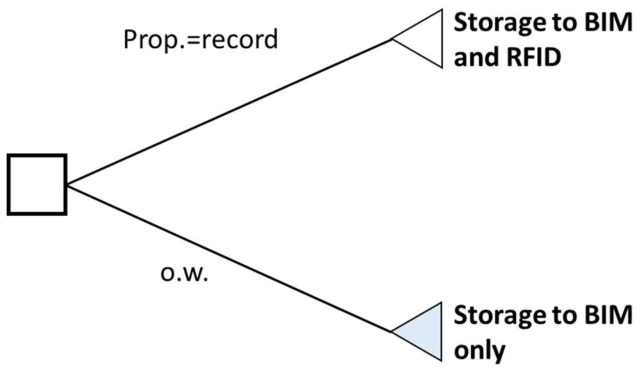


Figure 9. Decision tree for selecting information storage plan linking RFID to BIM

Notes: (1) Prop. = type of property to monitor; (2) Const. = construction phase, O&M = operation and maintenance phase; (3) dist. = distance, o.w. = otherwise.

Step 2: Identifying the data-coding schema of the RFID system and extending it when necessary. The data coding schema generally varies in line with different types of RFID systems. Likewise, if BIM does not include the properties of target objects, an extension of its data schema is needed. For example, the IFC schema adopted by most BIM can be extended by defining new entities or types, using proxy elements, and using the property sets or types (Motamedi et al., 2016). Commercial BIM platforms, such as Autodesk Revit, allow creation of new properties of their objects and development of add-on tools to automatically modify the properties.

Step 3: Installing the RFID system in physical construction projects. RFID installation method varies depending on the target object (e.g., components, equipment) or personnel. For example, tags can be embedded inside concrete components, pasted on the surface of materials, or attached to workers' gear. In case of possible failures, such as detuning and antenna failure, backup tags should be installed (Zhong et al., 2017). Stationed or hand-held RFID readers should be considered in line with factors including communication distance, working environment, and power supply.

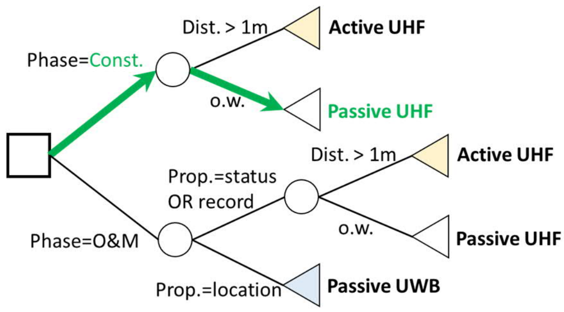
Step 4: Building an RFID-to-BIM gateway. A gateway is a software middleware on PDAs (Personal Digital Assistants), smartphones, or desktop computers. It implements the input/output interaction with RFID reader based on the entailed APIs through *ad-hoc* networks (e.g., Bluetooth), GSM, or readily available Wi-Fi (Zhong et al., 2017). In addition, the gateway is equipped with reasoning mechanisms, such as real-time checking and reporting, on the basis of the detected information contained in RFID tags. After receiving information from a RFID reader, the gateway can convert the received information into the suitable format and communicate the converted information to BIM through a message exchanging protocol such as XML). In circumstances where a communication network is not readily accessible, the gateway should also be able to operate in a standalone mode, holding all new information first and transferring it to the BIM when a network becomes available later (Chen et al., 2018).

Step 5: Processing and storing the collected information. The information received by the BIM may not be the demanded property. For example, in indoor positioning with a grid of readers and a tagged safety helmet, a series of signal strengths must be processed to get the demanded location. Using proprietary or standard APIs, the BIM can consolidate the information and calculate the desired outcomes, then visualize the processed information to support decision-making (Chen et al., 2015).

4.2 Demonstration

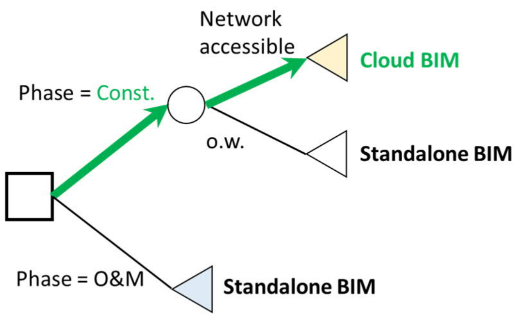
Applicability of the guideline was demonstrated in a real-life case, which came from a prefabricated construction project in Hong Kong. In this case project, an RFID-enabled BIM system was required to track the status of prefabricated façades from off-shore manufacturing, cross-border logistics, through to on-site assembly. The working environments included a prefabrication factory, transportation routes, and a construction site. There were no specific requirements on communication distance and radio frequency bandwidth during manufacture, transportation, and on-site assembly.

The guideline shown in Figure 6 was followed to determine the RFID, BIM, and information storage plan for this particular case. In Step 1, passive UHF was selected for binding in the reinforcement bar of the prefabricated façades (Figures 10.a and 10.b). A cloud BIM in a tailor-made platform was adopted since there were multiple end-users, including both client and contractor senior management, as well as frontline managers and operators requiring remote access with portable devices (e.g., iPads, smartphones). Existing commercial cloud platforms could not provide the protocols for receiving data captured by the selected RFID system in a real-time manner (Figure 10.c). Thus, the BIM was first developed in commercial BIM software (i.e., Autodesk Revit), and then converted into cloud BIM rendered by WebGL (Figure 10.d). The information to be traced was the status of prefabricated façades, which does not need to be stored in RFID tags (Figure 10.e).

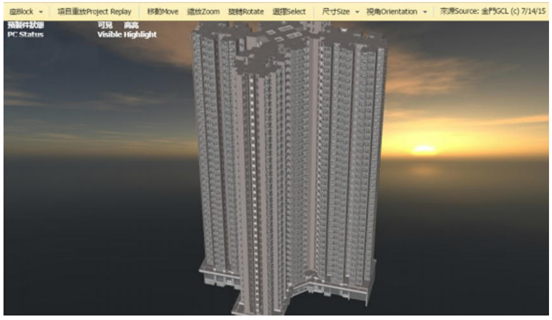


(a) Selection of passive UHF RFID system

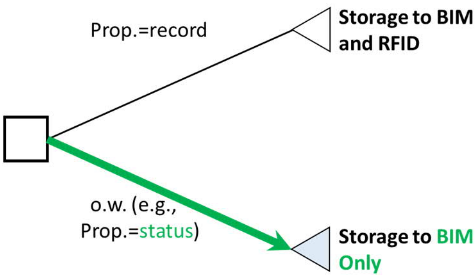
(b) Adopted UHF RFID reader and tag



(c) Selection of BIM



(d) Cloud BIM in a tailor-made platform



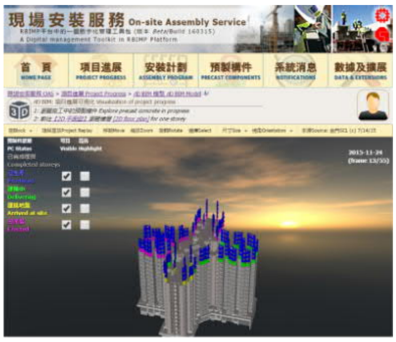
(e) Selection of information storage plan

(f) Data schema extension

(g) RFID installation

(h) Training workers to use the RFID reader

(i) RFID-to-BIM gateway



(j) Information process for decision support

Figure 10. Demonstrative case of linking RFID to BIM for monitoring prefabricated façades

In Step 2, the BIM schema was extended since the properties related to the status of prefabricated façades were not contained in the cloud BIM. The extensions of the BIM schema included six new properties: four timestamps (production, delivery, arrival, and assembly), current geolocation, and RFID tag ID. The tag ID would be used to link tag-attached physical prefabricated façades to their corresponding digital representatives in the BIM, and the remaining five properties would be used to generate the current status of prefabricated façades (Figure 10.f).

In Step 3, the RFID tags were fixed by workers before casting (Figure 10.g). Workers were trained to use hand-held RFID readers to capture tag-attached prefabricated façade data in production, transportation, and on-site assembly (Figure 10.h).

In Step 4, a smartphone app programmed in Java was used to turn a smartphone into an RFID-to-BIM gateway (Figure 10.i). In this project, the gateway provided three specific information collection and synchronization functions. First, it made used of the entailed API to receive the tag ID from the RFID reader via Bluetooth. Second, it automatically retrieved the corresponding facade information based on the received tag ID and recorded the four necessary timestamps of that facade. The geolocation was also automatically recorded using the GPS sensor embedded in the smartphone. Third, it wrapped the recorded timestamps and geolocation into an XML-based format and communicated them to the cloud BIM.

In Step 5, appropriate information processing approaches were developed to allow the cloud BIM to automatically process the data transferred from the gateway. As shown in Figure 10.j, based on the received timestamps and geolocation, the cloud BIM generated the status of individual prefabricated façades and visualized them in different colors (e.g., 'blue' representing 'production completed' and 'green' 'under transportation'). Stakeholders could review project progress down to individual component level through the cloud BIM platform rather than checking on-site.

This case demonstrates how the developed guideline could assist in selecting the RFID system and realizing the linkage, in order to enhance the value of both RFID and BIM. With the help of the guideline, the RFID-enabled BIM system ensured real-time information visibility and traceability, which eventually improved the efficiency of project delivery. For instance, the average time cost on locating individual prefabricated façades was decreased from 7-8 minutes to 5-6 minutes. In addition, the time cost on recording the on-site assembly was decreased from 30 minutes to 16 minutes.

5 Conclusion

Construction engineering and management (CEM) activities rely heavily on information visibility and traceability, and seamless coordination of numerous objects and people that are spatially and temporally scattered, onsite or offsite. Against this background, developments in RFID and BIM, in particular their connection, have gained momentum as evidenced by the growing number of related literature. Using a series of traditional and innovative analytical approaches, this study found several noteworthy points relating to the status quo and development trajectory of linking RFID to BIM from 42 actual cases. In summary, more cases adopted UHF and UWB RFID systems, stored information in BIM, and preferred a 3D model presentation to a 2D floor plan. Another important trend identified is the increasing use of cloud BIM as a platform to receive real-time information collected by RFID systems. This strategy facilitates the development of as-built BIM, enhancing information visibility and traceability.

Building on these findings, a guideline was developed for prospective practitioners to choose appropriate RFID-enabled BIM systems and thereby harness the powers of these systems in CEM. The guideline comprises five major steps: (1) selecting the RFID system, BIM, and information storage plan; (2) determining the extending definition of RFID data and BIM schemas; (3) installing the RFID system; (4) developing an RFID-to-BIM gateway; and (5) processing and storing the information. The usefulness of the guideline was illustrated in a case study of RFID and BIM integration in construction logistics and supply chain management.

This study covered a significant knowledge void in linking RFID to BIM. It articulated the status quo and several key development trajectories in important areas of CEM. The analytical methods and their presentations could be used for other related studies. Future research is recommended to verify the guideline in more construction scenarios and even scenarios at other project stages, such as demolition.

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