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# Information lifecycle management with RFID for material control on construction sites

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**Abstract**

Radio frequency identification (RFID) is an emerging technology in the building industry. Many researchers have demonstrated how to enhance material control or production management with RFID. However, there is a lack of integrated understanding of lifecycle management. This paper develops and demonstrates a framework to Information Lifecycle Management (ILM) with RFID for material control. The ILM framework includes key RFID checkpoints and material types to facilitate material control on construction sites. In addition, this paper presents a context-aware scenario to examine multiple on-site context and RFID parameters. From tagging nodes at the factory to reading nodes at each lifecycle stage, this paper demonstrates how to manage complex construction materials with RFID and how to construct integrated information flows at different lifecycle stages. To validate key material types and the scenario, the study reports on two on-site trials: read distance test and on-site simulation. Finally, the research provides discussion and recommended approaches to implementing ILM. The results show that the ILM framework has the potential for a variety of stakeholders to adopt RFID in the building industry. This paper provides the understanding about the effectiveness of ILM with RFID for material control, which can serve as a base for adopting other IT technologies in the building industry.

*Keywords:* Material control, Information Lifecycle Management, Radio frequency identification (RFID), Context-aware scenario, Construction materials, Construction management.

## 1. Introduction

Information management is an emerging issue in all industries including construction management (CM). Information plays a key role in making values throughout the entire lifecycle from production to consumption. Although ubiquitous information technologies have offered potential applications, accurate and real-time CM remains elusive [1]. This is because a construction project has an extremely complex process and can have large numbers of participants [2]. In addition, complicated contexts arise due to the variety of circumstances, equipment, and materials involved on a construction site.

As for automatically obtaining physical information, Navon [3] introduced various enabling technologies, such as embedded bar-codes, RFID, Global Positioning System (GPS), video and audio technologies, Laser Detection and Ranging (RADAR). Among these technologies, RFID has been widely adopted in various industries [4]. These studies have been collectively published in special issues of research journals such as Advanced Engineering Informatics and Automation in Construction. More recently, research has also focused on enhancing sustainability with RFID [5].

A straightforward barcode-based system has the potential for a simple supply chain system. By contrast, RFID has the potential to provide continuous tracking in the supply chain system [5]. RFID technology allows the dynamic identification and modification of the attributes of target objects as well as tracking without direct contact. That is, RFID can support continuously changing lifecycle management.

Material control [6, 7], a dominant factor for optimising project cost, is an important issue in CM. Many studies [8-11] have proposed approaches to material control with RFID. However, they have only been successful with specific material and from a technical perspective. The approaches are designed only for a specific lifecycle stage or a selected management need [12]. There is a lack of integrated understanding of adopting RFID to cover an entire construction lifecycle and to apply to a variety of construction materials. To provide a formal understanding of lifecycle management with RFID, this research investigates current RFID applications and critical information flows on construction sites. This paper then presents the Information Lifecycle Management (ILM) framework – an integrated conceptual framework – for material control with RFID.

RFID is referred to as the identification technology which contains indexing information of physical objects. It automates information systems and supplies the origin of information using mediators such as tags and readers. Material control with RFID starts by considering the properties of construction materials in order to abstract and represent them in the tags and readers. It also considers electronic information management processes for automated information indexing and tracking. The ILM framework for material control includes key RFID checkpoints and material types to facilitate material control on construction sites.

This paper then presents a context-aware scenario [13, 14] to examine multiple on-site contexts and RFID parameters. Some studies [12, 15, 16] have described the technical features of RFID in general, while this paper focuses on the ILM framework that RFID can support.

In this research, to demonstrate the effectiveness of the ILM framework, we adopt apartment construction sites as a case to study ILM with RFID for material control. Apartment construction in Korea is a type of mass construction which may include hundreds of housing units and even involves high-rise housing buildings. Apartment construction sites often appear to have a simpler and more repetitive process than other construction sites [17]. Although the demonstration is limited to the apartment construction sites, the ILM framework presented here can be extended to other construction sites.

The remainder of this paper is divided into six parts. Section 2 explores related literature on RFID technology. Section 3 then develops a conceptual ILM framework for material control, which contains the material typologies that can be used to represent a wide range of actual materials. A context-aware scenario examining multiple on-site context and RFID parameters is presented in Section 4.

Section 5 presents site trials to validate our two components of the framework: key material types and a context-aware scenario. Site trials include read distance tests for verifying the key material types, and on-site simulation of the developed scenario.

Section 6 discusses the effectiveness of the ILM framework and the recommended approaches for the implementation. Finally, Section 7 concludes the paper with an outline of future work.

## 2. Literature review

### *2.1. RFID system*

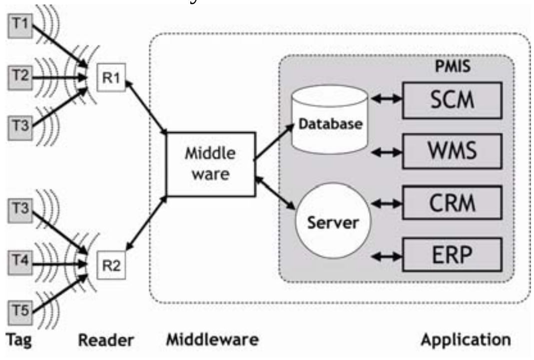
RFID provides wireless communication between tags and readers [9], which facilitate real-time management through automated identification processes. Both barcode and RFID technology are efficient for material control in a construction project. Especially, barcodes continue to be suitable for certain materials, which need visual confirmation and packaging like furniture. RFID is considered to be the next-generation of barcode technology [8]. Barcodes have been mainly used for materials tracking [2] as well as materials waste reduction [18]. It can also be used to monitor construction progress [19]. However, barcodes applied in construction suffer from a short read range and durability [2]. This is because a barcode scanner has to see the barcode in order to read it, so called ‘line-of-sight’. Even though barcodes are an affordable technology, they become unreadable if scratched or dirty [2]. Compared to barcodes, RFID is more advantaged, especially for material control [3, 20] on a variety of lifecycle stages.

In many circumstances, RFID is regarded as a method that can overcome the problems associated with barcodes [21]. RFID can be rewritable; tag life is approximately 10 years (barcodes are about 10 days); environmental sensitivity is low (barcode can be affected by moisture, dust, etc.); it has non-fixed form and it can handle multi-items and has high mobility [20]. This paper adopts RFID as the most suitable technology for the ILM framework due to these RFID strengths.

As illustrated in Fig. 1, the RFID system consists of tags, readers, middleware and applications. The tag information is recognised by readers and is delivered to applications through middleware where the database is managed. An RFID system, is basically utilised through tags and readers, a so called ‘RF subsystem [22]’. A tag has its specific identification number and consists of antenna and memory that transmits data or an identification code. The command code of the radio frequency is received from a reader.

Tag types vary depending on the main characteristics of tags, such as identifier formats, power sources, operating frequencies, functionalities, and other form factors [22]. In the case of readers, a PDA reader like an RFID-enabled PDA [2] has shown potential for portable data collection in the construction industry. With GPS [23] and web/mobile network [2], various information management methods are applicable. RFID middleware [22] collects data from readers and transmits converted data to multiple applications.

There are several applications such as ERP (Enterprise Resources Planning), CRM (Customer Relationship Management), WMS (Warehouse Management System), and SCM (Supply Chain Management). These applications allow various participants to effectively use and monitor RFID information for different management aims, which enables them to easily collaborate with each other.




ERP: Enterprise Resources Planning,
CRM: Customer Relationship Management,
WMS: Warehouse Management System,
SCM: Supply Chain Management

Fig.1. Structure of RFID system
(Revision from Figure 2-6. RFID System Architecture in Karygiannis et al. (2007))

Each arrow in Fig. 1 represents an information flow in the RFID system. Material characteristics must be identified before examining the information management flow with RFID. Tags in the system are regarded as a starting point for identifying material information. Tags are recognised as construction materials, because they are physically attached to the materials. The decision on attaching and reading tags results from key management needs as well as on-site contexts. The major characteristics of tags [22] also should be carefully considered. Therefore, attaching and selecting tags are the first step to start applying ILM with RFID to material control.

### *2.2. Lifecycle management with RFID*

RFID has been widely applied to various construction sites since Jaselskis et al. [24, 25] discussed concreting operations, cost coding for labour, equipment, and material control with RFID. In particular, material control takes priority in construction costs, and plays an important part in terms of the efficiency of the process and productivity [26]. Navon [3] also deals with material management and control as well as labour and equipment control. There is a variety of research on construction management with RFID, i.e. regarding material tracking [8-11, 20, 27], equipment tracking including vehicle and tool [28-31], and labour tracking for productivity and safety [32, 33]. In addition, some studies also present supply-chain management [2, 29] and multi-tracking systems employing both RFID and GPS [23, 30, 34, 35]. Although the previous studies present various approaches to material control with RFID, they are still limited in connecting complex construction contexts to lifecycle management. The studies have only been conducted with selected samples and technical scenarios.

More recently, lifecycle management with RFID technology has been discussed [12, 15, 16]. Kiritsis et al. [15] presents the concept for seamless e-transformation of information to knowledge. They describe various technological systems with a focus on product lifecycle management. Motamedi et al. [12] utilised permanently attached tags to allow different users to share lifecycle information. They present their detailed lifecycle stages: manufacturing, shipping, transportation, receiving, stockyarding, lifting up, piling up, fabricating, installation, inspection and control, and reuse/recycle/disposal. The lifecycle stages provide a good example for understanding construction management processes. Ergen et al. [16] present streamlining information flow with engineering-to-order (ETO) components on different lifecycle phases.

The previous studies show the importance of lifecycle management through generalising CM processes and material types. However, there is a lack of formal understanding of how to construct lifecycle information for material control dealing with complex construction materials. This paper, addressing the typologies of generic materials that can cover a wide range of complex materials, establishes the ILM framework to be developed on these theoretical backgrounds.

## 3. ILM for material control

### *3.1. A conceptual ILM framework*

Material control with RFID is based on the structure of an RFID system as illustrated in Fig. 1. Identifying the different lifecycle stages is the starting point of the ILM framework. RFID technology here identifies and tracks the information management of materials in the lifecycle stages. This study starts by establishing the critical information flows of the lifecycle stages.

This conceptual ILM framework is derived from three research activities: a literature survey, interviews with key stakeholders, and field research. Firstly, a literature survey provides the fundamental knowledge as well as an interview form. The interview consists of three sections: (1) the critical information flow of material lifecycle, (2) RFID usage for material control, and (3) general information of participants.

The interview involves ten stakeholders including project managers, material manufacturers, construction engineers, transporters and labourers. Some of them had already had experience in using RFID for material control on construction sites. Material manufacturers applied a barcode based system to their SCM (Supply Chain Management). Researchers integrated all the collected critical information flows into a single suit. Based on the survey results, this paper establishes ideal tagging and reading points in several lifecycle stages. A draft of the conceptual ILM framework is examined in a field research on three apartment construction sites.

Simplifying the lifecycle stages results in a better understanding of ILM than considering the entire management processes does. This paper found the key RFID checkpoints (three tagging and seven reading points) in the lifecycle stages on apartment construction sites. The lifecycle stages are similar to those of the framework by Motamedi et al. [12]. The illustration in Fig. 2 also shows the tagging and reading points, which are regarded as primary RFID checkpoints on the lifecycle stages.

Fig. 2 shows that the materials are first stocked in the warehouse and carried to the site as the construction process moves towards completion. RFID tags are normally attached by the manufacturer (T1). Specific tags are attached at the construction sites (T2, T3). T2 is designed to identify a transformed material on the construction site, while T3 is intended for the material maintenance after installation. It is also necessary to consider the maintenance and repairing steps (S8 in Fig. 2), which is one of the future management areas with RFID.

Although three tagging points may be an ideal guideline for material control with RFID, other tagging possibilities between each lifecycle stage may occur to fulfil specific needs. For example, it is possible to tag components between S2 (shipping) and S3 (carrying in), or between S4 (warehousing in) and S5 (warehousing out). These additional tagging points depend on specific requirements as well as the circumstances. Nonetheless, in terms of PMIS (Project Management Information System), tagging points before S3 is the same as T1. This is because PMIS needs only the information of R1 (shipping). Thus, even if there may be other tagging points, the three tagging points shown in Fig. 2 are typical locations in information management.

Lean and JIT (Just in Time) construction are widely used on current apartment construction sites. Materials are directly transported to each unit without stockyarding. In this case, important RFID checkpoints for ILM are three reading points: 'Shipping' (R1), 'Carrying in' (R2) and 'Allocation' reading (R5). A straightforward barcode-based system may have the potential for a simple supply chain system. By contrast, an RFID system allows for larger and faster automatic tracking in the supply chain system [5]. The RFID system also can track the hidden identification (tag) of materials.

'Carrying in' reading on a construction site (R2) and 'Warehousing in' reading (R3) can be thought of as a single process. If information refers to the absence or presence of materials on the site, the two reading processes can be unified because there is no difference between R2 and R3. In contrast, considering the needs of the stakeholders, allocation in Fig. 2 includes 'lifting up' and 'piling up' stages [12]. The location of the tracking allocation also can be divided into each floor and each unit. Therefore, structuring RFID checkpoints for ILM depends on on-site contexts as well as management needs.

The ILM framework in Fig. 2 also shows the cyclical concept of information management at the application level. Yagi et al. [11] presents some possible applications: quality engineering, lifecycle engineering, supply chain engineering, construction management, inverse manufacturing, standardisation of product model, process model, and parts specification. PMIS, as the top level application of ILM, includes WMS (Warehouse Management System) and MES (Manufacturing Execution System) for material control throughout the entire construction process. Using BIM [36] or 4D CAD [8] can provide visible reports. SCM (Supply Chain Management) [2, 29] is also involved to deal with the process from the manufacturers to the construction site. The information management may show the multiple logistic steps in Fig.2.

BMS (Building Management System) [21] must be formulated for follow-up maintenance. BMS including facility management can be extended to CRM (Customer Relationship Management) for apartment residents. Orders to replace outdated or damaged materials are triggered through BMS which connects with SCM. PMIS links the information to SCM, WMS, MES, and BMS. Also, material information circulates again to SCM by purchasing new materials through BMS. This can be explained as circulating lifecycle management. For example, 'Maintenance' reading (R7) in Fig. 2 can trigger the material order.

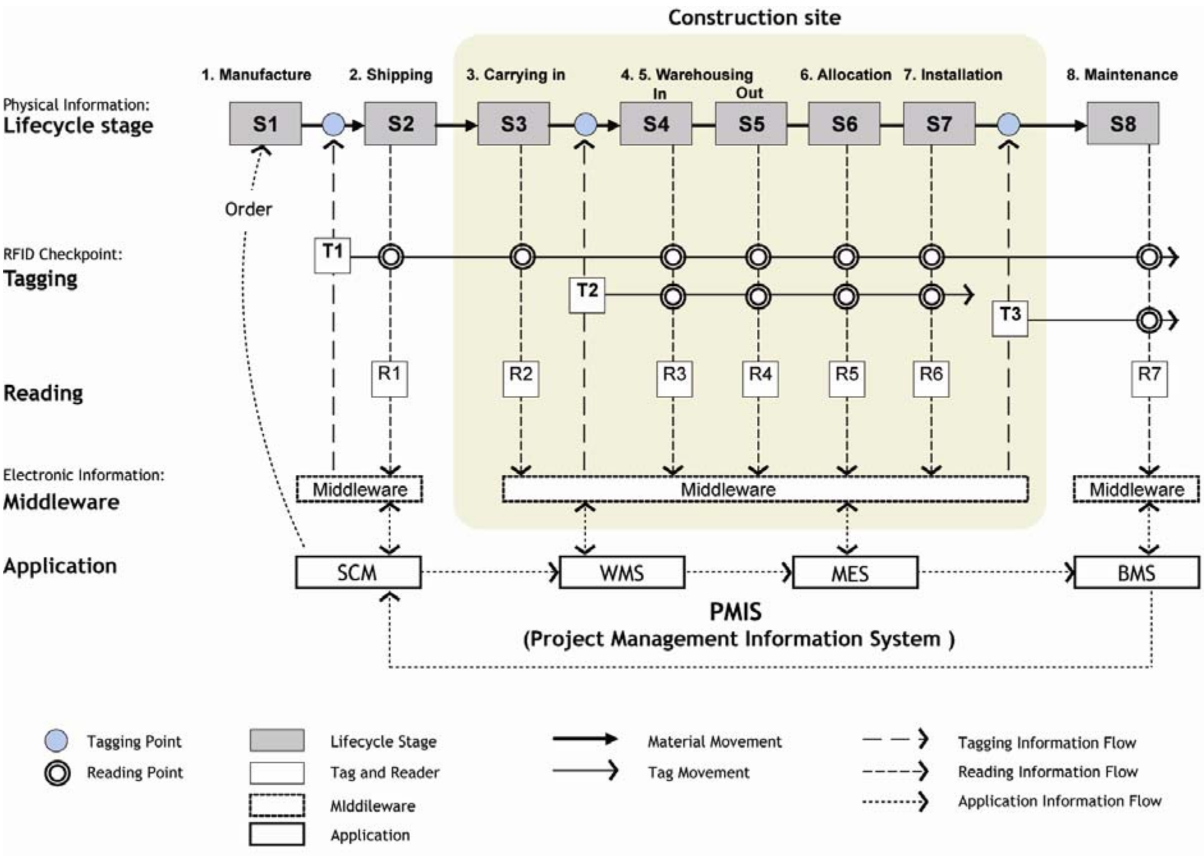



Fig. 2. A conceptual ILM framework for material control with RFID

The ILM framework can be used for material control with RFID as well as for bridging between information and construction technology. The information management will promote the sustainability of materials. Furthermore, the framework will help to develop an efficient information system for construction by providing the integrated information flow between construction stages.

### *3.2. Material types in the ILM framework*

Although the ILM framework provides an integrated understanding of material control, it continues to be difficult to apply RFID to complex materials on construction sites. To easily handle the materials, this section presents how to categorise different construction materials.

There is no formal way to classify the materials. There is a number of generic material types such as MasterFormat [37] and classification by CI/SfB [38]. Researchers have analysed material classifications of both the MasterFormat and the CI/SfB system with a focus on material control with RFID. Such classifications can cover all material types but are too complex. Moreover, it is not necessary to apply RFID to all types of construction materials. Target materials must demonstrate the possibility of adopting RFID. To present construction material types with RFID, this paper firstly extracts thousands of target materials from the MasterFormat. Next, target materials are narrowed down to prior materials on apartment construction sites. Key stakeholders at the interviews of Section 3.1 also suggest some prior materials. To facilitate ILM for material control, we develop five material typologies with RFID.

Fig. 3 represents the typologies of construction materials with RFID. Each material with RFID can be classified into three hierarchies: tagging method, location, and duration. As for the first level of classification, this paper considers how to attach tags to construction materials. Firstly, materials can be divided into two typologies: DTM (Direct Tagged Material) and ITM (Indirect Tagged Material). DTM is the typology that tags directly attached to, whereas ITM is the typology that tags are indirectly attached to materials.

DTM ideally attaches tags to materials at the factory (T1 in Fig. 2). DTM emerges with a single-tagged material as well as the second manufacturing process like iron bar, thereby integrating multi-tagged raw materials. Therefore, DTM is divided into STM (Single-Tagged material) and MTMs (Multi-Tagged Materials). STM is usually attached to a single component at the factory. STM is regarded as one of the prefabricated materials such as curtain walls, windows and doors or other such expensive materials. MTM stands for a type of material that needs the second tagging process (e.g. steel and iron bar). It requires the second manufacturing process followed by the first production which deals with multi-tagged raw materials at the factory. MTM has the second tagging process (T2 in Fig. 2) happening either on the construction sites or in the second factory for assembling and transforming steels or iron bars.

ITM is further classified by three material containers: VTM (Vehicle-tagged Material), PTM (Pallet-Tagged Material), and KTM (Packaging-Tagged Material). VTM (e.g. ready-mixed concrete) tracks a vehicle for material control, whilst the quantity of PTM is identified as a pallet carrying the material. So, the capacity and unit of the pallet for PTM is required to be standardised in advance. Tags for KTM are attached to the packaging of the material, indicating its quantity, weight and volume of the materials.

The second level considers tagging location. There are two locations where tags are attached to materials. Each material type attaches tags to materials ideally at the factory, while on-site tagging continues to happen on current sites. All the material types without tagging from the factory also have the on-site tagging process. For a specific need, MTM may have an additional tagging process for maintenance (T3). VTM can include additional on-site tracking. As for KTM, on-site customised pallets instead of delivered pallets can be used.

Further classification using tag duration (time level) is useful in making a decision as to which tag type is suitable for each material type. The proposed material types here can be categorised into permanent, removable and disposable types. A permanent type of tags is used if ILM is a longer process, whereas removable and disposable typed are used if ILM needs simple tracking like one or two stages in Fig. 2. As this study emphasises the simplification of material types, time level for material types is beyond its scope. Nevertheless, this paper provides some discussion about the time level in site trials.

Table 1 shows the information flow between RFID checkpoints for five material types that come from each material typology. Curtain wall, steel and ready-mixed concrete are chosen as the representative materials related to productivity on construction sites. In the case of some materials such as bricks and tiles, tags are attached to pallets or packaging. Many kinds of materials use indirect tagging so that PTM and KTM have a high ripple effect on the building industry. The characteristics of the packaging and forms of each material are also considered. The five material types with RFID checkpoints have the potential to construct ILM for material control with RFID.

Among STMs, curtain wall and window systems which have parts fabricated on sites are representative materials. RFID check-points will be extended to the history management (T3 and R7). The information flow of STM starts from attaching tags to each material part and ends on the maintenance stage.

Vehicles delivering ready-mixed concrete (VTM) can use GPS [30], which has been widely used in the building industry. As an on-site tagging process, VTM can involve the second RFID tagging (T2) for the management of concrete curing (e.g. 03–1. sub-process) to improve concrete quality inspection and management [39].

Compared to other material types, PTMs like bricks have a simple process. ILM highlights the point that PTM needs an improved tracking approach to reduce waste. A specific RFID-pallet can be developed to monitor its location as well as the quantity of materials on the pallet.

The unit price of tiles is relatively high and must be handled with care; therefore tiles can be considered as an ideal material for KTM. Table 1 shows ideal RFID checkpoints for KTM. On-site tagging to improve material safety [40] is also illustrated. If there is specific tagging (T2) on construction sites, it is worth considering the sub-process (05–1).

The five material types presented here are can be extended to other variations from the basic processes. The variation demonstrates how ILM processes can be customised to the needs of the stakeholders. To evaluate and validate the five material types with RFID, this paper illustrates and examines RFID checkpoints for each material type in Table 1. On-site tagging processes as well as a specific need result in an alternative information flow. One of the processes (05–1) is discussed in Sections 4 and 5, using a context-aware scenario and site trials. Section 6 provides the approaches recommended for each material type.

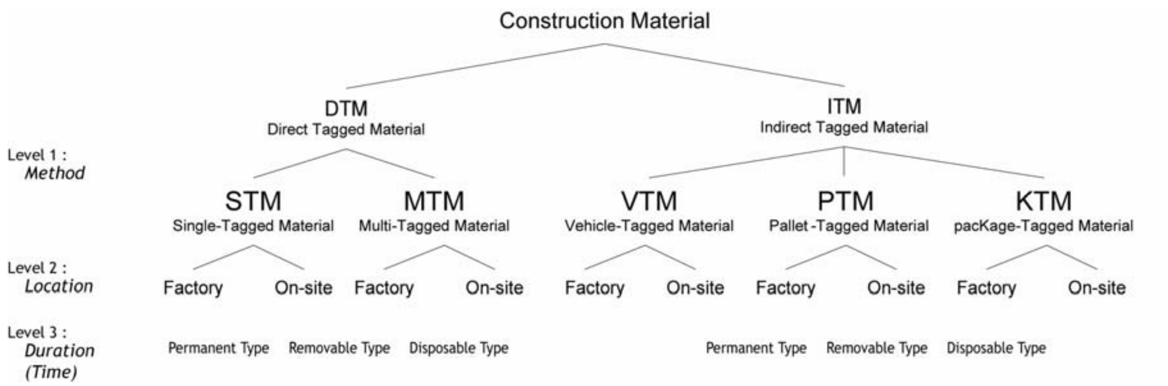



Fig. 3. Typologies of construction materials with RFID

Table 1. RFID checkpoints for five key material types

| No. Type | Material | Information flow between RFID checkpoints |
|---|---|---|
| **01. STM** (Single-Tagged Material) | Curtain-wall, Window System | T1 → R1 → R2 → R4 → R5 → R6 → R7 → (Factory → Site) |
| 01-1. sub-process (Additional tagging for T3) | | T1 → R1 → R2 → R4 → R5 → R6 → T3 → R7 → |
| **02. MTM** (Multi-Tagged Material) | Steel, Iron bar | T1 → R1 → R2 → T2 → R3 → R4 → R5 → R6 → R7 → (First manufacturing factory → The second manufacturing process on site) |
| 02-1. sub-process (just on-site tagging) | | → T2 → R3 → R4 → R5 → R6 → R7 → |
| **03. VTM** (Vehicles-Tagged Material) | Ready-mixed concrete | T1 → R1 → R2 → |
| 03-1. sub-process (Curing tagging) | | T1 → R1 → R2 → T2 → R6 → R7 → |
| **04. PTM** (Pallet-Tagged Material) | Brick, Cement, Gypsum board | T1 → R1 → R2 → R5 → |
| 04-1. sub-process (Using on-site pallet) | | → T2 → R5 → |
| **05. KTM** (packaging-Tagged Material) | Tile, Furniture | T1 → R1 → R2 → R3 → R4 → R5 → R6 → |
| 05-1. sub-process (On-site tagging) | | → T2 → R3 → R4 → R5 → R6 → |

## 4. A Context-Aware Scenario

### *4.1. A context-aware scenario for ILM*

To effectively adopt RFID on construction sites, this paper considers on-site contexts. A scenario-based project planning effects on intelligent, self-maintaining, and even repairing operation for facility management [4]. Previous research [13, 14] has used a context-aware scenario to identify common situations.

Contexts on construction sites are on-going variables resulting from a given environment as well as a variety of participants, equipment, and scheduled works. A context-aware scenario describes ILM with a focus on RFID checkpoints. Multiple contexts on the RFID checkpoints in Fig. 2 construct a phase of our scenario. Entire phases, from starting to end points on an ILM system, construct a context-aware scenario. The scenario allows us to expect the specific context of a construction site in advance and facilitate the application of RFID to the building industry.

A context-aware scenario involves five components: a target material, the needs of management, information flow, context parameters, and an RFID system. After selecting a target material, the needs of management and information flow follow the RFID checkpoints for the five key material types listed in Table 1. Context parameters are the prime components representing the information of material control. Information on the user, time, and location is essential to describe the context electronically. 5W1H [41-43], used to explain an inference process, has also been a fundamental approach for interpreting contexts into meaningful information.

An RFID system has to identify the attributes of what, where and when about the materials as well as their states [11]. Being similar to the identity [44] and context-information [45], key context parameters between RFID checkpoints can be examined and managed through a context-aware scenario. The ILM framework for material control with RFID must identify information about the construction materials at the specific location and time. This paper identifies the key context parameters as RFID checkpoint, user, time, location and lifecycle stage. These key context parameters then comprise a context-aware scenario for ILM.

Each RFID checkpoints listed in Table 1 establishes a step in a context-aware scenario. Labourers, site technicians, builders, construction companies, etc. are users who manage the information on materials at different lifecycle stages. Many construction sites have already used RFID labour management. An RFID system for ILM, therefore, needs to connect with the RFID labour system so as to track user parameters. Instead of directly tracking users, RFID equipment representing users can also be automatically tracked.

Time is a basic parameter connected to a construction schedule. Considering the curing quality of concrete or spreading material on a field, time may also have an impact on construction quality. Time is automatically captured in the RFID system when context changes take place. The location of users and materials can influence the entire construction process. To track the location using RFID, many systems use RFID-gates. When materials pass through the gates, the location parameters of the materials are changed. To identify the location in detail or in person with a material inspection, a specific tag can be attached to the location. In this case, the locations are detected manually by a mobile reader, such as a PDA reader.

To construct an RFID system, a context aware scenario identifies the RF subsystem (tag and reader), the trigger, and material status. Therefore, the scenario describes which types of tags and readers are needed and what triggers the change of context automatically or manually. The status of current material location as well as availability can be one of the most important parameters. The material status is identified by the lifecycle stage. Using key contexts and RFID parameters (see Table 2), a context-aware scenario does not only enable us to examine the ILM process of material control in advance, but also to clarify a variety of construction contexts.

### *4.2. An example of a context-aware scenario*

As an example of a context-aware scenario, the information flow of a tile as KTM in Table 1 will be followed. The target material is tiles. Tiles are distributed and carried by their packaging. As a tag is attached onto the paper box packaging of the tiles, the tracking target is the packaging itself. Construction managers pay special attention to expensive tiles. Whilst attaching tags for KTM ideally happens at the manufacturing stage (T1), the scenario deals with the second on-site tagging point (T2). Consequently, RFID checkpoints include T2, R3, R4, R5 and R6. The main users are a worker and an engineer in each step, as well as other stakeholders. Table 2 shows the key contexts and the RFID parameters.

RFID parameters for the scenario include two types of tags and readers between RFID checkpoints. In addition, the scenario describes a unit-tag identifying a housing unit. The unit-tag is attached to the entrance door frame at each housing unit to check the location of allocated materials.

Fig. 4 illustrates the information flow between users and the RFID application. The flow shows how the communication between stakeholders, main users and RFID applications, e.g. stakeholders track the location of materials such as ‘warehousing in’ and ‘allocation’ as well as monitor the status of construction processes like ‘installation’. A project manager puts the allocation and installation plan into the RFID application. The main users also interact with the stakeholders and RFID applications.

The context-aware scenario describing the key parameters are as follows.

"On December 18th, tiles are brought in through a site entrance. The tiles will be transferred from a warehouse to a required housing unit."

1. Worker A attaches RFID tags to each package of tiles. After the tags are coded as specific information for material control by an RFID application, the tags are attached to the packaging. Then Worker A uses a PDA reader to read the tags. (This enables the RFID application to recognise the location of the tiles as 'warehousing in' in the lifecycle stages.)

2. Carrier A at the warehouse requests a material allocation plan to the RFID application and receives the information. Carrier A reads the tags on each package of tiles with a PDA reader, and then starts the 'warehousing out' of the scheduled packages. After passing through GATE A at the warehouse and GATE B in front of building No. 115, the packages are delivered to the stockyard of this building.

3. Carrier B transfers the packages of tiles from the stockyard to the required housing unit. Using a PDA reader, Carrier B reads the tags on each package to check the quantity of the delivered materials and reads the unit-tag above the entrance door of the housing unit. (This allows other stakeholders to determine the status of the material in its precise location in unit No. 201.)

4. On December 19th, the tiles are installed in unit No. 201. After reading the unit-tag with a PDA reader, Worker B requests the installation plan for the unit and receives the information at unit No. 201. After Worker B has checked the quantity of the tiles for the installation plan and indicated 'starting installation' to the RFID application, he proceeds with the installation.

5. Worker B completes the installation at 6:00 PM and reports 'ending installation' to the RFID application.

As an additional step of the scenario, the engineer in charge of the installation can confirm the installation information for each housing unit. The manager with a PDA reader can count, check and report the status of the completed installation based on the information of the RFID application.

Table 2. Key contexts and RFID parameters

| Step | Context parameter | | | | | RFID parameter | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Checkpoint** | **Need** | **User** | **Location** | **Time** | **Tag** | **Reader** | **Trigger** | **Material status** |
| 1 | **T2, R3** | Warehousing in | Worker A | warehouse | 18-12-08 (dd-mm-yy) 06:00 PM | Packaging-tag (Label type tag attached to tile packaging) | PDA Reader | Reading tags (manually) | Warehousing in |
| 2 | **R4 (R4-1)** | Warehousing Out, Tracking | Carrier A | GATE A (warehouse) | 18-12-08 06:15 PM | Packaging-tag | GATE A (warehouse) GATE B (building no. 115) | Reading tags (automatically) | Warehousing Out, Locating such a place (in front of building No. 115) |
| 3 | **R5** | Allocation | Carrier B | Unit-201Ho | 18-12-08 06:30 PM | Packaging-tag (for material quantity) Unit-tag (for unit location) | PDA Reader | Reading tags (manually) | Allocation (Carrying in 201Ho) |
| 4 | - | Checking materials, Starting installation | Worker B | Unit-201Ho | 19-12-08 09:00 AM | Unit-tag Packaging-tag | PDA Reader | Reading tags (manually) | Starting installation |
| 5 | **R6** | Ending installation | Worker B | Unit-201Ho | 19-12-08 06:00 PM | Unit-tag | PDA Reader | Reading tags (automatically) | Ending installation |

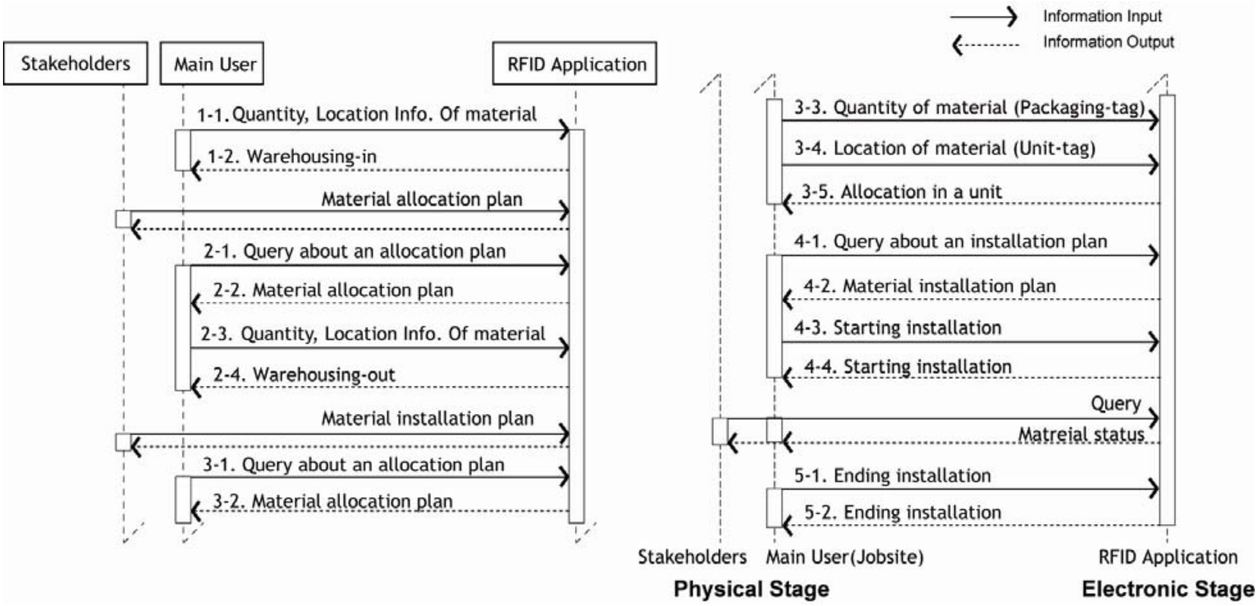



Fig. 4. Information flow in a context-aware scenario

## 5. Site trials

Site trials aimed to validate the ILM framework presented in this paper. The first trial examines the key material types through a read distance test. A simple test of the RFID performance can validate the material types in terms of ILM with RFID for material control. A test sheet presents the read distance and rate (Table 3) as well as the feasibility of five key material types on the RFID checkpoints (Table 1).

The second trial examines an RFID application based on the scenario presented above. This trial is intended to exemplify an RFID application and examine the scenario through on-site contexts for material control. A check list consisting of key contexts and RFID parameters listed in Table 2 were used. Participants, including the researchers as well as project managers, construction engineers, and labourers, compared the scenario with real on-site contexts. Before the site trial, the participants examined the check list in advance and set up equipment according to the scenario. After the on-site trial, the participants discussed about ILM with RFID for material control and the scenario.

### *5.1. Read distance test on key material types*

The five material types with the tagging hierarchy shown in Fig. 3 will affect on RFID checkpoints for ILM as well as the decision making regarding the type of tags and readers. Even though it is a simple test, the read distance test on material types can enhance the understanding of material control with RFID on construction sites. This section highlights not only the discussion on the reading performance of different tags attached to each material type, but also the importance of integrating different types of tags and readers into an RFID system for material control.

Due to a limitation on a construction schedule at that time, key material types for the read distance test only involved four key material types: STM (Window system, Curtain-wall), MTM (H-Beam), PTM (Gypsum board), and KTM (Tile). The read distance and rate depends on the characteristics of the material as well as various test conditions, viz. the antenna types of an RFID reader, RFID frequency, packaging design of an RFID tag, reading angles and temperature [20, 31]. Keeping those constraints in mind, this paper highlights the performance of the tags and material types in terms of ILM.

The experiments also examined three tag types: label (paper sticker type: 100 × 25 mm), metal (100 × 25 × 2.5 mm), and card (85 × 54 × 0.8 mm). All the tags are passive tags with the same FR frequency (UHF 908.5 ~ 914MHz) and protocol (900 MHz, EPC Class1 Generation2, ISO 18000-6C). The metal tag can be used for permanent management, while the paper tag will be regarded as a disposable type. After attaching the three types of 900 MHz tags onto each material, the read distance test was carried out with a 900 MHz PDA reader configured at 1 W output and a 900 MHz fixed reader with long range antenna.

The results of the read distance and rate test on each material are shown in Table 3. The researchers conducted the experiment 10 times per tag. To formally evaluate the RFID performance, we need to consider a number of experimental variables [20, 31, 46]. Tzeng et al. [20] conduct the performance test 120–350 times. With the limited experiment, the read distance and rate test in our research only aim to examine and indicate the feasibility of the key material types.

Table 3 shows the mean value. Except for STM (glass), the performance of the metal tag is relatively higher above all types. However, the expensive metal tag is not ideal for all materials. Both cost and performance needs to be considered in the selection of suitable tags for each material type.

The two tagging types of STM show different results caused by the tagging surfaces (metal frame and glass). This is because the properties of the material affect the read distance and rate. Since the test aims to validate key material types, this paper considers the material properties as well as on-site contexts. For example, pallets for PTM are made of wood, plastic or iron. Regardless of the material properties, this paper highlights the points that a metal tag is ideal because the pallets must be reused and then the attached tags have to be firm and well packaged.

Table 3. Read distance and rate test results

| Material | Type | Result | | | |
|---|---|---|---|---|---|
| | | Fixed Reader | | PDA reader | |
| | | Read Distance (㎝) | Read rate (%) | Read Distance (㎝) | Read rate (%) |
| STM (Window system) | Label Tag | 13 | 26 | 5 | 30 |
| | Metal Tag | 421 | 100 | 203 | 100 |
| | Card Tag | 32 | 60 | 15 | 47 |
| STM (Curtain-wall) *Glass | Label Tag | 143 | 100 | 63 | 20 |
| | Metal Tag | 127 | 100 | 79 | 100 |
| | Card Tag | 61 | 100 | 47 | 100 |
| MTM (H-Beam) | Label Tag | 0 | 0 | 0 | 0 |
| | Metal Tag | 411 | 100 | 197 | 100 |
| | Card Tag | 12 | 82 | 20 | 68 |
| PTM (Gypsum board) | Label Tag | 332 | 100 | 136 | 100 |
| | Metal Tag | 385 | 100 | 178 | 100 |
| | Card Tag | 278 | 100 | 147 | 100 |
| KTM (Tile) | Label Tag | 352 | 100 | 126 | 100 |
| | Metal Tag | 391 | 100 | 178 | 100 |
| | Card Tag | 275 | 100 | 138 | 100 |

Table 3 demonstrates that the fixed reader is more advantageous than the PDA reader in terms of both read distance and rate. The difference in the performance is probably accounted for by the power of the reader's antenna. In contrast, this paper concentrates on the differentiation of material types and the utility of tags and readers. Even though the readings of the fixed reader are higher than the PDA reader in general performance, there may be a different purpose in usage.

PDA readers can not only allow quality inspection, but also increase the read rate of the reader according to its accessibility. PDA readers and fixed readers can complement each other on a construction site. Fixed readers are advantageous in the case of quantity inspection for STM, bulk materials and VTM. PDA readers are more advantageous for comparatively smaller quantities of materials like STM. It is also an ideal reader for the quality inspection of materials like KTM, which simultaneously require visual confirmation and special attention for ILM.

For the window system in STM, three types of tags were attached to the inside surface of the metal frame. The metal tag is suitable for the window system. In addition, a small tag (e.g. 30×21×2 mm) is attached inside the window frame. The small metal tag inside STM provides integration between T1 and T3 among RFID checkpoints as shown in Table 1. The tag attached at the manufacturer (T1) can show the changing contexts of the material throughout the entire construction lifecycle.

Using the curtain-wall as another example of STM, three types of tags with a special shield were attached to a glass surface. The special shield allows the tag attached to the glass to be read. Some glass panels which have metal or other mixed-properties need the special shield or packaging. As STM mainly deals with material quantity rather than quality, label tags and fixed readers are regarded as a suitable 'RF subsystem' for the glass type of STM.

If there is a need for quality inspection, metal tags and PDA readers may be suitable for an RFID system. The installation (R6) and maintenance (R7), tags for STM have to last for a long lifecycle. The duration level of the tagging hierarchy shown in Fig. 3 presents another easy way to select a suitable tag type on construction sites.

Since H-Beam as MTM has a metallic property, only the metal tag is applied to an RFID system. The packaging of the metal tag considers the methods used to attach it (e.g. magnet, ring, label, etc.) as well as sizes and rigidity. The fixed reader is suitable for RFID checkpoints between the first tagging point (T1) at the manufacturer and 'Carrying in (R2)'. After the second tagging point (T2), the PDA reader is more useful for the control of this type of material in the subsequent lifecycle stages.

As for PTM (Gypsum board) and KTM (Tile), the test shows all tag and reader types can be effectively applied to ILM. Tags were attached to the wooden pallets mainly used for PTM and the cardboard packaging for KTM. The surfaces of both materials are easy to tag and score relatively highly in the results of the read distance and rate test. After the test, authors have an insight that RFID pallets for such PTMs can be developed. It is also recommended that the tag packaging should protect the tags from damage as well as to comply with the changes in physical contexts.

PTM is very similar to KTM in terms of the information flow for ILM as well as the practical usage. Moreover, the read distance and rate test in Table 3 demonstrates similar results. However, the information flow of PTM differs from that of KTM. The point is whether 'warehousing in/out' (R3/R3) and 'installation' (R6) happen or not. PTM highlights the monitoring of quantity in the material control, while KTM pays attention to both the quantity and quality of materials. Thus, ILM for the material control has to consider both the RFID checkpoints of material types and RFID performance.

RFID read distance and rate for construction materials depends on physical properties such as tagging surfaces and environmental contexts. The needs of the various stakeholders can also affect the lifecycle management. However, this paper only highlights the on-site performance of each type of material to examine the feasibility of our ILM framework. The other focuses are beyond the scope of this paper. Nonetheless, the results indicate that ILM framework is advanced in terms of the selection of ideal tags and readers regardless of the material properties. The five material types will better facilitate decision-making about where/how to use RFID for material control.

### *5.2. On-site trial using the context-aware scenario*

Before the trial, participants examined and discussed a check-list consisting of key context parameters and the RFID system as shown in Table 2. According to the scenario, the trial highlights initial tagging and four RFID reading points, viz. ‘Warehousing in’, ‘Warehousing Out’, ‘Allocation’, and ‘Installation’ on material lifecycle.

Metal, label and card tags, two fixed readers (Gate A and B) and a PDA reader were used in accordance with the scenario. To obtain the identity of each housing unit, unit-tags (metal tag type; see Fig. 5) were attached to the entrance door frame of each housing unit. The price of the metal tag is comparatively high. By contrast, the read distance and rate are high regardless of the physical properties of the material. The metal tag is also sufficiently durable to last over the lengthy period of lifecycle stages to permanently identify the information of each unit. The unit-tag allows an RFID application to monitor ‘Allocation’ and ‘Installation’ described in the scenario, as well as the maintenance and repairing of materials after installation. The introduction of the unit-tag has considerable potential in construction management.


Fig. 5. PDA reader and Unit-tag

The PDA reader in Fig. 5 was very useful for reading RFID checkpoints, while fixed readers had an advantage of automatically counting and monitoring the quantity of the material (R4). Compared to the results in Table 3, the reading rate of the fixed readers was low. Tags on a fork lift were tracked with better performance than a burden vehicle. The reading rate might be accounted for by the antennas of the readers or the interruption of transfer-equipment itself. We need to optimise the angles and power of the fixed reader’s antennas.

On several lifecycle stages, the PDA reader had advantages, viz. issuing tags from an RFID system (T1), checking the quantity and quality of materials in the warehouse (R3), the allocation of materials to each housing unit (R5), and monitoring the installation of the materials (R6). The PDA reader must be used as an important device for issuing tags and reading the tags attached to materials, as is required to identify the materials visually. It also allows for exchanges of information such as the beginning and the end of the installation. The unit-tag identifies each unit in an inexpensive and simple way, compared to installing a fixed reader on each floor or a unit to stand for the locations.

During the trial, researchers verified key context parameters and an RFID system using the check list. Compared to key parameters listed in Table 2, researchers found consistency between the contexts of the scenario and the on-site trial. Fig. 6 illustrates the on-site contexts: RFID checkpoints, users, locations, tags, readers, and lifecycle stages (material status).

All participants discussed the material control with RFID and the scenario after the trial. The feasibility and effect on lifecycle management with RFID was extremely impressive to the researchers as well as the participants. The participants started to pay attention to the automated tracking and monitoring of materials with RFID on the construction site.

Participants all agreed that the context-aware scenario facilitated preparing and conducting the on-site trials. The scenario tested the ILM framework involving RFID checkpoints for KTM. Considering the extremely complex contexts on the construction site, a variety of contexts needs to be examined in advance with related stakeholders. The context-aware scenario tests the ILM framework with RFID for material control and improves the RFID system with the test results.

Fig.6. On-site trials using a context-aware scenario for ILM

## 6. Discussion and recommendation

### *6.1. Discussion*

The ILM framework developed here includes (1) RFID checkpoints, (2) key material types, and (3) information flow between RFID checkpoints and the key material types. The integrated framework can play a crucial role in applying RFID to material control in the building industry. Whilst some researchers have studied lifecycle management for material control with RFID [12, 15, 16], it is highlighted that our research has advanced the field in terms of the following two aspects.

- *How to construct an integrated information flow of material control at different lifecycle stages?* Considering the needs of stakeholders, previous research [8-11, 20, 23, 27, 30] has identified and monitored a few specific RFID checkpoints. There has been a pressing need for an integrated understanding of adopting RFID over the entire construction lifecycle. To present such a rigorous understanding, we have investigated lifecycle stages on several construction sites with a focus on RFID checkpoints for various types of material.

  The conceptual ILM framework illustrated in Fig. 2 is the result of observations and interviews on construction sites. Though the observations and interviews on apartment construction sites have limitations, RFID checkpoints presented here demonstrates similar results to the lifecycle stages by Motamedi et al. [12]. This indicates that material lifecycles can be generalised into several key stages, because many stakeholders have similar information flows for material control with RFID.

  RFID checkpoints will facilitate the structuring of an integrated information flow for controlling materials. Specifically, three tagging points (T1, T2, and T3) serve as the starting point of an RFID application for the entire information lifecycle. Although the other tagging point would possibly occur at particular stages, T2 for the fabrication stage and T3 for the maintenance of materials are identified as the key turning points in the entire material lifecycle. The seven reading points should also be effective for monitoring materials at different lifecycle stages. The ILM framework will enable us to easily develop an integrated information flows for the control of materials in the entire material lifecycle.

- *How to effectively deal with the information of complex materials on a construction site?* A material classification such as MasterFormat and CI/SfB classification [37, 38] is an essential foundation to the study of material control. Nonetheless, literature [8, 11, 23, 30] has described very few materials to present material control with RFID.

  To effectively deal with complex materials, this paper presents new typologies of construction materials with RFID. The material typologies consider both RFID and material properties. Focussing only on the properties of materials, such as physical properties, size, shape, and even cost, the classification would be too complex. Considering RFID within the ILM framework has enabled us to capture complex materials with several typologies.

This paper classifies apartment construction materials into five typologies with representative material types listed in Table 1. The classification hierarchy consists of tagging methods, locations, and duration. The material typologies with RFID can effectively deal with complex materials on a construction site. On-site trials support that the five key material types allow us to facilitate the construction of the information flow between RFID checkpoints. The life-span of the types of material will allow more practical usage. Previous research on lifecycle management for material control [12, 16] considered permanent tag types. However, the control of some material types may need removable and disposable tag types to ensure the effectiveness of the ILM framework. The issue needs to be investigated more carefully.

The information flow of the ILM framework shown in Fig. 2 varies with the key material types. The RFID checkpoints for five key material types listed in Table 1 have been tested with a context-aware scenario. On-site trials have tested the ILM framework.

The framework allows various stakeholders to examine and optimise their practices. ILM with RFID supports seamless information management at different lifecycle stages. This paper has provided the enhanced understanding of ILM with RFID for material control in the building industry.

### *6.2. Recommendation*

The framework presented here can provide a foundation to apply ILM with RFID for material control. Whilst the framework presents integrated RFID checkpoints, it may still be difficult for stakeholders to connect RFID information flow and physical materials in the real world. Thus, the authors highlight two suggestions. One is to consider the key material types with RFID. The other is to use a context-aware scenario describing both on-site and RFID contexts to better understand the actual implementation.

For most construction material types, a fixed reader has the potential to automatically monitor the materials' quantity (R4), while a PDA reader has many advantages for lifecycle stages, such as issuing tags, quality inspection in warehouse (R3), allocation confirmation (R5), and installation (R6). The following recommendation was derived from the on-site trials regarding the five material types:

- Since STM (e.g. curtain wall) is the type of material with a longer lifecycle, it requires a permanent tag [12] which can represent the material's changing status throughout the entire construction lifecycle. Therefore, lifecycle management for STM should consider the integrated information flow with all possible RFID checkpoints: from T1 to T3; from shipping (R1) to maintenance (R7). Engineered-to-order materials [16] and precast production materials [27] will be included in STM. Parts and packets unification application [11], field tests of interior decorating materials [20], and lifecycle management [12, 15, 16] will provide a better understanding of technical features for ILM of STM.
- The information flow from T1 at the first factory to T2 at the second factory is an additional flow. Therefore, materials which have T2 at the fabrication stage are regarded as MTM. Structural steel (e.g. H-Beam) as MTM has significant effects on the construction schedule. ILM for the structural material can consider visualisation with 4D CAD [8] or BIM [36].
- As for VTM (e.g. ready-mixed concrete), the time management (linked to GPS) is essential to maintain the quality of the materials for delivery and distribution. Multi-tracking systems employing both RFID and GPS [23, 30, 34, 35] will be a potential approach. In addition, it can involve the second tagging (T2) for concrete curing management [39] to facilitate the concrete quality inspection and management.
- A pallet used for PTM (e.g. brick) is a key component to effectively adopt ILM for material control on the construction site. The pallet will contain the optimised quantity of the material as well as other material properties such as origin and even quality information. Therefore, it is necessary to develop an effective pallet or container for PTM. This is an important research direction for future work. Tags are currently attached to the surface of the pallet but they can be inserted to improve tracking and the movement of the pallet.
- ILM for KTM is significantly more important on the construction site owing to the small-size and high-prices of materials compared to other types. KTM is very similar to PTM. KTM has additional RFID checkpoints such as warehousing in (R3) and installation (R6). PTM focuses on quantity monitoring, whilst KTM highlights both quantity and quality inspection.

Secondly, authors suggest that stakeholders related to construction management use a context-aware scenario to explore and examine material control with RFID. Shen et al. [4], introducing the Capital Projects Technology Roadmap by FIATECH, suggest that scenario-based project planning can affect automated design and construction. Context awareness [41-45] has been widely researched in computer science, especially in pervasive computing. The authors emphasise that context awareness is an essential approach for enabling the computer to infer and recognise the physical contexts. This is useful for the application of an RFID system. The on-site trial described in Section 4 is very effective in this regard.

## 7. Conclusion

This paper presents Information Lifecycle Management (ILM) with RFID for material control. The ILM framework shows that RFID checkpoints on lifecycle stages can be simplified. This paper highlights five key material types in the ILM framework, and examines multiple on-site context and RFID parameters using a context-aware scenario. The ILM framework was intended to easily bridge between a wide range of actual materials and RFID applications. On-site trials have been used to validate that the ILM framework can facilitate material control with RFID.

The discussion section shows that RFID clearly facilitates accurate and real-time construction management in the building industry. Notably, this study differentiates from other studies in terms of the integrated lifecycle management with five key construction material typologies. The procedure we undertake to apply the ILM framework for material control also serve as a base for adopting other IT technologies in the building industry.

Future work will include refining the material classification with the time level, and verifying the ILM framework with other material types at different lifecycle stages. Although the five typologies of generic materials with RFID are effective, these refinements will optimise the ILM framework covering a wide range of highly customised parameters on construction sites.

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