AALTO UNIVERSITY
INTELLIGENT PRODUCTS IN HIGHWAYS ENGLAND

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HIGHWAYS ENGLAND RESEARCH FRAMEWORK

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1. Project Background and Description

Introduction

The Highways England is one of the largest clients in the UK, which manages a supply chain worth approximately £2.5-4 bn. HA has already recognised the importance of efficiency improvements in both construction, operations and maintenance aspects and has formed a lean division to help drive this internally as well as across the supply chain. The HA is also actively engaged with driving BIM across its projects and is part of the UK Government's BIM implementation roadmap.

As a large organisation that is responsible for overseeing construction, operation and maintenance of a large asset portfolio, The HA has significant interest in improving the lifecycle management of the assets.

The proposed vision aims to bring significant improvements throughout the lifecycle of the facility, from design to construction to operations and maintenance. The vision is built on the foundation of proven concepts and brings together expertise from a unique team of researchers ranging from design and construction to manufacturing, automation and computing at Aalto.

Background to research

In management of a large asset portfolio, a significant number of organisations interact with the product (asset) throughout the process, requiring intensive information handling and synchronisation between these organisations. However, with deep supply chains predominant within the construction industry and problems with the lack of information integration, the information synchronisation across the lifecycle poses a significant challenge. Currently, the information regarding each of these aspects resides in disparate information systems, which are seldom integrated, leading to problems of information flow.

Figure 1 depicts a typical construction project workflow, where the linear nature of the process becomes obvious. It should be noted that at each stage, the stakeholders interact with each other to develop the project which comprises of several products, assemblies, components and systems put together. There are rarely information loops between these stages, which ultimately affects the knowledge management and efficiency of each stage. Combined with the fact that the communication of information within the supply chain is also problematic and reliant on informal and ad-hoc methods (phone calls, emails, faxes, etc.), the management of product and project development remains a significant challenge.

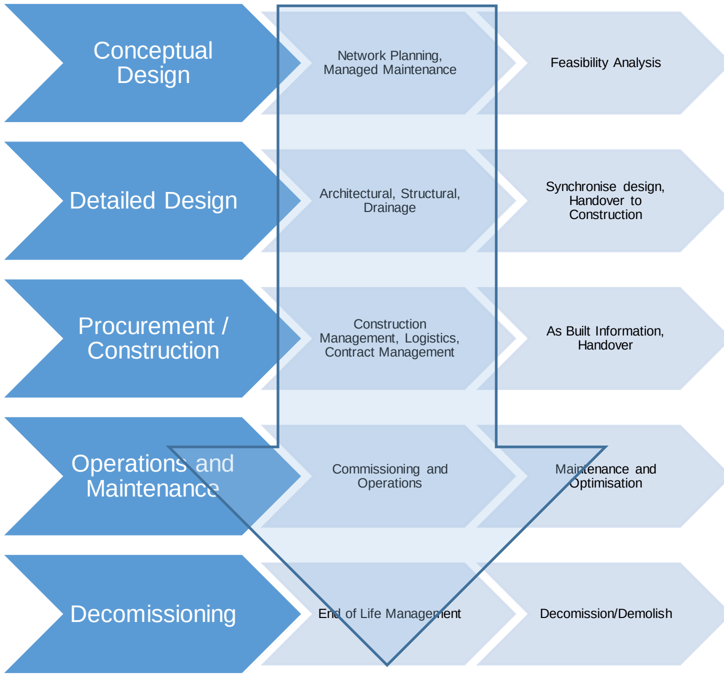

Figure 1 Traditional project lifecycle

Production planning and control affect construction processes directly, and have been one of the major aspects affecting construction productivity. Koskela (2000) attributes many of the problems related to the planning process in construction to the lack of an explicit theory and the predominant “Transformation” or “T” view of production. Koskela (2000) argues that this has led to the neglect of “flow” and “value” views in production and in turn has resulted in wasteful processes. The direct manifestation of this “T” approach can be seen in how the projects are organised and managed, as the activity guidelines/instructions for the next step in production are always pushed from outside of the production system (often according a CPM plan/schedule) and the flow of information is often dependent on systems external to production.

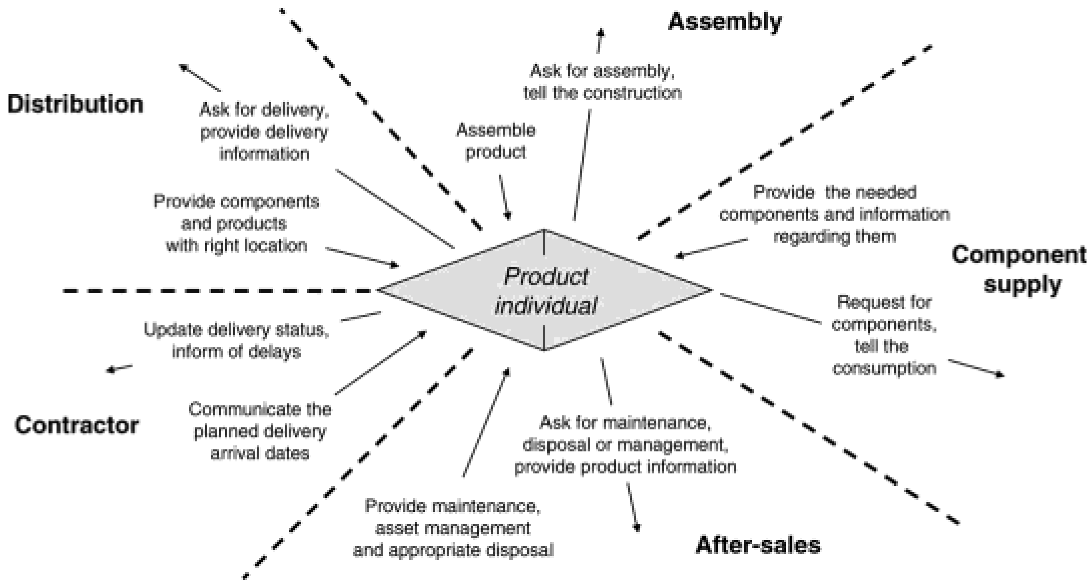

Figure 2 - Product Centric Information Management (Karkkäinen et al, 2003)

To overcome this challenge, we propose a product centric system as shown in Figure 2, where the control logic of the production and operations process is embedded within the individual components or assemblies themselves right from the design phase. The solution is enabled by a number of technologies and tools such as Building Information Modelling, Internet of Things, Messaging Systems and Lean Construction processes. The vision affects the entire lifecycle of the production process from design to construction and maintenance, where the products can interact with the environment and its actors through various stages supporting a variety of actions.

2. Problem Statement, Research Aim and Objectives

Problem Statement: The Highways England is one of the largest clients in the UK, and manages a large asset portfolio. Due to the information flow and communication problems there are significant gaps in the asset lifecycle management that lead to inefficiencies, loss of knowledge and cause waste. Potentially, losses of 20-30% in lifecycle costs can be attributed to loss of information or lack of integration within the asset management solutions.

Aim: To improve information flow, communication and production control through intelligent products – i.e. products that embed/carry/communicate all necessary information about them.

Vision: To develop a system where information flow is seamless across all stages of the project lifecycle, and where products themselves "pull" the next action from the supply chain.

Objectives:

1. Develop a framework combining the basic building blocks (BIM, Lean, Internet of Things and methods for Product Centric Control) to help realise the vision.

2. Develop an early prototype demonstrating embedded intelligence in product over the lifecycle (from design to construction to maintenance).

3. Work with HA supply chain partners to test the vision and prototype above, refine them and document the methodology.

3. Need for Intelligent Products / Business Case

Lifecycle management of any asset, product or component in Highways England is a major activity that encompasses design, procurement/construction, logistics, operations, maintenance and eventually demolition or replacement. The assets/products can be fixed such as roads, bridges, buildings or assemblies such as traffic management gantries, road traffic displays, etc. The coordination of the entire lifecycle involves a significant number of participant that make up almost whole of the Highways England supply chain. Design, delivery and operation of a single asset or component involves a wide range of design, construction and operations/maintenance processes which are based on an equally diverse array of software and information systems. Needless to say, this is a complex process that requires intense coordination over a long period of time.

Most decisions at the design stage are largely made in isolation from life-cycle aspects through local optimization (Reed, 2009). Some of the reasons behind this include managerial and technological limitations (Koskela, 2007). Global life-cycle optimization either for cost, building performance or user experience requires different organizational structures, as information from all domains are typically needed for making accurate life-cycle assessments (Putnam, 1985; Forgues and Koskela, 2008). Design is based on direct costs, at best on short-term profitability. Even when the lifecycle performance of a building or building subsystem is modeled, an unknown gap between potential and actual performance remains in the absence of tools and methodologies to spot opportunities.

The results of these information gaps are that costs are higher and performance lower than would be possible (Clark, 1991). This represents a significant waste of resources in design and construction and ongoing derision of value in use and operations. In the presence of the information gaps the service providers and solution developers remain unable to systematically improve performance of buildings in use or improve the design of solutions based on evidence (Reed, 2009).

Cost-effective transfer of tools and materials from the supplier location to the point of consumption with a high level of customer satisfaction is defined as logistics (Said & El-rayes, 2013). Logistics management essentially is recognized as the management of both information and materials flows through the supply chain. As several researchers (Koskela, 1999; London and Kenley, 2001; Shakantu et al., 2003) have found construction as an assembly operation, efficient information sharing plays a vital role in improved functioning of construction supply chain; moreover, it guarantees “major assemblers” are provided with building components and materials by the suppliers effectively (Jones, 2005). Not many construction companies have utilized the logistics management in its organizations; however, initial studies estimated a 10% to 30% of cost saving in effective logistics management (BRE, 2003; IAI, 2010). Fragmented nature of construction industry and logistics and challenges in data integration and compilation can be potential reasons for ineffective logistics management (Sargent R.G, 1991). Hence, it becomes essential to develop mechanisms for effective logistics management in order to enable data integration and seamless information flow on construction sites.

From the initial data collected by interviews with tier 1 supply chain members, it emerges that there are significant "breaks" in the information flows due to misalignment between various stakeholders' design, information and delivery mechanisms. While there are several initiatives that support collaboration within each stage, for example implementation of Lean Collaborative Planning in design and construction, there are still major gaps between each stage and product and project development, delivery, and operations remain silo based with little scope for iteration and feedback. Similarly, even after the deployment of government's BIM roadmap, the overall project delivery processes remain relatively unchanged.

Data Collection

Interviews were carried out with tier 1 supply chain companies of Highways England. Desk based study of previous reports was also used to verify collected data.

In total 5 interviews were carried out with the following persons.

- Stephen Greenhalgh, Highways England
- Lucia Fullalove, Highways England
- Andrew Fielding, Costain
- Katie Jones, Carillion
- Adam Bennett, Costain

The collected data was coded and analysed and categorised under main themes. The following presents the main findings from the collected data.

Decision support tools and processes

Key decision makers

Since the projects are complex and there is a deep supply chain involvement, there are several decision makers. However, project managers were identified as key decision makers for project related decisions. However, the project managers don't have authority over design or specifications related decisions, which could delay the project. In general, project managers

- Have programme related authority
- Don't usually set deadlines, but decisions are timing and scheduling are left to contractors
- Timing is related to pricing so that way the schedules are controlled
- Have the responsibility for Stakeholder management (i.e. end users, councillors etc)

Decision support systems

Decisions are mostly made in a "local" way, i.e. there is no holistic decision support system or a framework based on which decisions are evaluated. Decisions are supported through

- Cost benefit analysis in a traditional way (i.e. lifecycle approach is not taken)
- Project control framework – schedules various information that needs to be provided in order to go through respective gateways. At the last count there were six gateways.
    - Gateway 1-4 are design and development stages
    - Gateway 5 is construction related
    - Gateway 6 is Operations and Maintenance
    - Each gateway has requirements such as option reports, design development reports, construction reports, etc.
- In majority cases, capital cost wins against whole life cost, in particular this aspect was highlighted as a major shortcoming, i.e. inability to take a holistic view.
    - Nicholl's report in 2005 highlighted this particular area for improvement
    - The report highlighted that most decisions and projects are allowed to go ahead without much analysis or scrutiny, so projects tend to just "evolve" over time.
    - For example, a project related solution can have a life of its own, can become a small project that may be procured without analysing its impact on the overall aspect of the parent project or other parallel schemes.

Organisational Processes

Highways England is a typical silo organisation where, Design | Construction/Procurement | Operations are three major units. As a result, the projects tend to be over specified, cheap to construct and expensive to maintain. It was identified that through the new DBFO (Design Build Finance and Operate) organisations such as Connect+, there may be opportunities to improve.

Knowledge management

There are two major systems for managing knowledge; i) POPE – Project Opening Post Evaluation and, ii) Trackers.

POPE (Project Opening Post Evaluation)

This is a post project evaluation checklist to analyse if the project achieved its main objectives, e.g. "did the congestion ease or environment improve?". It was carried out by an external party and in a neutral way.

Trackers

Trackers are knowledge banks that maintain a database of costs and programmes. The trackers contain unit costs of each major operation, i.e. steel costs, concreting costs, ductwork costs, which are then used to carry out cost comparison analysis at the time of tendering etc.

Forums

Some independent areas within Highways England such as Smart Motorways have a forum consisting of variety of stakeholders, internal and external. However, these have typically a narrow coverage.

Logistics

One key aspect is that the focus is still on transformation and physical work, rather than “flow”, i.e. flow of information or materials, that pertain to logistics related aspects. There is very few analysis of logistics and flow activities and lean principles are not generally followed. On most projects, massive inventories are maintained due to the nervousness of the project manager. One example of lighting columns was mentioned where a particular project ordered 100s of such columns which were left unused for almost more than 2 years, even when there is a 3 month lead time.

Despite the linear nature of the schemes, the flowline or production view is not taken. In many cases, less than 10% of work is value adding, and 90% is either waste or non-value added. The most important aspects that affect logistics:

- Contractual issues. Final constructors (tier 2 and 3) are still procured at a lowest price contracts even through tier 1s are on framework agreements.
- There is a constant change in project scope and specifications and resources are limited.
- There are problems with information sharing systems as suppliers are not allowed access to Highway England’s project extranets.
- Collaborative planning is deployed on projects but it is not very effective due to such information sharing problems.

4. Main components of Intelligent Products

“Intelligent products” has the potential of resolving significant problems with production and supply change management within the construction lifecycle (Dave et al., 2015). With the aim of intelligent products, the sequence and control logic of the production can be attached to individual construction assemblies and components from design phase. The technologies such as IoT communication frameworks, Lean construction Techniques, BIM and multi agents should interact and cooperate together in order to enable individual products to be context-aware with the ability of sensing the production status and adapt their behaviour accordingly.

BIM

Building Information Modelling (BIM) plays a central role in this concept. Products start their life as virtual representations in the BIM system and are assigned an URI (Uniform Resource Identifier, used to locate and link information across web) (or recognised with an existing one) from their inception in BIM, and also when in physical form (i.e. when it is purchased/assembled/constructed) and is associated with the product for its lifecycle. For example, by selecting a product in BIM from a manufacturer’s catalogue will link all the product specification, installation and tolerance related information that is available from the manufacturer’s system. This information is not integrated or input in the BIM model but only linked to it using the URI of the product. This way the model remains "light" and yet enriched with information. Although BIM systems may not be needed to input the information or store in the database/model, they should have appropriate user interfaces in order for users to interact with the information and visualise it.

Lean

Lean construction is the process enabler the intelligent products concept through the application of "pull" production concept and also through alignment of value across the supply chain. The underlying motivation behind intelligent products concept is to maximize value generation (or minimize value loss) and reduction of waste due at all lifecycle stages – the central tenets of lean.

While the concept proposes to automate several scheduling and control functions, it still relies on collaboration between project team that could be achieved by the Last Planner System. In production management the vision support "just in time" logistics and pull production by automatically scheduling deliveries and requesting next task action based on current status. Also, it aims to support Lean Design techniques such as Target Value Design and Choosing By Advantages by providing real-life data about components/previous designs when designing for new projects.

Internet of Things (IoT)

Like BIM, IoT also plays a key role in the proposed concept, as it provides the infrastructure where each individual product or indeed any object, organisation or entity within a project can be assigned a URI and information attached to it, which can then be accessed through appropriate interfaces. The IoT concept is nowadays mainly used for describing a network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment. The IoT encompasses hardware (the things themselves), embedded software, communications services and information services associated with the things. In practice, the IoT concept also includes data systems that contain information about those physical objects, such as design and manufacturing documents, service records etc.

Open IoT Standards

A communication framework for the IoT has been developed by the IoT Work Group of The Open Group called O-MI (Open Messaging Interface) and O-DF (Open Description Framework) that enables system-system, system-human and human-system communication, and also plays a key role in the concept. The communication standard has a potential to address the construction project lifecycle with BoL (Beginning of Life), MoL (Middle of Life) and EoL (End of Life) stages as depicted in **Figure 3**. Communication is at a centre stage in construction as the information has to be delivered to the right actor at the right time and in addition information has to be captured at the right moment (also in the field or on the move when concerned with logistics). The Open Group standards enable such a dynamic exchange of information to support the product lifecycle at each stage as shown in **Figure 3** through the O-MI cloud.

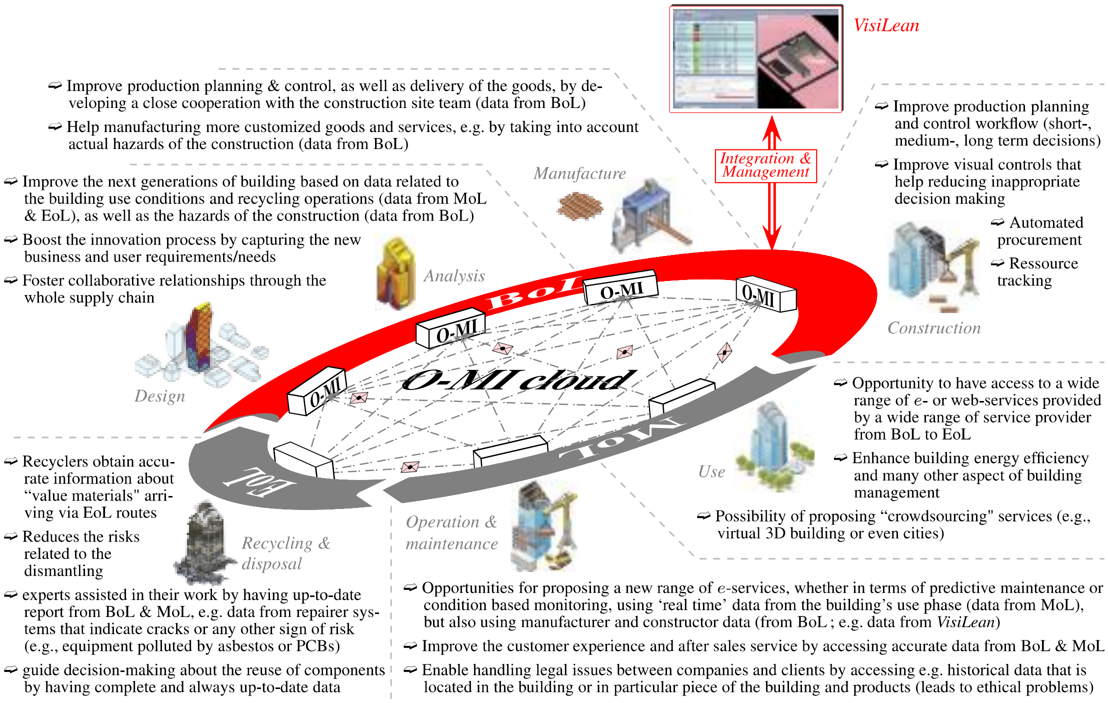

Figure 3: Open Group IoT Standards across the Project Lifecycle.

Agents

The notion of virtual enterprise (Aerts, Szirbik and Goossenaerts, 2002) describes a setting where supply chains become increasingly dynamic and network-like. Agents have been used for representing the participants of the supply chain, e.g. order acquisition agents, logistics agents, transportation agents, scheduling agents etc.(Fox, Barbuceanu and Teigen, 2000). The purpose of the agent architecture is typically to model, simulate and analyze supply chain operations in order to achieve better control of them (Scholz-Reiter and Höhns, 2003). Product items can have associated agents (Holmström, et al., 2002; Kärkkäinen, et al., 2003), which can greatly simplify access to product information. It can also simplify updating product information in tracking applications, for instance. In a multi-company setting, agents usually communicate over Internet connections.

Internet has become nearly ubiquitous for companies in all developed countries, making point-to-point connections obsolete. So if Internet access is available, there is no point in moving all product data along with the physical product. A challenge is that the link should be valid for the whole product life cycle. The information should also be constantly available (24/7).

As shown in Figure 4, in the agent model, information is fetched and/or updated only when needed. Information access can be split into two main functions, namely:

1. Accessing product data. Typical product data that needs to be accessed are user instructions, maintenance records, assembly instructions etc.
2. Updating product data. Typical updates concern tracking of shipments, maintenance records, status monitoring of machines etc.

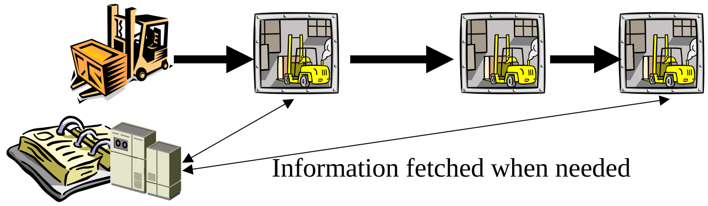

Figure 4: The "agent model" for real-time access to product information.

Multi-Agent System and Intelligent Products

Multi-agent systems add another layer to agent intelligence, because in multi-agent systems there is an opportunity to exploit collective intelligence, which is greater than the sum of the parts. In such a scenario it is possible to achieve fairly complex set of tasks using simpler agents, because the complexity is achieved through the interaction between the agents and the knowledge distributed across the different agents.

The ability to deal with complex tasks with fairly simple agents is particularly relevant to the proposed view of intelligent products. While construction projects and the information flow in such projects are known to be complex, the control logic and sub-tasks can be broken down to simpler rules at individual product levels. Thus, the rules and logic encoded within each product can be simple, but the ability for these products to interact with each other, and the human agents around them, will allow complex set to actions and activities to be realized within the construction projects.

5. Potential Use Cases

Just-In-Time Logistics Based on Production Status

Resource management on construction sites is one of the most important areas from production management perspective (Koskela, 2000; Ballard, et al., 2002). Through intelligent products, the individual components and assemblies will have the sequence and control logic of the production embedded or attached with them already from the design phase. Through multi agents and IoT framework and a pull based production system, the products will themselves “know” when the next operation that needs to be performed on them and the related schedule. Hence, a product would “call” for delivery from a manufacturer or a supplier when it is ready to be shipped to the site. Once on site, the product would provide information about its location and “call” the worker when it is ready to be installed. Such production logic would be extended to the lifecycle of the product and can even include design and operations.

Design Lifecycle Analysis

The concept of intelligent products can become resourceful for designers and engineers building new structures. Spaces are needed for fulfilling client’s functional requirements and if one considers space also as a product, even though abstract, then feedback loop from previously built buildings and their actual spatial performance can facilitate building workspace planning (Pennanen, 2004). Based on programming, performance requirements can be assigned to these spaces, e.g. what should be the level of humidity, temperature, air volume exchange, safety etc.

What is fundamentally important here, is how different elements become sub-systems, and systems. Therefore, intelligent products can support the synthetic integration of basic entities into greater wholes for meeting client functional needs and performance requirements. Building information modelling combined with lean design practices such as target costing, target value design, choosing by advantages can benefit from intelligent products as it helps to maintain the whole life-cycle view of designing product either in building programming, developing a conceptual design or choosing proper physical structures and products.

Lean Maintenance

The operations and maintenance phase of a built facility accounts for the major share of project cost and resource consumption, hence it can have a significant impact on the realized project value. One of the key characteristics of the maintenance related issues is their time criticality and potential disruption of routine. Typical maintenance issues can disrupt existing value-delivering activities that are already running smoothly. With effective information management, such disruptions can not only be reduced, but potentially prevented. Thus, among other approaches, maintenance response time and preventive maintenance are two important pathways to technology-enabled lean maintenance. While such trends are already visible in current building automation systems, the intelligent product approach extends the possibilities to a new dimension. In the new paradigm, the various systems and sub-systems can also be envisioned as agents that interact through instant messaging, self-diagnose and self-organize, reducing the information delay, reducing the layers of information exchange, and prevent potential waste that may occur due to cascading damages that could result from delayed maintenance of a critical sub-system.

6. Logistics Case with Intelligent Products

After collecting initial data through interviews and to demonstrate the feasibility of the concept within the Highways England supply chain, the area of logistics management was chosen for the use case development. The first part of the use case demonstrates the need for Intelligent Products in construction projects through review of literature and requirements development through Quality Function Development. Subsequently, the developed prototype has been described that demonstrates an example implementation of Intelligent Products through integration of BIM with mobile tracking technologies.

Logistics Management in Construction Projects

Cost-effective transfer of tools and materials from the supplier location to the point of consumption with a high level of customer satisfaction is defined as logistics (Said and El-rayes 2013). Logistics management essentially is recognized as the management of both information and materials flows through the supply chain. As several researchers (Koskela, 1999; London and Kenley, 2001; Shakantu et al., 2003) have found construction as an assembly operation, efficient information sharing plays a vital role in improved functioning of construction supply chain; moreover, it guarantees “major assemblers” are provided with building components and materials by the suppliers effectively (Jones, 2005). Not many construction companies have utilized the logistics management in its organizations; however, initial studies estimated a 10% to 30% of cost saving in effective logistics management (BRE, 2003; IAI, 2010). Fragmented nature of construction industry and logistics and challenges in data integration and compilation can be potential reasons for ineffective logistics management (Sargent R.G, 1991). Hence, it becomes essential to develop mechanisms for effective logistics management in order to enable data integration and seamless information flow on construction sites.

"Intelligent products" has the potential of resolving the significant problems with production and supply change management within the construction lifecycle (Dave et al. 2015). With the aim of intelligent products, the sequence and control logic of the production can be attached to individual construction assemblies and components from design phase. The technologies such as IoT communication frameworks, Lean construction Techniques, BIM and multi agents should interact and cooperate together in order to enable individual products to be context-aware with the ability of sensing the production status and adapt their behaviour accordingly.

The purpose of this research is to aim construction project actors with a practical approach which has a potential to eliminate the information gap through the supply chain and facilitates the project planning and facility management. The authors of this paper propose a technical and practical solution that makes it possible to enable the construction tools and components to carry construction life cycle information from their inception to construction and maintenance. To this end, this paper is followed by a critical review of existing problems through current approaches of logistics management. The third section discusses the proposed solution and the major high level enabling technologies. In fourth section, requirement analysis using QFD is performed in order to translate system functional requirements into technical specifications for implementation of logistics management system. Finally, the method and materials for development of prioritized requirements of the prototype are explained by reflection of high level architecture and modules` components of the entire system followed by the conclusion.

Current Approaches to Construction Logistics

Construction logistics is a set of activities including strategic management of procurement, delivery and storage of parts, materials and components and relevant information flows through different agents to maximise the current and future profit by effective fulfilment of requirements (Wegelius-Lehtonen, 2001). Typically, construction logistics itself contains supply logistics and site logistics. Supply logistics includes iterative activities in production process such as supply planning, resources acquisition, delivery of materials and components and storage control. Site logistics comprises activities related to managing, directing and monitoring on-site processes such as activity sequence management and resolving production teams' conflicts about on-site activities. In traditional construction practice, there was an information gap between resource management and workflow (Arbulu *et al.*, 2005). Subsequently, the planning team organized all schedules related to operations, workers and tools with the assumption that all facilities and materials for installation are available.

Effective logistics management plays a vital role in systematic reduction of waste, project speed up and safe site environment (Tischer *et al.*, 2013). On the other hand, poor logistics investment can affect the quality of construction and also late delivery which itself can result in time and budget overruns. The construction supply chain is suffering from the lack of stakeholder's incentive to invest in logistics since there is a wrong belief that the amount of investment will not be compensated by the value provided from an adequate logistics management (Caron *et al.*, 1998). Blumenthal and Young (2007) categorized the existing construction logistics approaches into four categories as it is indicated in *Table 1*. First three methods are considered as the traditional construction logistics approaches, where only the fourth method is applied in modern construction companies. It can be argued that about 95% of construction companies are still using the traditional methods to provide materials and components throughout construction lifecycle.

Table 1. Construction logistics approaches (Blumenthal and Young 2007)

Logistics Methods	***approach***	***Usage***
Method 1	The construction company directly refers to supplier to pick up the materials and components.	~10%
Method 2	The construction company already ordered and has the material and goods in storage.	~50%
Method 3	The company uses portfolio analysis in order to divide into call of arrangements and part ordering processes	~35%
Method 4	The construction company manages beginning-to-end process and includes information, people and material flow	~5%

The study of logistics management challenges in construction indicates that mostly, the sources of problems have resulted from inefficient materials handling, inappropriate delivery scheduling (RW.ERROR - Unable to find reference:1; Ying *et al.*, 2014) and shortcomings of interactions between suppliers and clients due to highly fragmented supply chain (Agapiou *et al*., 1998; (Dave et al. 2015). Azambuja and O`brian (2009) recognized the important reasons of on-site inefficiencies can be caused by problems in decision making on buffers, off-site production and delivery planning. The most common solution to decrease the risk of delays on site production is to keep inventory on construction site more than requirements. However, this practice results in significant space and resources allocation that leads to unnecessary investment, and inventory is one of the major waste from lean perspective.

Wegelius-Lehtonen (2001) developed a framework for performance measurement for construction logistics that categorized its metrics according to their target and focus. Caron et al. (1998) presented a stochastic model to plan the material delivery to construction sites taking into consideration the variety in delivery dates and construction throughput rate. The developed model was not detailed enough to integrate the supply and construction. A study by Jang et al (2003) noted the importance of five main parameters on project managers` satisfaction of construction logistics such as contractor`s organization, material and information flow. Moreover, this study highlighted the necessity of construction logistics software and technical improvement. Last

Planner System (LPS) developed by Ballard (2000) partially tackled the variability and “flow” aspects of construction problems by providing a detailed construction planning and control workflow. However, Dave et al (2015) pointed out that such systems have relatively long “look-ahead” responsive planning to construction requirements where daily or even hourly control is needed.

Product tracking technologies such as radio frequency identification (RFID), global positioning system (GPS) and ultra-wideband have been applied in construction logistics. However, implementation of such technologies has been deployed in limited levels (Young *et al.*, 2011) and implementation of integrated technologies within construction supply networks is still needed. Present logistics management systems with localized information system are capable to serve specific amount of requirements. Nevertheless, they are not adequate due to requested changes and updates in design and manufacturing can result in incorrect specifications and receipt of wrong components on site (Cutting-Decelle *et al.*, 2007).

In order to tackle the problems from existing studies in construction logistics management, there is a need to implement a framework with the capability of supply chain data integration and elimination of information flow problems with the goal of synchronization of project resources and providing high level of project planning. In the next section, a potential solution will be proposed which can help overcome the aforementioned gaps in construction logistics management.

Logistics Based on Product Centric Control

Nowadays, products with unique identification and integrated control instructions are being developed for simplification of seamless information flow, material handling and customization throughout the supply chain (Kärkkäinen & Holmström, 2002). The basic idea of product centric control is while it is in the production or delivery process, the product itself requests and organizes all the necessary facilities from appropriate providers. Dave et al. (2015) noted that intelligent products have contextual operative logic linked within individual components already from design phase and they are able to support whole lifecycle from design to construction and maintenance. The derived advantages of intelligent products such as autonomous behaviour and responsiveness to real-world circumstances can considerably reduce the need for planning and organization, improve inventory management and finally improve product quality and project performance (Musa *et al.*, 2014; Rönkkö *et al.*, 2007).

The basic principle of product centric control is to embed the products and process related information, which is necessary for construction project actors’ communication across supply chain, within products themselves. Consequently, the individual component and assemblies within intelligent product are capable to carry the required sequence and instruction of construction project with themselves from design phase along the entire lifecycle as shown in *Figure 5*. In other words, the intelligent construction components should be aware of when is the next operation on them and the relevant schedule. Therefore, a construction product itself would request a delivery service from the supplier or manufacturer whenever it is ready to be delivered to the construction site. As the product is shipped to site, it should provide the information about its location in site storage and then inform the specified worker to be installed based on designed time schedule. From the logistics point of view, such scenario is completely implementable with the aim of intelligent products capabilities in flowing information between different project agents. To this end, it should be investigated what technologies are required for Implementation of intelligent products.

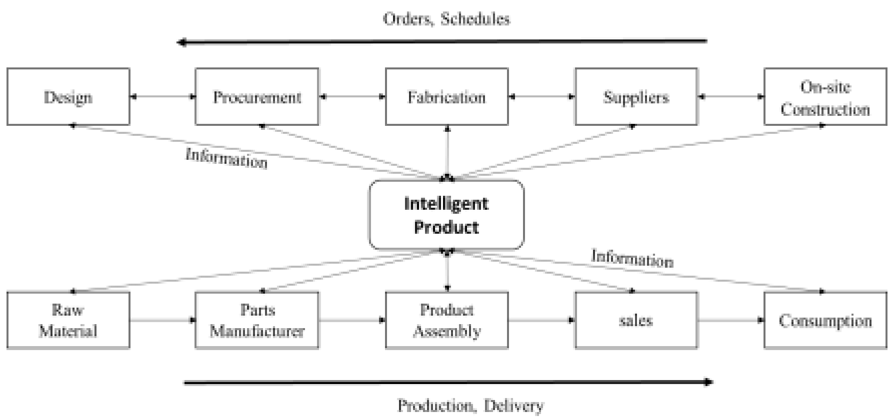

Figure 5. Information handling by intelligent product through construction supply chain

Internet of Things (IoT), Building Information Modelling (BIM) and Lean construction techniques are the main enabling technologies for implementation of intelligent products (Dave *et al.*, 2015). Through IoT communication framework, an infrastructure where the product ‘information can be exchanged between organizations` agents and individual products is provided. In this context, a high level abstraction-level of communication interface is required to leverage heterogeneous organizational information systems. To enable this, a recent IoT standard published by The Open Group IoT Work Group, namely O-MI (Open Messaging Interface) and O-DF (Open Data Format), is deployed to facilitate the information exchange between any organization agents or products (Dave *et al.*, 2016).

BIM plays a vital role in the reduction of planning redundancy and raising engineering efficiency with capability of storing virtual and multidisciplinary information about products (Said and El-Rayes 2014). From intelligent products perspective, BIM helps products to start their virtual representative lifecycles with assigned URI (Uniform Resource Identifier) to them. It is not reasonable for product model to store all specifications related to its lifecycle; Instead, URI will be used to connect the product model to its physical form to retrieve all lifecycle information such as procurement, assembly and installation schedule.

Lean construction is considered as the alignment and holistic following of simultaneous and continuous improvement in all dimensions of construction stages (Abdelhamid & Salem, 2005). Just-in-time logistics system based on intelligent products operates on lean construction technique such as “pull” based production to maximize value across supply chain and reduce waste from lifecycle stages by providing materials in construction site when and only when it is needed. To this end, a smart selective control with the ability to draw the activity with highest priority is needed to implement such pull based-driven system (Tommelein, 1998).

Requirements Capture and Framework Development

The aim of this study is to develop a framework for a “logistics management system utilizing intelligent products” concept to track individual materials and components from their inception, assembly and installation across construction stages. In this section, the materials, tools and methodologies for such development are investigated in order to better understand the technological and scientific perspectives of the proposed solution. Considering the technological limits, the prioritized technical specifications are needed to develop the first proof-of-concept based on the proposed framework.

In the previous section, some of the main enabling technologies were investigated. However, a requirement analysis should be performed in order to recognize the detailed technical specifications for implementation from initial requirements. In this respect, Quality Function Deployment will be done in order to identify the principal system requirements and prioritize quality specifications.

Quality Function Deployment (QFD)

During an efficient product design, a designer or design team should identify the end-user expectations accurately. Quality Function Deployment (QFD) is a systematic approach to better understanding of customer requirements in order to design a product or service considering all stakeholders involved in production and supply chain process (Esan *et al.*, 2013). The ultimate goal of QFD is to quantify and measure objective quality specifications in order to design and manufacture the final product based on assigned priorities in product development (Reilly, 1999).

The QFD approach taken in this research is adapted from (KublerIMS, 2010) and contains two levels of matrix evaluation namely “house of quality” in order to translate high-level requirements into scientific and technological specifications as indicated in *Figure 6*. In addition, the product functional analysis is performed to extract requirements from investigation of existing literatures and surveys related to the expectations of an automated logistic management system. However, it is intended to collect real customer requirements from the industry partner`s key personnel in further studies.

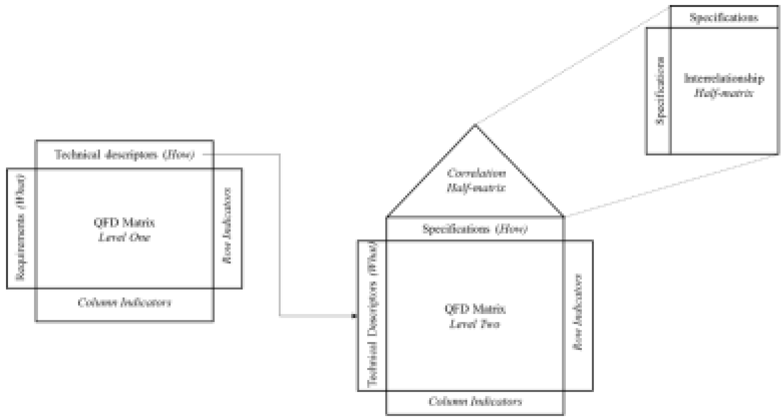

Figure 6.Two level QFD matrices (House of Quality)

In level one, the requirements (*What*) are listed in rows with their initial priorities (from low priority 1 to high priority 5) and technical descriptors (*How*) are placed in the columns of this matrix. Finally, the relationship matrix is developed between *What-How,* based on four levels: 0,3,6,9, where they mean to what extent the relation is strong between the elements of matrix as shown in *Figure 7*. The column indicators of matrix presents the information about the relative influence of a single technical descriptor on all requirements and row indicators shows the relative effects of technical descriptors on single requirements.

What	How / Periority	Different IFC schema compliant	support various agents Technologies	Simulation tools from building design phase	Different levels of accessibility	encryption and decryption of information	Data history availibility	IoT data standards compliant	Product and process Dashboard	Decision making support	Positioning system cordinates	Web-based Interface	Agents`ability to communicate through Internet	
		lifecycle tools			Security & Privacy		Operation Management							
Upload BIM model design based	4	9		9			6							96
Register the agents for material tracking	5		9		6	3		6	6			3	6	195
Provide users privacy and security requirement	3				9	6	3		6			9		99
provide security for exchange of information	3					6		6			3		6	63
Record the production tracking location	5	6					9		3		3	6		135
Enable users to view/manipulate supply chain stages	2			6	6		3	9		3		9		72
Connect the product model to physical product URI	5	3	3					6	9			6	6	165
Provide automated material delivery based on project schedule	3			6		3			6	9			6	90
Provide information about the location of material on site	2						6	3	3	3	9		3	54
		0.810	0.600	0.660	0.690	0.600	0.960	1.020	1.320	0.390	0.420	1.200	1.020	

Figure 7. First Level QFD matrix

Through second level of QFD, the previous approach should be reiterated between the technical descriptors (*How*) of first matrix, which become "*What*" of this matrix, and specifications of logistics management system placed in columns. In this manner, the quality is ensured by constraints spreading since the technical descriptors of the first level matrix become the *What* for level two matrix as illustrated in *Figure 8*. Once the specification of second matrix get solved, the requirement of system become fulfilled. Subsequently, interrelationship or correlation half-matrix (which exist also for first level matrix and also known as the “roof” of House of Quality) between system specifications (*How* of second level matrix) should be developed in order to identify correlations between specifications which may be positive, negative or not related. In fact, the aim of this work is to identify areas which some specifications can conflict with others and some of them can inform other processes.

As it is noted from above matrices, the used QFD approach is not similar with classic way. In fact, the second level matrix is highlighting the technical specifications for functional requirements fulfilment. It is figured out of the row indicators of level one matrix, the requirements “connect the product model to physical product URI”, “register the agents for material tracking”, “record the product location across production and delivery” and “provide expected security and privacy for system users” have higher priority to fulfil respectively. The column indicators of second level matrix shows that the specifications “Open IoT messaging communication framework”, “3D Web technologies”, “Distributed Architecture” and “IFC standard compliant” are respectively the most important. Consequently, a logistics management system prototype is developed in order to validate the pertinence of the achieved results from requirement analysis.

Figure 8. Second level of QFD matrix with correlation half-matrix on roof

7. A prototype demonstration

Potential Solution and Own Contribution

To address the formulated problem for Logistics (in the previous chapters), NFC tracking system has been proposed. The proposed framework should accomplish two main functions:

- Relate the actual product with the virtual one represented in the BIM model
- Retrieve and visualize the latest tracked location of the actual product in BIM

A conceptual framework has been developed for the fulfillment of above requirements and a prototype system has been implemented.

This chapter has been divided mainly into two parts. In first part, detailed analysis of the requirements for candidate solution has been done. In second part, a framework for the logistics tracking has been designed and development of the prototype system implementing the proposed framework has been discussed.

Requirement Analysis

Detailed functional requirements for the candidate solution has been listed and discussed below:

- Upload BIM/IFC model
- Register the agents for material tracking
- Authenticate users
- Connect the virtual BIM product model to the actual physical product
- Maintain data privacy of the BIM
- Record production tracking locations
- Provide location information of the product on site
- Enable data versioning

Upload BIM/IFC model

This is a basic requirement for a construction logistics system with IoT to support BIM/IFC model upload and 3-D model rendering. This enable visualize and locate product accurately in the BIM.

Register the agents for material tracking

Agents can be either software agents or human users. Here, they are referred to software agents with NFC readers. These agents have to be registered to the server before it can identify each software agents. During registration, each agent is assigned a unique identity which is used later on to identify it.

Authenticate users

Only valid users should be allowed to use and communicate with the server. During registration of the software agents, their identity should be verified. Moreover each request from agent to the server should be authenticated before they can access the services. There should be provision for generating unique authentication token every time while initializing the agent. The generated authentication token should then be checked in all the communication requests between agent and server.

Connect the virtual BIM product model to the actual physical product

BIM is or tends to be a data-rich, intelligent digital representation of the construction site. The virtual products represented in the BIM should hold sufficient information the product including location information. In order to track and visualize the product in such systems, it is crucial to be able to link between the actual physical product and the one represented in BIM model. Such linking can be accomplished by means of NFC tags or RFID tags.

Maintain data privacy of the BIM

The information contained in BIM might be domain specific and private. Leakage of such private information may have intellectual as well as economic loss. Data privacy is of utmost importance in construction management systems since such systems has to deal with multi-party agents.

Record production tracking locations

The system should keep track of most recent tracked location of the product. Moreover, all the locations that had been recorded for a particular product has to be maintained in the location history. Such location history can then be analyzed in the production life cycle.

Provide location information of the product on site

Exact location of the product on site has to be recorded by the system. This is significant not only from ergonomic perspective but also efficiency point of view. GPS Coordinates with resolution up to 20 meters can cutback a tedious process of locating products and save valuable time of workers as well as machinery.

Enable data versioning

The system should maintain a reliable versioning system of all the data. Data versioning system is required in order to keep track of the work history and its analysis. Every object in the database should have its own version along with other information such as date, author and comments.

Design of Prototype system: NfcTracking

NfcTracking has been designed as a prototype system implementing the proposed Logistics Framework. The overall architecture of the system has been shown in Figure 9.

NfcTracking has mainly three major components: (a) a central server with all the control logic and database storage, (b) a thin web client for rendering BIM and information about the products and (c) agent for reading and transmitting NFC/RFID tag’s information to the server.

For storing the product information in the actual products, RFID or NFC technology can be used. Both RFID and NFC falls into the same category of identification technology using radio frequencies. RFID has larger range than that of NFC, which also signifies that NFC is more secure among the two since NFC reader has to be close up to a range of few centimeters from the tag to be able to read the data. Since NFC reader comes with most of the smartphones now-a-days, NFC has been chosen for the prototype development and hence the name, NfcTracking. Product reader agent has been deployed in a smartphone with android OS.

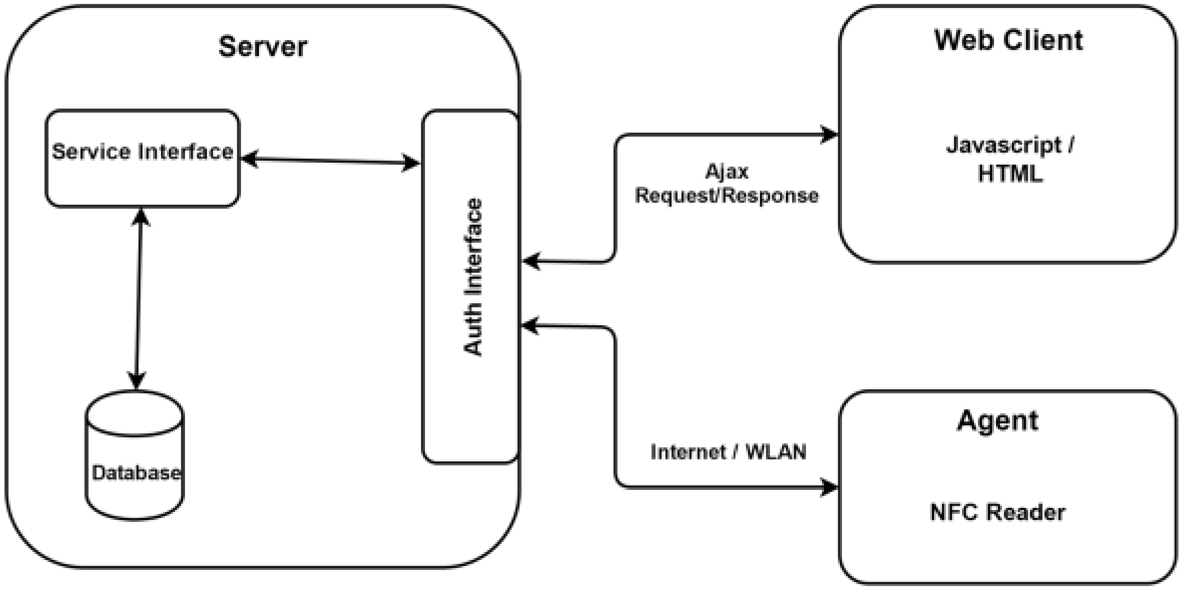

Figure 9 - Overall System Architecture of NfcTracking

Server

Server is the most important component of the system since it consists of all the data handling logic along with the database. It consists of a web server which is publicly accessible through internet. Web server communicates with other components, namely web client and agent, in the form of web requests and responses via a basic network protocol, HTTP.

All the incoming requests has to go through "Auth Interface", a component in the server for authenticating the requests. Auth interface checks for either a valid authentication token or user-name and password, to make sure that the request is not coming from an unauthorized user or agent. Authentication token is a random temporary sequence generated each time a valid user logs in to the system, and is valid for the span of the session until user logs out. Thus generated authentication token is then passed along with each and every request.

Valid requests are then handled by "Service Interface". Depending upon the type of requests, they are processed accordingly.

Upload Requests: Upload requests are passed on to the "Upload Interface". Such requests have BIM model (for example IFC file) along with them. IFC file is parsed and then stored in the database.

Download Requests: Download requests are handled by the "Download Interface. Specified revision of the model is then retrieved from the database and sent to the client in the response.

NFC Requests: NFC requests are passed on to the "NFC Interface". All the requests related with the NFC tags and readers are handled by this interface. NFC requests can be of following types:

- NFC reader registration request
- NFC product/tag registration request

- NFC product location update request
- NFC product details retrieval request
- NFC reader's list retrieval request

BIMServer has been used as the main core of the server. BIMServer is an open source software based on open standard IFC which supports parsing IFC files and storing them in database maintaining revisions. It has a nice interfaces and JSON/SOAP APIs for outside systems to utilize its functionalities. NfcTracking has been built on top of BIMServer by adding an NFC interface to handle all the NFC requests.

Web Client

Web client as shown in Figure 10 is the dashboard for managers and other users to retrieve and manipulate all the information such as project plan, BIM model, project progress, product details, etc. Web client should be designed to be thin without any business logic in it. Thin web client is significant for two reasons:

Data Security: Web client runs in browser of users' machine. Any sensitive business logic in client side is a security risk. Instead, processing of such business logic should be moved to the server side. Hence web client's responsibility is limited to: (a) sending requests with necessary input fields; and (b) parsing and displaying the response in the client machine's web browser.

Performance: The lighter the web client application is, the better it performs. Performance-wise, central server is more computational capacity than client's browser. Moving all the computational load to the server increases the performance of the web-client. From web-client's perspective, the only bottleneck is the latency between the server-client communication. The number of requests should be optimized in such a way that one request is independent of other responses. In addition, it is critically important that all the requests to the server are asynchronous, which means they are processed in parallel.

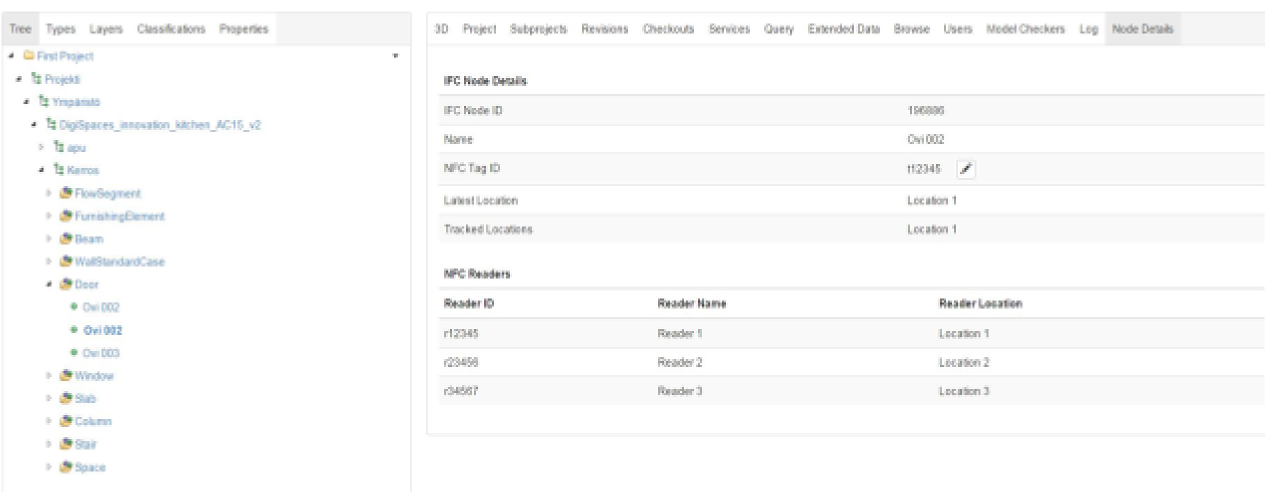

Figure 10 - Web-client - BIM node details with NFC agent

Since this prototype is designed to address the construction logistics system, product location details portion of the web client has been focused. It has two parts: (a) product location details and (b) product tag readers' list.

(a) Product Location Details: Details of the selected product is displayed in this part. If the product has been linked with actual product, then its tag ID is shown along with its most recent location as well as its previously recorded location information. If the product is not yet linked to the actual product, then it can be accomplished here.

(b) Product Tag Readers' list: Product tag readers are referred as agents. All the registered agents along with their name, location and ID are enlisted in this part of the web-client.

Agent

Agents can be defined as autonomous software process with a set of predefined goals, that are capable of communicating with other such agents. In supply chain management systems, different agents can have different objectives. NfcTracking consists of product reader agents that communicates with the server directly via internet.

- The major functionalities for a product reader agent are broken down as below:
- Read product information from the tag attached to them.
- Get the location from GPS coordinates of the agent
- Communicate with the server to fetch and send information about the product
- Write data to product tags
- Authenticate users before using the agent software.

Register the agent and the actual product to the server. NfcTracking has been developed on Android OS with access to NFC device, GPS and internet. The architecture of agent has been shown in Figure 11.

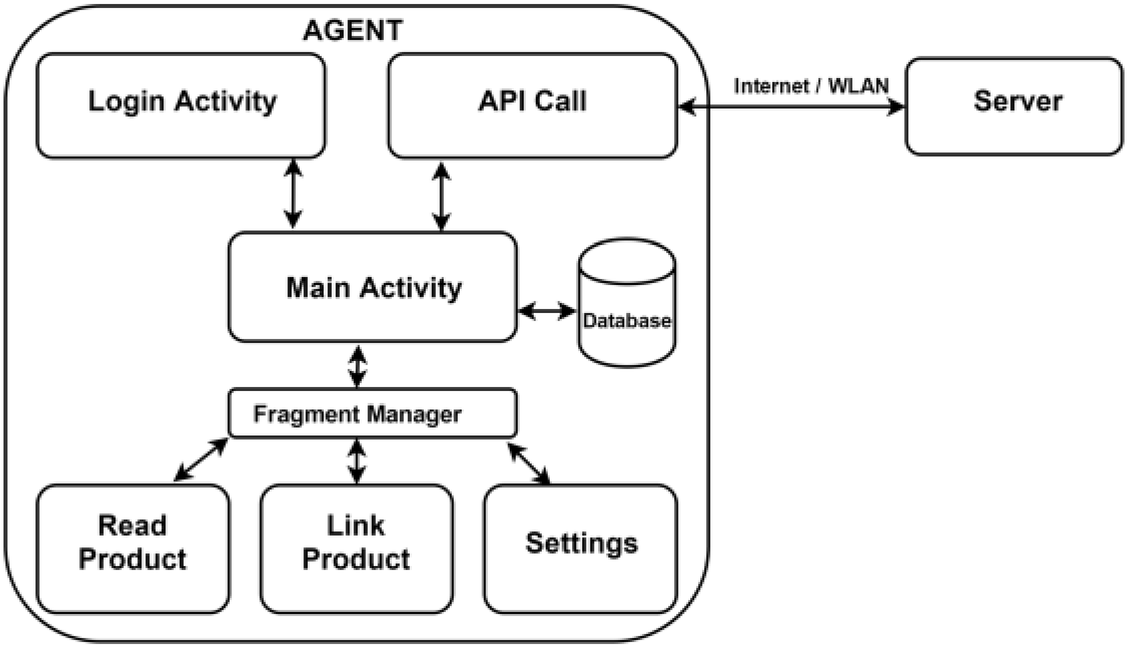

Figure 11 - Agent Architecture

Agent consists of API Call to communicate to the server via internet. It has "Main Activity" which acts like the main core of the application. Main Activity has access to a local database for storing settings and agent information. For authentication, it has a Login Activity. User interfaces are handled by Fragments. Main Activity interacts with the fragments through a Fragment Manager. It comprises of three fragments, each for: reading product tag, writing product tag and settings.

The basic workflow of a NFC reader agent can be summarized in these points:

(a) Agent Registration: After installing the agent application to an android device, it needs to be registered to the server. Server then stores the location information of the agent and assigns a unique ID.

(b) Authentication: User needs to login with valid credentials before using the agent software. Authentication token is stored for the session.

(c) Linking products: While writing to NFC tags, agent fetches unique NFC tag ID from the server and writes it to the tag. The tag ID is stored in the server as well which is linked to the virtual product in the server through web client. The written NFC tag is then attached to the actual product, thus a link between actual product and virtual product is created.

(d) Reading products: While reading NFC tags attached to the actual products, agent creates a message with NFC tag ID, agent/reader ID, GPS coordinates of the agent, and authentication token.

(e) Updating settings: Agent information such as agent name and address can be edited from the settings interface.

NfcTracking (Android Agent) Screenshots:

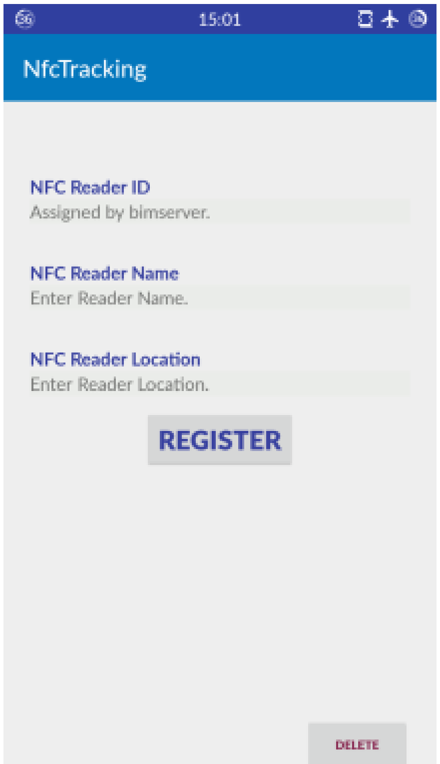

Figure 12 - Agent registration screen

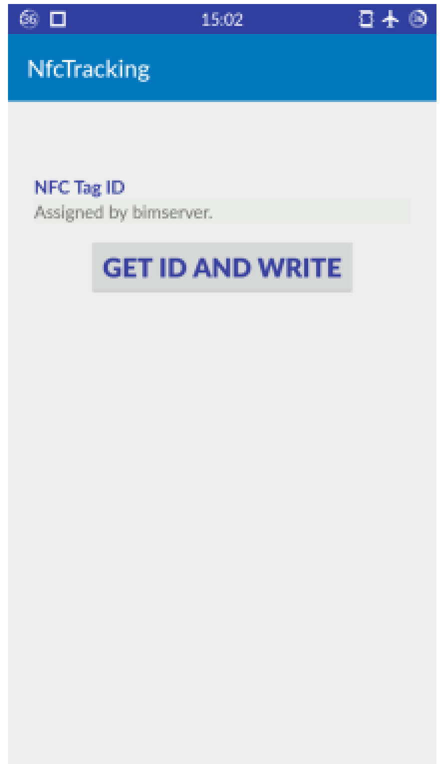

Figure 13 - Link product screen

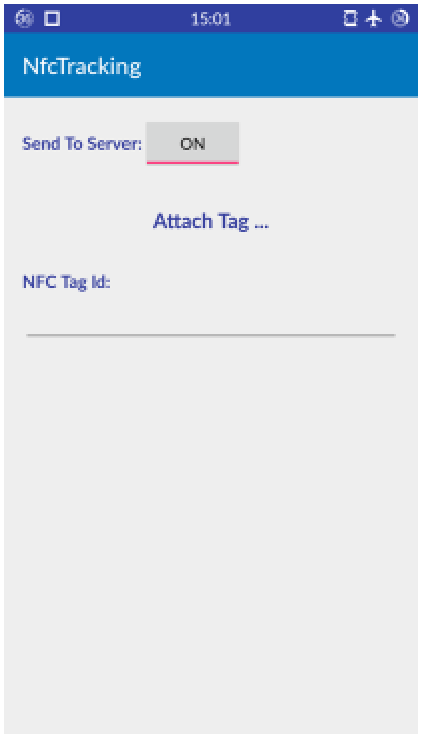

Figure 14 - Read product screen

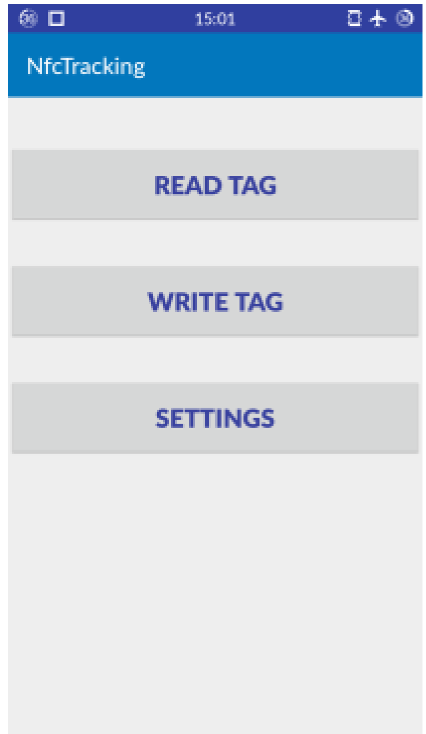

Figure 15 - Agent home screen

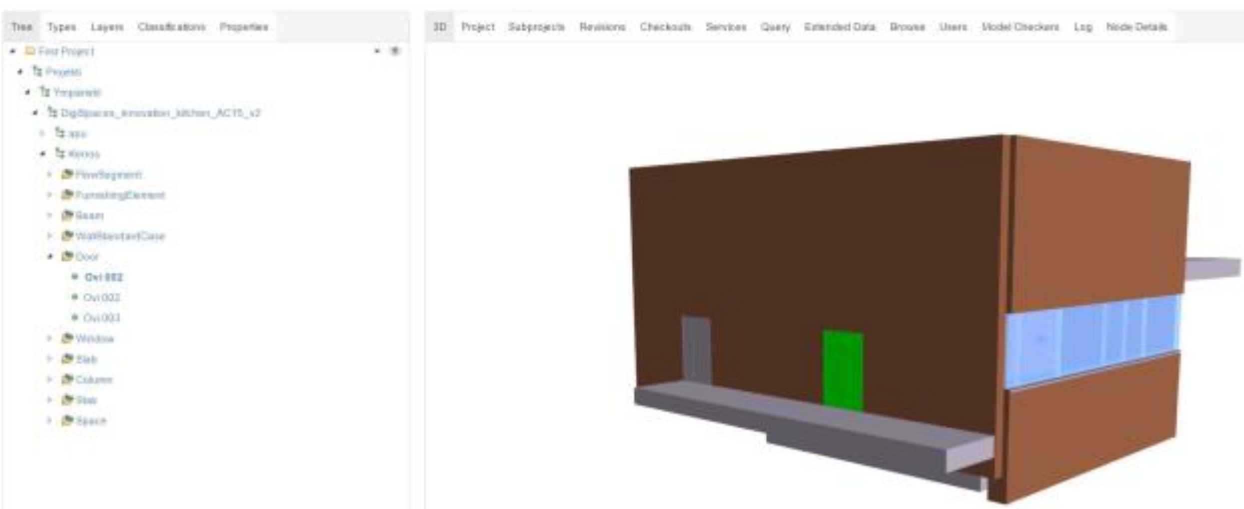

Figure 16 - Highlighted element and details following tag update

8. Benefits

From the data collection, desk based research and development of the proof of concept, it emerged that there are significant gaps in the lifecycle phases of a major asset. This leads to wastes which not only affect individual activities such as design management, logistics, production management, etc. but also the overall lifecycle that includes operations and maintenance. It is proven that despite a small proportion of value is spent in design and construction of a facility, these two aspects have a significant impact on how the asset is operated and maintained over a long period of time. For an organisation such as Highways England, where assets are maintained and operated for much longer durations as compared to ordinary assets (such as commercial, industrial or residential properties), managing the information flow across the boundaries provides significant challenges and opportunities.

It has been proven that there is as much as 50% waste due to inefficient processes (Dave et al. 2008; Dave et al. 2015) in construction lifecycle (including design). It has also been highlighted by several researchers that significant gaps exist in the integration of construction supply chain through information technology (Tatari and Skibniewski 2011). One survey conducted across over 100 firms concluded that less than 2% of the processes were integrated across construction supply chains in its entirety with less than 13% reporting partial integration. The integration is likely to be lower across the lifecycle stages.

- A concept such as Intelligent Products has potential to support the asset lifecycle from "cradle to the grave"
- Individual phases can benefit by 20-30% efficiency gains while the whole project lifecycle can benefit by more than 50% efficiency gains
- Indirect gains such as safety and quality improvements can be manifold.
- Integration across boundaries

Knowledge Management (generation, retention and reuse)

One of the most significant challenges in construction is that due to temporal supply chains, "singular" production lines and organisational silos, the generation, retention and reuse of knowledge remains a major problem. Knowledge is generated every day on construction projects in devising innovative solutions to tackle problems which are seldom unique and are often relevant on other projects (Dave and Koskela 2009). However, this knowledge is rarely documented in a way that is accessible to other project stakeholders and as a result is not retained or reused to improve efficiency or to avoid costly mistakes that occur time and over.

Also, knowledge from one phase is rarely passed on to the other stage in order to devise innovative and value adding solutions. For example, knowledge from design phase can improve the construction and fit-out activities and similarly operations and maintenance. At the same time knowledge from construction and operations and maintenance phase can inform design in order to devise/design solutions which are efficient from construction and operations and maintenance perspective. In a nutshell knowledge can

Thelwall Viaduct

For example, lessons learnt from failures such as Thelwall Viaduct can be very valuable for subsequent projects. On the Thelwall viaduct projects, stainless steel bearings failed causing the viaduct to remain closed for xx months and costing the tax payer £xx. While the reason for the failure are out of the scope of this discussion, the lessons from such failures can inform future designers who can then factor the cost of replacement of such bearings when they are being selected on subsequent projects under similar conditions. By taking such a proactive approach such unwanted “surprises” can be minimised and costs to maintain a facility can be predicted with better accuracy. There may be solutions to document such incidents, however they are rarely connected to the product or the design itself making it nearly impossible to make them available to stakeholders across boundaries and support a lifecycle view.

In order to realise these benefits, the recommended next step is to organise controlled pilots which will demonstrate the benefits in a real-world project setting within the Highways England.

9. Discussion and conclusion

Highways England project lifecycles are complex and involve multi-tier supply chain, where the information management is key to project success. However, it was found during this study that information delivery and coordination across the Highways England supply chain are key problems affecting project efficiencies. This is as information flow is not smooth and silo culture prevails across the client organisation (i.e. HE) and also the supply chain. One of the key reasons is that the main project control logic is outside-in, i.e. the flow of resources (including information) is managed from outside the production – i.e. through a plan, or a process framework. The direct result of this is reduced efficiency and **higher costs of as much as 30-40%** over the lifecycle.

Initiatives such as the Lean and BIM level 2 in Highways England are pushing for better integration across supply chain including information delivery. However, due to process alignment issues and silos prevailing, they are not enough to address the information management problem.

This study highlighted that within this context, **Intelligent Products** – supported by lean, BIM and IoT offer an excellent platform to enable the next generation of information systems for Highways England which has the potential to address the aforementioned problems. Intelligent Products has been applied through other projects such as S4Fleet, Find3D and Otaniemi3D in industries ranging from building and construction to fleet management and manufacturing. When applied in a construction project for a leading Finnish communication company in the logistics phase, the Intelligent Product concept reduced the wastage of material and idle time by 60%.

Due to the scope limitations, this project could not demonstrate the practical aspect of intelligent products implementation on pilot projects. Hence, the next steps should identify potential implementation areas where real-life pilots can be carried out. Since the concept affects the whole project life, a long term pilot is recommended.

The benefits of this concept can be wide reaching as the solution can enable cost savings through the project lifecycle and enable smooth information delivery. Hence, Intelligent Products can help with both capital project delivery and maintenance and repair projects. Within the domain of Intelligent Products, feedback loops with decision support systems can close the knowledge gap enabling knowledge retention and continuous improvement, the final frontiers of lean.

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