# INTELLIGENT PRODUCTS: SHIFTING THE PRODUCTION CONTROL LOGIC IN CONSTRUCTION (WITH LEAN AND BIM)

**ABSTRACT:**

Production management and control in construction has not been addressed/updated ever since the introduction of Critical Path Method and the Last Planner® system. The predominant outside-in control logic and a fragmented and deep supply chain in construction significantly affect the efficiency over a lifecycle. In a construction project, a large number of organisations interact with the product throughout the process, requiring a significant amount of information handling and synchronisation between these organisations. However, due to the deep supply chains and problems with lack of information integration, the information flow down across the lifecycle poses a significant challenge. We propose a product centric system, where the control logic of the production process is embedded within the individual components 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 within the conceptual process framework of Lean Construction. The vision encompasses the lifecycle of projects 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. We describe the vision and the tools and technologies required to support it.

**KEYWORDS:** Intelligent products, Building Information Modelling, Lean Construction, Building Lifecycle Management

## INTRODUCTION

Information and communication systems and novel management concepts are evolving faster than ever before to enable construction companies organize their work more effectively and efficiently, however the industry has not been able to achieve the desired benefits (Adriaanse et al., 2010; Kang et al., 2013; Stewart and Mohamed, 2004). Many of these benefits are achieved through deeper levels of automation of information flows. However, most of these new concepts are developed in isolation and do not sufficiently balance the people and process aspects, and have not been able to improve the core construction processes (Dave et al., 2008). Therefore, there lies an opportunity for building a new framework that can provide a comprehensive technological and process solution supporting construction lifecycle.

Management in construction traditionally relies on "push" based logic, for example the production management process based on CPM (Critical Path Method), where the plans are pushed from the top (Ballard et al., 2002; Ballard, 2000). Even though, lean production and Last Planner® are based on the "pull" logic, the predominant information delivery and control logic supports "push" based processes (Dave et al., 2014). This coupled with the separation of product and process (production) information, and in general the separation of information from "product individual" makes information management and flow difficult across the supply chain (Kärkkäinen et al., 2003).

This research aims to introduce a new production logic for construction, one where the control logic of production, i.e. assembling instructions, sequencing and manufacturing, and information about the product is linked to the product itself and "travels" through the production lifecycle, (i.e. from conceptual design through to construction and facilities management). The concept consists of several building blocks, which include: a) Building Information Modelling (BIM); b) Internet of Things (IoT); c) Lean Construction; and d) Intelligent Agents. As such, the proposed technologies or concepts on their own are not new, but their emergence and maturing is opportune to the development of the proposed concept for construction. The idea of product centric control (Kärkkäinen et al., 2003) has been successfully tried in manufacturing environment, and with a limited scope in logistics process in construction (Ala-Risku and Kärkkäinen, 2006). However, the proposed vision builds on these ideas and attempts to address the construction lifecycle. The paper begins with a critical review of the current production management and its major components. In the following section the proposed solution is outlined and its major building blocks explained. A case study and potential application scenarios are presented next followed by a discussion and the conclusion.

**the vision – Intelligent products in construction**

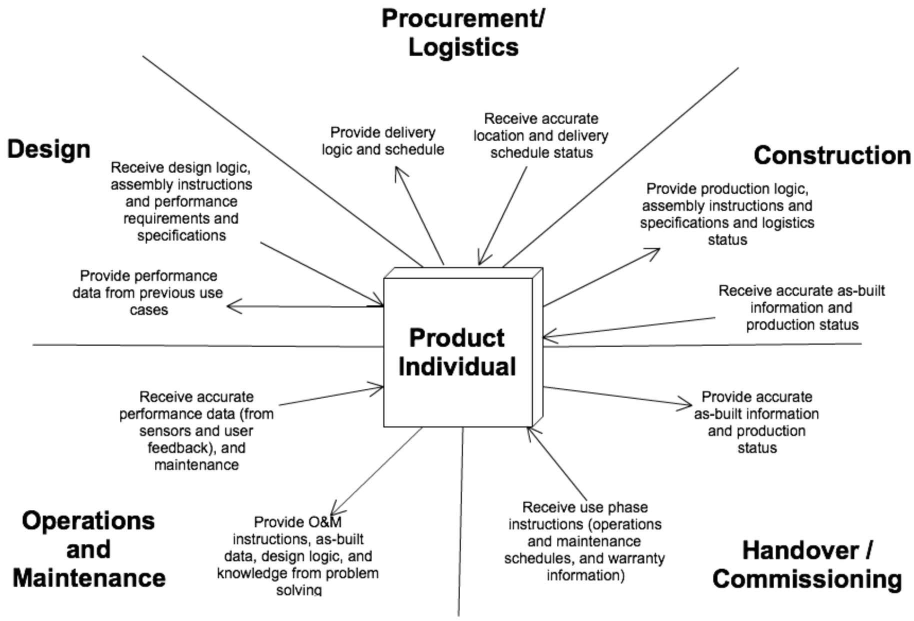


Figure 1, where the contextual operative logic of a product individual to support the lifecycle is embedded (or linked) within individual components already from the design phase. The vision covers the lifecycle of the production process from design to construction and maintenance, where the products can interact with the environment and its actors supporting a variety of actions. This new vision will help designers focus on value provision by making available real-life, context sensitive data from previous installations, enable self-organization of construction projects (minimizing the involvement of general contractor), reduce the cost of owning facilities, facilitate feedback function for improving product design.

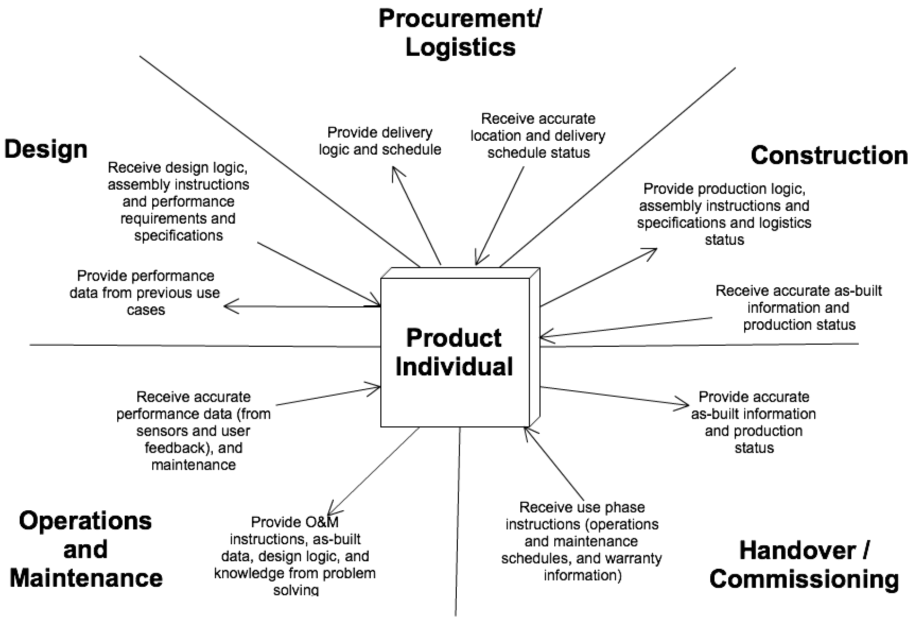


**Figure 1 - Product Centric Information Management (based on Karkkäinen et al, 2003)**

For developing the new framework, we use the theory of technology as a basis together with an inside out logic; BIM as a platform for modelling product and process information; the internet of things for connecting different realities (virtual and physical); and direct connection to manufacturing. Whilst all these have been maturing separately, these concepts are now brought into one common framework.

## CONCEPTUAL UNDERPINNINGS

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. Here, the assumption is that optimisation of parts (i.e. work packages or tasks) will result in optimisation of the whole (i.e. the project). And, another powerful assumption is that the resources needed for the tasks will always be available through the entirety of task. 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.

From a technological viewpoint, Building Information Modelling (BIM) has the potential to transform the way products/building elements are managed in construction supply chain (Aram et al., 2013; Eastman, 2011). BIM not only provides a product modelling platform but an information management platform that can serve stages of entire project lifecycle. (Sacks et al., 2010) have discussed the synergistic potential of lean construction and BIM across the project lifecycle. While these synergies have been realised in individual implementations and projects, there is not a systematic exploitation strategy, and a general lack of integrating technologies or systems that help realise these synergies. In particular, the aspect of information flow and communication across supply chain is the one where there are major gaps (Adriaanse et al., 2010; Stewart and Mohamed, 2004).

While the product centric control logic idea has been proposed and trialled for logistics process in construction (Ala-Risku and Kärkkäinen, 2006), it has not been applied across the lifecycle. Some of the main problems that the vision tries to overcome are outlined in the following section.

### PROBLEMS WITH THE FRAGMENTED SUPPLY CHAIN

The construction industry is highly fragmented with a large number of small companies operating in the sector. Over the last 30 years the industry has increasingly grown risk averse and relies mostly on subcontracted workers to execute projects. (Dainty et al., 2001). Figure 2 shows that almost 90% of the firms operating in the countries represented are micro size (1-9 employees), and 9.4% are small (50-249), where the Large and Medium size only form 0.7% of the overall proportion. This severe fragmentation present in the supply chain makes it increasingly difficult for information to be synchronised and communicated at various lifecycle stages. Dainty et al. (2001) report that the UK construction sector is a long way from being able to achieve true supply chain integration and that an adversarial culture is ingrained within industry's operating practices, where a general mistrust between companies prevail.

**Proportion of Firms by Size Category**

| *Size (No. of Employees)* | Micro (1-9) | Small (10-49) | Medium (50-249) | Large (250+) |
|---|---|---|---|---|
| GB[1] | 89.8 | 9.4 | 0.6 | 0.1 |
| France[2] | 91.6 | 7.7 | 0.7 | 0.1 |
| Germany[2] | | | | |
| Structural Firms Only | 69 | 27 | 3.7 | 0.4 |
| All Construction Firms | 95 | | | |
| US | 81.1 | 16.3 | 2.4 | 0.1 |

1. Size bands for UK are 1-7, 8-59, 60-299, over 299
2. Medium Size Band 50-199

*Source: DTI, Hauptverband der Bauindustrie, Service, Economique et Statistique, US Census Bureau*

Figure 2. Proportion of Construction Firms by Size (DTI, 2004).

### ALIGNMENT OF VALUE IN SUPPLY CHAIN

Fragmented project organizations and the silo effect in design, construction and maintenance phases means that a single company has typically a limited role in a construction supply-chain and it tries to capture value from upstream and downstream partners for its own use (Matthyssens et al., 2008). This has led to a product centric business logic in which value is seen to be created when technically functional product or solution is sold and delivered to customer. However, recent research underscores that value is fundamentally derived and determined only in use - the integration and application of resources in a specific context (Vargo et al., 2008). With current practices, lack of appropriate information about how to use products during its life-cycle from production to delivery, assembly and maintenance, lead to waste of resources and decreased overall value.

### NEED TO DESIGN FOR LIFECYCLE/OPTIMISE TOTAL COST OF OWNERSHIP

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 (Forgues and Koskela, 2008, Putnam, 1985). 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).

## WHAT DO WE PROPOSE TO DO

The central tenet of the intelligent product vision is to either embed or link contextual product and process related information, which needs to be communicated to actors operating on them across the supply chain, within the products themselves. With this, the products "flow" across the lifecycle "demanding" actions to be performed on them and providing necessary information needed to do so. The products collect information about their performance, either automatically through sensors or qualitative feedback from users, which can then be used to analyse its performance in its given contextual space. The basic building blocks and the role they play is provided in this section. These building blocks consist of technological components in BIM, IoT (Internet of Things) based communication systems, Agents and process and people related enabler in Lean Construction.

### BUILDING INFORMATION MODELLING

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. This URI is then used to identify the product also when in physical form (i.e. when it is purchased/assembled/constructed) and is associated with the product for its lifecycle.

It may not be necessary (and wise) to attach the entire product and process related information to the model, as most of the information should be accessed from the cloud using agents/web services as and when needed. The main identifier or integrator is the URI of the product.

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.

### 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.

## STANDARDS FOR IOT COMMUNICATION

A communication framework for the IoT has been developed by the IoT Work Group of The Open Group (formerly called Quantum Lifecycle Messaging: QLM) 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 (here the actor could be a human being or another system) 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.

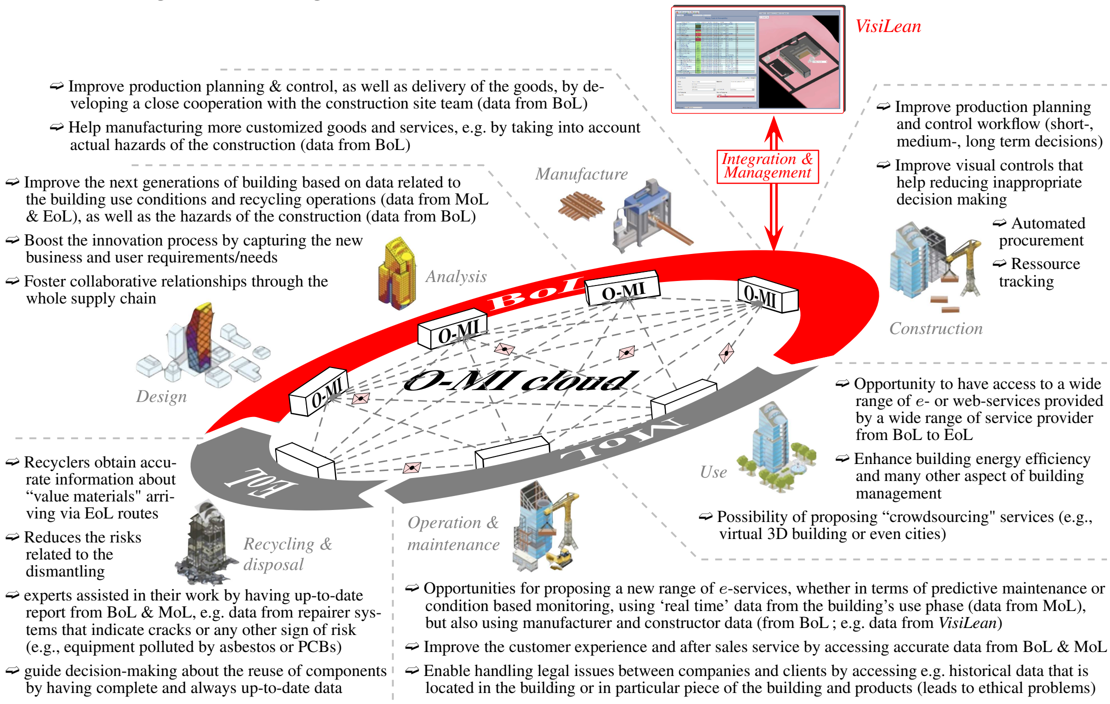


Figure 3 - Open Group IoT standards across the project lifecycle.

## AGENTS

The notion of virtual enterprise (Aerts et al., 2002) describes a setting where supply chains become increasingly dynamic and network-like. Agent-oriented methods have been proposed as a solution for handling information (Fox et al., 2000) in the virtual enterprise. There is no universal agreement on what an agent is, but common aspects to most definitions seem to be that an agent should be autonomous, social, reactive and pro-active (Helin and others, 2003; Jennings et al., 1998). Autonomy signifies that agents operate without direct intervention of humans or others. Social ability means that agents interact with other agents via some communication language. In order to be reactive, agents perceive their environment and respond in a timely fashion to changes that occur in it. Finally, agents do not simply act in response to their environment; they are also able to exhibit goal-directed behavior by taking the initiative (pro-activity).

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 et al., 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). Agents have also been successfully applied to manufacturing processes (Langer and Alting, 2000). 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. Access to product data is currently mainly done through web sites. 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.

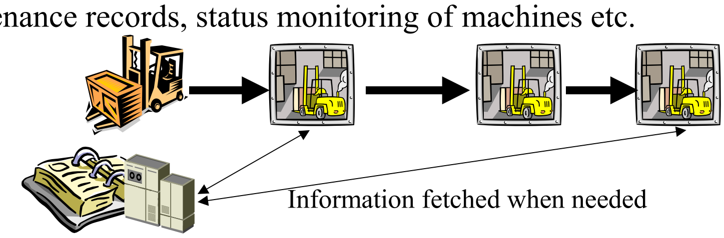


Figure 4 - The "agent model" for real-time access to product information.

Moving to the agent model can be compared with the big paradigm shift in computer programming during the 1980's. The old procedural programming paradigm changed into an object-oriented paradigm. A main reason for this was that object-oriented programming makes it easier to manage data and functionality of a program by concentrating them around the object-concept. This means that anyone (usually another object) that has a reference to the object can access information about the object through the object's methods. In software engineering, object-oriented programming has become dominant.

### MULTI-AGENT SYSTEM AND INTELLIGENT PRODUCTS

Multi-agent systems add another layer to agent intelligence, because in multi-agent systems there is opportunity to exploit collective intelligence, which is greater than the sum of the parts. From a multi-agent point of view, agents intelligence can also be explained in terms of their social and cognitive capabilities, which determines how they interact with each other and the task, and how the task is accomplished with their collective effort. 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.

### LEAN CONSTRUCTION

Lean construction plays a central role in 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.

## POTENTIAL SCENARIOS

### JUST-IN-TIME LOGISTICS BASED ON PRODUCTION STATUS

Resource management on construction sites is one of the most important areas from production management perspective, as it affects the input flows and is directly linked to variability and uncertainty (Ballard et al., 2002; Koskela, 2000). 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

While natural sciences describe things existing in nature, then design and engineering sciences in the other hand form purposeful physical reality for solving human needs - science of artificial (Simon, 1981). Contemporary design management focuses on producing better products with reduced resources. The concept of intelligent products can become resourceful for designers and engineers building new structures. Spaces are needed for fulfilling client functional requirements in the context of his/her business or personal interests. If to consider 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.

The actual design starts from here, all the previous steps are for analyzing conceptual aspects and client needs and requirements (Reed, 2009). In a schematic design, architect designs a building physical form with some theme in mind. Spatial requirements defined in pre-design stage can be compared to architectural design alternatives. Also, if to consider the whole building also as a product, then performance requirements specified by client can be evaluated and compared to previously built buildings. After that, architect starts to choose and specify building materials and therefore also structures. This continues through several design stages becoming more detailed in every sub-sequent stage. In early stages, designer is specifying products in terms of functional requirements and later specific products are chosen. What is fundamentally important here, is how different elements become sub-systems, sub-systems systems and systems as a whole building. Therefore, intelligent products must 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. Therefore, improved efficiency and waste reduction in the maintenance phase 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. That is, unlike the design and construction phases where the delayed activities can hold back a future activity, 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 seen as 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.

## DISCUSSION AND CONCLUSION

There are significant problems with production and supply chain management, information management and design management within the construction lifecycle. There have been attempts to provide solutions to individual areas including lean construction techniques of design management, supply chain alignment and production management and control. However, there is not yet a unified vision to address these problems across the entire lifecycle. The proposed vision attempts to tackle these problems through a combination of process-product-technology solutions. It is an ambitious vision, where most building blocks have individually proven their merit, however it is hypothesized that when combined their collective benefits will be much more significant. It is also anticipated that there will be many obstacles in realizing this vision, and it is a medium to long-term vision that has a potential to change the built environment lifecycle.

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