An SCO-enabled Logistics and Supply Chain Management System in Construction

Yuhan Niu[1*], Weisheng Lu[2], Diandian Liu[3], Ke Chen[4], Chimay Anumba[5], and George G. Huang[6]

1)Corresponding author, Ph.D. Candidate, 535A, Knowles Building, Department of Real Estate and Construction, the University of Hong Kong, Hong Kong. Email: yuhanniu@connect.hku.hk
2) Ph.D., Assoc. Prof., 5/F, Knowles Building, Department of Real Estate and Construction, the University of Hong Kong, Hong Kong. Email: wilsonlu@hku.hk
3) M.Phil. Candidate, 535A, Knowles Building, Department of Real Estate and Construction, the University of Hong Kong, Hong Kong. Email: liudd@connect.hku.hk
4) Ph.D. Candidate, 534, Knowles Building, Department of Real Estate and Construction, the University of Hong Kong, Hong Kong. Email: leochen@connect.hku.hk
5) Professor, 104 Engineering Unit A, University Park, Department of Architectural Engineering, The Penn State University, The Unites States. Email: anumba@engr.psu.edu
6) Professor, 8/F, Haking Wong Building, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong. Email: gqhuang@hku.hk

Abstract:

Logistic and supply chain management (LSCM) is of paramount importance to a construction project but is often problematic. Many researchers see LSCM *per se* as a web of decisions to be made, and attribute problems to a lack of process and information concurrence. This is exacerbated by fragmentation, discontinuity, and heterogeneity in construction LSCM. The bi-directional information flow remains unachieved in the existing sensing-based systems for construction LSCM. Without panoramically interconnected to other smart abilities such as the automatic action-taking ability, most existing sensing-based systems are insufficient to realize their full potentials in facilitating construction LSCM. Building on previous studies on smart construction objects (SCOs), this paper aims to develop an SCO-enabled system that can enhance concurrence of process and information, with a view to informing better decision-making in construction LSCM. It does so by first analyzing the problems in prevailing LSCM practices using business process reengineering. Based on this analysis, the architecture for an SCO-enabled LSCM system is proposed and developed into a prototype. Then the system is calibrated and validated in the rich context of offshore prefabrication housing production in Hong Kong. It is found that SCOs, with their properties of awareness, communicativeness, and autonomy built into a smart management system, can supplement the existing LSCM process with more concurrent decision-making information. This paper contributes to the body of knowledge in two areas. It adds to the theoretical debate on decision-making by arguing the importance of information and process concurrence and trying to explicate it in the context of construction LSCM. In addition, the SCO-enabled LSCM system can be implemented in real-life practice to alleviate the many problems existing in construction LSCM.

Keywords: Logistics and supply chain management (LSCM), Smart Construction Objects (SCOs), Business process reengineering, Information and process concurrence, construction.

Introduction

Logistic and supply chain management (LSCM) is of vital importance to construction. Every construction project is fixed commodity, which is site-specific and purpose-built (Dubois and Gadde, 2002). A myriad of contractors and vendors supply countless materials and components for assembly on construction sites, often amid congestion. Any interruption to the logistic and supply chain may result in severe losses, while stocking sufficient buffer is not always possible on a congested site. LSCM is particularly challenging nowadays where supplies are sourced from a geographically dispersed international market (Lu et al., 2014). Managers must now comply with requirements relating to carbon emission reduction (Bhattacharya et al., 2014), fair trade promotion (Moxham and Kauppi, 2014), and enhancement of employee welfare down the logistics and supply chain (Wieland and Handfield, 2013). The rule-of-thumb cost formula in construction suggests that direct costs such as materials, machinery, and manpower consists of large expenditure of total cost (Kaiser and Snyder, 2012). Late delivery of materials directly leads to nearly a quarter of project time-delays (Koushki and Kartam, 2004). Therefore, efficient management of the logistic and supply chain has significant and immediate material implications for construction projects.

In the search of theories and practices that are applicable to construction LSCM, researchers have also started to recognize the importance of information. For example, Zsidisin et al. (2000) articulated that management of materials and information flow is the key aspect of LSCM. Likewise, Handfield and Nichols (1999) view LSCM as being concerned with not only moving and transforming goods, from raw material extraction through to delivery to end-users, but also the associated flow of information. The central tenet underpinning these studies is that LSCM *per se* is the making of an array of decisions across the construction process based on available information and knowledge. To improve LSCM performance, one needs to manage information to allow more informed decision-making. The main objective of information management, in layman's terms, is to support decision-making by ensuring that accurate information is always available at the right time in the right format to the right person (Chen et al., 2015). In this paper, this objective will be redefined and elaborated upon as *process and information concurrence*.

Recently, Niu et al. (2015) developed the concept of smart construction objects (SCOs): "construction resources (e.g. machinery, tools, devices, materials, components, and even temporary or permanent structures) that are made smart by augmenting them with sensing, processing and communication abilities so that they have autonomy and awareness, and can interact with the vicinity to enable better decision-making". With their core properties and representations, SCOs have various computational applications, one of which is construction LSCM. SCOs can act as the elementary building blocks of smart LSCM by sensing, processing and communicating information. Properly linked to building information modeling (BIM) and the Internet of Things (IoT), SCOs can provide concurrent decision-making information, and in turn, lead to more efficient LSCM (Niu et al., 2015). However, an operable LSCM system based on SCOs is yet to be developed.

The primary aim of this research is to develop an SCO-enabled system with a view to informing better decision-making in construction LSCM. Informed by decision science, the theoretical argument of this research is the importance of *process and information concurrence*, including how to define, measure, and achieve this concurrence. The remainder of the paper comprises five sections. Subsequent to this introductory section is a literature review examining definitions of LSCM, the theoretical foundation of LSCM, information concurrence from a decision science perspective and SCOs as a development trend in achieving this concurrence. Section 3 is an elaboration of the research methodology, at the core of which is a mixed method. First, prevailing LSCM is revisited by engaging business process reengineering (BPR) as an analytical tool. Then, the multi-layer architecture of an SCO-enabled LSCM system is proposed and further developed into an operable prototype. Finally, the system is calibrated and validated in the rich context of offshore prefabrication housing production in Hong Kong. Section 4 reports the results and analyses. Section 5 discusses the prospects and challenges of the SCO-enabled LSCM system, and conclusions are drawn in Section 6.

Literature review

Logistic and supply chain management in construction

While logistics and supply chains are often mentioned in tandem, they refer to two different concepts in the literature: supply chain management (SCM) and logistics management. According to the APICS Dictionary (Ray, 2012), a supply chain is “the global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash”. Originating in the manufacturing industry, a simple supply chain network may include a supplier, manufacturer, wholesaler, and retailer. Its management refers to management of the flow of goods and services as well as associated cooperation works (Cooper et al., 1997; Handfield and Nichols, 1999). In contrast, logistics management has been differentiated as a constituent component of SCM by the Council of Supply Chain Management Professionals (CSCMP) (Stock and Boyer, 2009). It is only concerned with the flow and storage of goods with related information between the point of origin and the point of consumption (CSCMP, 2005). SCM encompasses coordination, collaboration and integration of business operations that are beyond the scope of logistics management (Cooper et al., 1997). Nevertheless, contemporary understandings of SCM and logistics management have not been appreciably different (Cachon and Fisher, 2000; Lambert and Cooper, 2000). In practice, they are often referred to as a single term logistics and supply chain management (LSCM), but it is suggested that readers bear these differences in mind while reading this paper.

Movahedi et al. (2009) provided a summary of the evolution of LSCM from creation, integration, and globalization through to LSCM as service, i.e. the so-called LSCM 2.0. The scope of LSCM has been continuously developed and enriched (Stock and Boyer, 2009). In earlier studies, for example, the management of material flow is the key aspect of LSCM (Zsidisin et al., 2000). The concern of material flow is with moving and transforming goods, from extraction of raw materials through to delivery to end-users. Service flow and finance flow were next proposed for inclusion in LSCM (Mentzer et al., 2001). Flow management aside, LSCM was later expanded to include management of networks between inter-organizational stakeholders and across intra-organizational functional units involved in the process (Dainty et al., 2001; Rameezdeen, 2016). LSCM has now successfully evolved into a discipline in its own right and the body of LSCM literature has grown exponentially. This growth makes a comprehensive review of the literature difficult, even when focusing on the construction sector only.

LSCM theories have been applied to construction to improve the industry's obsolete and myopic means of controlling its logistics and supply chain (Vrijhoef and Koskela, 2000). While general LSCM theories and practices have enjoyed a period in vogue, considerable difficulties have been encountered in their application to construction, largely owing to the heterogeneity of the sector. Thus, the performance of LSCM in construction is still widely perceived to lag behind other sectors (Bankvall et al., 2010). It is essential to develop standards for alignment of LSCM systems (Gibb, 2001), methods of quality assurance and risk reduction (Bankvall et al., 2010). Besides increasing the efficiency of internal systems, construction LSCM should also develop greater synergy and longer-term relationships between inter-organizational stakeholders (Saad et al., 2002). Some researchers have attributed the sluggish performance of construction LSCM to the root characteristics of the industry. For example, the sector's entry barrier is fairly low (Chiang and Cheng, 2010) so "construction output is dominated by a plethora of small firms with high levels of sub-contracting and a widespread reliance on self-employment" (Green et al., 2005). In addition, high market concentration is rarely seen in the construction sector (Ye et al., 2009). Unlike Boeing and Airbus in the aerospace industry, no construction firms are able to dominate the global logistics and supply chain so that they can introduce proactive management measures, e.g. inspection and certification of suppliers. Numerous reports have recognized the fragmentation and discontinuity in construction, and suggestions are increasing that construction LSCM adopt collaborative working practice initiatives such as strategic alliances and partnering (Tennant and Fernie, 2014)

Enabling technologies are integrated into the LSCM process to facilitate the tracking and monitoring of logistics. The radio frequency identification (RFID) technology is the mostly addressed enabling technology in assisting the component tracking and inventory management in the construction LSCM (Flanagan et al., 2014; Lu et al., 2011). Besides, sensing-based systems enable the data capture and data transfer within the sensors network in the LSCM process. Shin et al. (2011) integrate the RFID technology, sensors network and service-oriented architecture to achieving the just-in-time (JIT) delivery in construction LSCM. The existing sensing and identification technologies manage to bring in new sights to the construction LSCM. However, there is still space for further improvement. The adoption of RFID technology often involves extensive manual work in reading and updating tags information (Akanmu et al., 2014). Sensing-based networks are subject to confine of range. Moreover, while the existing sensing-based LSCM system manage to capture and transfer the logistics data back to the virtual models or management system, Akanmu et al. (2014) highlight that there is a need for a more effective approach that will enable bi-directional coordination between virtual models/ management system and the physical construction.

The concurrence of process and information in construction LSCM

A clear trend emerging from the LSCM literature is an emphasis on the importance of information management (IM). For example, Zsidisin et al. (2000) asserted that the management of material and information flows is the key aspect of LSCM, which echoes Handfield and Nichols (1999). Lambert and Cooper (2000) argued that operating an integrated supply chain requires a continuous information flow integrated with the product flow. Information has been unequivocally highlighted as a new dimension to be managed in LSCM.

One view of management is that it involves making decisions, programmed or non-programmed, to solve problems in human organizations. From a decision science perspective, management *per se* is making a web of decisions based on the information and knowledge available (Grant, 1996). Instead of pursuing completely correct decision-making, decision scientists nowadays seem to be advocating ‘informed decision’ (Bekker et al., 1999). According to this tenet, a decision-maker should be well informed of the facts, implications and consequences when he/she makes a rational decision (Amendola, 2002), even though the outcome may not be as expected. This decision science view of management underpins previous studies and emphasizes the importance of information in LSCM. It also partly explains the vogue of information management (IM) and information communication technologies (ICT) in LSCM.

One of the main objectives of IM is to support decision-making by ensuring that accurate information is always available at the right time in the right format to the right person (Chen et al., 2015). In this paper, this objective is rephrased as *process and information concurrence* for two main reasons: (a) it is easier to communicate, and (b) it better reflects the researchers’ beliefs regarding the importance of information flow in parallel with traditional goods/services flow. *Process and information concurrence* is also the central theoretical argument of this research. Readers are reminded of the nuances of this argument, which critiques inefficiency on both sides of LSCM, i.e., process and information, and emphasizes concurrence of the two as the way forward. In the past, LSCM experts and consultants in particular have suggested revolutionizing existing LSCM processes by introducing new systems of questionable efficiency such as Enterprise Resource Planning (ERP). Information, meanwhile, has been treated as a panacea. The assumption has been that any problems in LSCM can be solved by managing information, yet the fact is we understand little about the information that is to be managed. Summarized from Kahn et al. (2002), Lee et al. (2002), Lu et al. (2011), and others, information has its own properties (see Table 1), which determine its usefulness in decision-making. While these properties help us probe information as a concept, how they can be measured (e.g. what are the indicators of information completeness or timeliness) is far from crystal clear. In addition, questions remain with regard to process and information concurrence, such as how it can be ensured and measured, and how its effects on decision-making throughout the process can be monitored.

<Table 1 here>

Simon's (1976) bounded rationality theory answers these questions in part. The theory's 'triangle of limits' suggests that rationality of individuals in decision-making is limited by information, cognitive ability, and the finite amount of time they have to make decisions. The acquisition, circulation and processing of information underpin decision-making. One implication of the bounded rationality of individuals in an organizational management context is that decision-makers are noticeably biased in their acquisition of information (Choo, 2001). In selecting information source for decision-making, rationally, higher-quality resources that dovetail with the information need will be chosen. Further, decision-makers tend to select information that is convenient and accessible (Fidel and Green, 2004). With the help of ICT, decision-makers are less limited in their selection of information sources. Therefore, ICT could be implemented to enhance process and information concurrence in construction LSCM. For example, sensing technology can be used to capture large amounts of environmental data previously perceived as inaccessible (Behzadan et al., 2008). It can also increase the capacity of communication channels to deliver data efficiently and expeditiously (Choo 2011). However, the bi-directional flow of information between the virtual information model and physical construction that has been discussed in the prior section is yet to be achieved.

Smart construction objects

In place of a completely new system, smart construction objects (SCOs) augment existing construction resources with core smart properties including awareness, autonomy and communicativeness (Niu et al., 2015). Niu et al. (2015) have elaborated the theoretical foundations, definitions, core properties and representative application scenarios in details. The ‘Awareness’ denotes SCOs’ ability to sense and log their real-time condition and that of the surrounding environment. SCOs have activity, policy and process awareness (Kortuem et al., 2010). ‘Communicativeness’ denotes the ability of an SCO to output information it has obtained through its awareness. Communication between an SCO and managerial personnel or among SCOs can be conducted through information *pull* or *push* modes. ‘Autonomy’ refers to the ability of an SCO to take self-directed action or alert people to the need for further action based on preset rules. Different types of core properties may combine to function, depending on decision-making needs and requirements of different circumstances throughout the construction process.

Apparently, SCOs portrayed a new way of capturing, processing, and communicating information to support decision-making in construction. It is acknowledged that there have been studies investigating on one or two aspects of the SCO properties, such as the autonomy of machine or sensors networks. Most of those studies only focus on a specific function. Single or scattered smart objects that have been proposed are insufficient to realize their full potentials. Unlike conventional sensing based system, SCOs are based on the augmentation of existing construction objects and components that are already involved in the construction process. These augmented construction objects carry value-added and interconnected properties while not compromising their original appearance and functions.

SCOs are like basic particles flowing through the LSCM process; sensing, carrying, processing, and communicating information with different attributes (e.g. as shown in Table 1) to support decision-making. They seem to offer a natural and promising means of enhancing process and information concurrence in construction LSCM. Beyond providing decision-making information to human decision-makers, what makes SCOs particularly different is that they can talk to each other directly. Hence, some routine or clear rule-based decisions can be made by SCOs autonomously without necessarily involving human decision-makers in the loop (Niu et al., 2015). Nonetheless, an operable, real-life LSCM system based on SCOs is yet to be developed, necessitating the present study. By developing an SCO-enabled LSCM system, this study also intends to test the theoretical argument of *process and information concurrence*.

Methodology

This research adopts the mixed methods of process reengineering, case studies, experiments, non-participant observation, and interviews. Firstly, a process reengineering approach is utilized as an analytic tool to (1) diagnose the traditional construction LSCM process, and (2) compare the traditional LSCM process and the re-engineered process once the SCO-enabled system is developed and tested. The process reengineering approach is developed from business process reengineering (BPR), defined as the fundamental rethinking and redesign of business processes so as to achieve dramatic and sustainable improvements in the performance of an organization (Hammer and Champy, 1993). Another interpretation of BPR advocated by Davenport and Short (1990) suggests that the analysis and design of workflows should take place both intra- and inter-organizationally. With multiple parties involved in the whole life cycle of construction, a reengineering philosophy that adopts a ‘process view’ rather than a ‘task’ or ‘function’ view is, in principle, well-suited to the project-based nature of the construction industry (Ruika et al., 2003). Process reengineering in construction aims to progressively develop an integrated project delivery process that focuses on optimizing process predictability and enhancing the value of the final product (Chan et al., 1999), which resonates with the thoughts underpinning the SCO-enabled LSCM system, i.e. process and information concurrence.

LSCM of prefabrication housing provision in Hong Kong was adopted as the case study. Around 50% of Hong Kong's population of 7.8 million live in public housing while the other half occupy private properties (Census and Statistics Department, 2007); most of both types is high-rise given Hong Kong's extreme land scarcity. In view of widespread discontent over housing issues, the government has implemented a series of interventions to increase housing provision. However, on the production side, capacity to provide housing is often confined. Prefabrication has thus been increasingly advocated owing to potential benefits including better quality, a faster construction process, and a cleaner and safer working environment. Hong Kong has moved its entire prefabrication sector offshore to the Pearl River Delta (PRD) region where land, labor, and material supplies are relatively cheaper. Unlike high-rise buildings in the U.S. which use steel structures, steel-concrete composite structures predominate in Hong Kong. A high level of prefabrication has been developed with major precast elements including facades, staircases, parapets, partition walls, semi-precast slabs and, more recently, volumetric precast bathrooms and kitchens. These are designed in Hong Kong, ordered in advance, precast in the PRD, and transported to Hong Kong by truck for on-site assembly. In reaping the claimed benefits of prefabrication, LSCM is extremely important.

With the support of the client and main contractor, the research team was installed in a Hong Kong public housing construction project including five high-rise residential towers and one commercial center. Process reengineering analysis was adopted to understand the pros and cons of the existing LSCM process. Then an architecture of the SCO-enabled LSCM system was proposed: basically, a multi-layer SCO-enabled smart system to facilitate information capture, distribution, processing, presentation, and communication in line with the LSCM process. Much effort was paid to the development of the system into a prototype linking database, building information modeling (BIM), and Google Maps in a single page. The prototype was then piloted in the daily operation of the prefabrication construction, namely, manufacturing in the PRD, cross-border transportation, and on-site assembly. Then process reengineering analysis was conducted again to understand the changed process, with a view to examining the concurrence of process and information and its effects on decision-making throughout the LSCM. This analysis involved experiments, non-participant observation, and interviews with managers, foremen, and workers. Although these research activities are described in a sequential manner here, they actually formed an anthropological study lasting for around a year with many trails between researchers and practitioners.

Results and analyses

Existing construction LSCM process

Derived from a process reengineering analysis, Fig. 1 demonstrates a traditional generic configuration of LSCM in construction. There are three parties involved in the LSCM process including the offshore supplier of prefabricated components, the cross-border transporter, and the main contractor. For the current practice in Hong Kong, the main contractor would issue a bill of quantities (BQ) of total prefabricated components needed in the project to the supplier. The order for producing each batch of components would be made throughout the construction process depending on the programme. There would be another order from the main contractor to specify the delivery deadline for each batch of prefabricated components so that the supplier could prepare for shipping. There orders are issued as electronic files and delivery by separate emails between the supplier and the main contractor. A third-party carrier would transport the prefabricated components across the Guangdong-Hong Kong border to the construction site. After delivery, the transporter would need to present a paper receipt from the main contractor to the supplier to confirm delivery.

<Fig. 1 here>

Limited corresponding information flow (e.g. *ad-hoc* telephone communication) is normally available in parallel with the production, transportation, and on-site assembly processes. The logistics and supply of the components must be planned months ahead and stated on paper documents (e.g. delivery dockets), but real-time information can only be available to a project manager when the components are delivered. Material flow and information flow are one-directional and separate. Information flow occurs concurrently with the contractor's scheduled orders with the supplier, and relies on paper-based document exchange, email communications, and sometimes telephone conversations. Variations and rectifications form part of an extended information flow. At any point, lack of accurate and updated information could lead to severe wastage on the production side and contract-supplier discrepancies.

The architecture of the SCO-enabled LSCM system

A multi-layer SCO-enabled LSCM system (whose architecture is shown in Fig. 2) is proposed to enhance process and information concurrence. At the shopfloor layer are the materials, components, and machinery (e.g. forklifts or lorries) that have been augmented into SCOs. With the three core properties embedded, the type and level of each property are customized in the second layer by adopting smart technologies such as Bluetooth, WiFi, Zigbee, and GPS. For example, a precast façade in at the shopfloor layer can be augmented with the policy awareness by using a GPS sensor and the push communicativeness by using a global system for mobile (GSM) module. In the LSCM system, SCOs such as the smart façade are expected to sense real-time locations during the delivery process and push the information back to the smart management platform (SMP).

The SMP layer serves as an information database as well as a centralized management platform. All the data captured by SCOs, when generated along the LSCM process, can be transferred concurrently back to the SMP in the GSM channel. This layer could incorporate a BIM-oriented database of established project information. By communicating with SCOs, the SMP also receives and stores data in the online IoT database. Meanwhile, applications in the top layer such as real-time information sensing, conditional alerting, and information sharing, are executed based on the needs and requirements of the SMP. Linked to the BIM model and the real-time location database, an online interactive map could present SCOs' real-time locations. Data exchange between the application layer and the SMP ensures information and process concurrence during the LSCM process.

<Fig.2 here>

The LSCM process after the SCO-enabled process reengineering

With the SCO-enabled LSCM system, the LSCM process can be improved (see Fig. 3). When the material flow remains relatively the traditional way, the information flow throughout the whole LSCM process is revolutionarily changed. The SMP serves as a shared database for the supplier and the contractor, allowing these parties to exchange information in a real-time manner. Thus, there is a two-way information flow via the SMP as a hub. The procurement list, orders for production and orders for delivery can be issued online in the SMP and the supplier alerted to receive these documents and confirm receipts. Meanwhile, the off-site supplier could submit queries through the SMP to seek clarification from the contractor side. Unlike previous studies proposing web-based systems similar to the SMP for LSCM (Soroor and Tarokh, 2006; Wang et al., 2007), the object-to-object (O2O) communications in this study are performed autonomously. When traditional construction objects are augmented into SCOs, they proactively share information with people, alleviating the extensive human work of finding and gathering one-way logistical information. The combination of the SCO's interconnected properties could enable a bi-directional flow of information between SCOs and the SMP.

<Fig.3 here>

The SCO prototype

Unlike prevailing collaborative project management platforms (even those using cloud technologies), the proposed system is enabled by SCOs. These can sense their own status and push back to a centralized platform, i.e. the SMP. The smart properties of the SCOs are programmed using C/C++ on an Arduino UNO chip, with an integrated GPS module, GSM module, and battery supply. The GSM locating module is adopted because GPS signals are often blocked in Hong Kong's urban areas. The chip with connected modules is incorporated into a black box design, which can be embedded in the surface recess of a prefabricated component when loaded for shipping. Thus, damage can be avoided during loading and unloading, and the black box can be demounted for reuse. The hole left after removal of the black box can be filled with concrete when the component is assembled. In addition, each SCO is assigned a unique identification code associated with the basic design parameters in the SMP database.

As discussed above, SCOs have different smartness modes. In this specific scenario, SCOs apply active autonomy, policy awareness and information push during the LSCM process (see Fig. 4). When each SCO is shipped, it updates to shipping status once its real-time coordinates pass the preset supplier site threshold. This is achieved using the active autonomy mode, where the SCO could take autonomous actions. Then SCOs push their real-time geographical coordinates to the SMP at regular intervals for monitoring and record-keeping, enabling the information flow to stay up-to-date with the material flow during the transportation process. Applying policy awareness, SCOs sense certain thresholds (Niu et al., 2015). For each SCO, the coordinates within certain geographical ranges are programmed as the thresholds. Once a threshold is reached, the SCOs take passive or active action accordingly. The default status of each SCO is set as standby, and this status is maintained as long as the sensed geographical coordinates are within the range of the off-shore production site. When each SCO enters the range of the construction site, it will update to on-site status by policy awareness and active autonomy again. The SCO will then sense its coordinates and altitude against the digitized 3D site coordinates. To facilitate this, the construction site will be digitized with 3D coordinates to assign each location assigned a unique trixial (x, y, z) coordinate (Liu et al., 2015). For an SCO with on-site status, the designated installation coordinates are set as the policy threshold. Once the SCO's real-time location matches the designated location, the SCO updates its status to confirm installation.

<Fig.4 here>

The SMP prototype

An SMP is essential for utilizing SCO data and thereby enabling SCO-enabled LSCM process reengineering. In the SMP prototype developed in this research, the online user interface consists of three panels written in JavaScript and JavaScript-based Libraries, including the Google map application programming interface (API) and the Web Graphics Library (WebGL) (see Fig. 5). The data panel presents the ID of each SCO and its real-time location in latitude and longitude. Each record is linked to a location tag in the Google Maps panel, plotting the delivery route of the SCO. This increases real-time information visibility and traceability (Lu et al., 2011). The delivery status of each SCO is stored in the data panel, and can also be synchronized with the BIM model. The BIM model panel are backed up by WebGL presentations in the webpage. The 3D BIM model is presented in the BIM panel of the SMP, where each prefabricated element is associated with an SCO. When the status of SCO changes, so does the color of the block in the BIM model.

<Fig.5 here>

The SMP supports the smart properties of SCOs while it also possessing its own. Serving as a central management platform, the SMP can reduce tedious, error-prone manual work with process awareness and passive autonomy. For example, schedule-checking activities can be done in the SMP using process awareness. When receiving real-time status updates from SCOs, the SMP can make comparisons with the default schedule and, based on processes designed in the SMP, offer different options. If the LSCM activities are on schedule, the SMP would allow progression to the next scheduled activity. If not, the SMP would use passive autonomy to issue an alert so that action could be taken to adjust the schedule. Since the SMP also serves as an information database, stakeholders can extract information from the SMP or seek further information when needed.

Process and information concurrence in traditional and SCO-enabled LSCM systems

The SCO-enabled LSCM system is expected to enhance process and information concurrence throughout the logistics and supply chain. To better understand how this system works, the detailed goods/services flow and information flow before and after SCO-enabled process reengineering are mapped (in Fig. 6 and Fig. 7, respectively) based on case study data collected using non-participant observations, unstructured interviews, and archive study. In some key processes, SCOs have replaced humans in capturing and preparing information. For example, in the traditional LSCM process, there are two schedule-checking activities associated with stages MC6 and MC8 (Fig. 7) which would be done manually by foremen. These checking activities are essential since the results could influence further installation progress and proceeding orders. In the reengineered process, crosschecking is carried out by the SMP. Previous studies (e.g. Reason, 2000; Sterman, 1989) which acknowledged that human beings are not infallible when it comes to processing information and making informed decisions. Table 2 is a detailed comparison of the differences of goods/services and information flows by linking them to Fig. 6 and Fig. 7. The table is largely self-explanatory. It can be seen that the goods/services flow remains largely unchanged. What has been changed is the information flow; enabled by SCOs, the information flow is concurrent with the goods/services flow and the right information is available at the right time for decision-making. Real-time information visibility and traceability have improved, and the problems of fragmentation and discontinuity have been alleviated.

<Table 2 here>

The SCO-enabled LSCM system is effective in terms of allowing more informed decision-making, evident by practitioners' willingness to further invest in developing the system. The research team explored two slightly different solutions on applying the SCO-enabled system. Initially, the SCOs are enabled using *RFID+App+SMP*. RFID tags are tagged on prefabricated components to indicate their locations when being scanned by APP installed on handheld devices (e.g. smartphones). The *RFID+App+SMP* solution was well received by managerial people as it could tighten the process, but resistance was also recorded; some foremen felt it was still somewhat interruptive and labor-intensive to scan RFID tags. Much calibration effort has thus been paid to minimize the possible interruption of current LSCM process. Therefore, the research team explored the alternative approach, using *GPS/GSM+SMP*. The practitioners are willing to collaborate in further developing the *GPS/GSM+SMP* solution as they foresee that the process will be leaner; decision-making information such as location and status will be automatically sensed, computed, and pushed to the SMP without any human intervention or labor. To give an idea of the extra resources involved in developing the SCO-enabled LSCM system, in Hong Kong, sub-contractors charge around HK$250,000 (US$32000 equivalent) for only tagging 150 RFID tags to building components according to specifications. Without evident benefits, the practitioners will not be keen to push the research.

<Fig.6 here>

<Fig.7 here>

While the comparison analysis in Table 2 and the welcoming attitudes from the industrial practitioners towards the SCO-enabled system could partially evident the effectiveness of this system, it is acknowledged that more measurable criteria should be used to assess the effectiveness of the proposed SCO-enabled LSCM system over traditional LSCM approaches. A detailed evaluation of the SCO-enabled LSCM system is undertaken to validate the system, considering both the objective effectiveness criteria and the perceived effectiveness criteria. The objective criteria concern data such as the average delivery time, rate of on-schedule delivery, rate of on-schedule installation that are directly captured and recorded by SCOs. As for the perceive effectiveness criteria, constructs from the technology acceptance model (TAM) (Davis 1986) will be adopted to assess the perceived usefulness and intentions from the perspective of the people who use the system. The validation criteria, process, and outcomes are envisaged to be given in future studies.

Discussion

Logistics and supply chain management (LSCM) has been so widely advocated across sectors including construction. It may be time to call for a moratorium on *logistics and supply chain managerialism*. Prevailing LSCM has been much exhorted to introduce radical changes, e.g. via business process reengineering or buying in new systems, to streamline its leanness and in turn to improve its efficiency. This research questioned the stream of suggestions, as current LSCM process, despite its reported inefficiency, should have reached to an optimal stage no longer need radical changes. Buying in new LSCM systems to solve the problems in old systems very often invites more problems. As evident in the *RFID+App+SMP* system developed in this study, some simple taps on RFID readers, if interrupting the readily accepted LSCM process, could be a factor to prevent a LSCM system from being widely diffused. Simply blaming the industry being slow to respond to changes (Woudhuysen, 2004) adds no new knowledge and is largely futile.

Cynics may say that the authors are actually introducing a new LSCM system for construction use, despite the fact that the type of solutions has just been critiqued above. The LSCM system here is enabled by smart construction objects (SCOs): augmented construction goods that can gather, process, and exchange information (Niu et al., 2015). By connecting these SCOs to a smart management platform (SMP), the SCO-enabled LSCM system allows not only automatic synchronization of information with a single, shared platform, but also autonomous actions which do not necessarily need to include human decision-makers. Building on previous studies on SCOs, this research has integrated SCOs with an SMP and detailed an operable LSCM system. The multi-layer architecture of the SCO-enabled LSCM system developed in this study provides clear direction for replication of the work done here.

The *concurrence of process and information* provides the theoretical underpinning for this study's reengineering of the LSCM process, encouraging information management which supports decision-making by ensuring that accurate information is always available at the right time in the right format to the right person. The information attributes explored in this study (accuracy, accessibility, and timeliness) are good directions to make the concept of process and information concurrence operable. Nevertheless, further studies are desired to better define and measure these attributes.

If properly connected to BIMs and the IoT, SCOs represent a great opportunity to improve current construction practices (Niu et al., 2015). Their smart properties enable them to help synchronize as-built information with a BIM in a real-time manner, thereby supporting decision-making. SCOs can also serve as elementary nodes in the construction IoT (Niu et al., 2015). Based on this vision, this study has developed a real SCO computational application, i.e. the SCO-enabled LSCM system. The effectiveness of this system is evidenced by construction practitioners' keenness to apply it in their daily LSCM operations. Nevertheless, future studies are recommended to develop a more measurable set of indicators so that the effectiveness of the SCO-enabled LSCM system can be quantified using empirical evidence. In addition, it is desired that the architecture of the canonical SCOs-enabled system, together with its theoretical underpinning, should be customized and scaled up to other construction scenarios requiring more informed decision-making. Construction is well known for its heterogeneous processes varying from one trade to another. Achieving customization and scalability of smart construction is thus certainly not easy but needs innovative ideas. For example, the authors have developed a canonical integrated chip, which can be massively ‘implanted’ to existing construction objects and processes to perform customizable and scalable smart functions, including awareness, communicativeness and autonomy. A system cannot be linearly scaled up; it is almost certain that the system will slow down, overflow, or even break when the size of the LSCM increases. These will be tackled in future studies.

While construction practitioners enjoying the leanness and productivity enhancement offered by the SCO-enabled LSCM system, it is acknowledged that barriers remain to its full operation. A pervasive conservatism in the construction industry prevents participants from embracing new technology and new working processes. In addition, the cost saving in reducing time buffers is not instantly realized, which may hinder the application of the system in organizations that are particularly sensitive to ICT expenditure before costs and benefits are articulated. However, the potential of SCOs in information acquisition, distribution and processing are shown to be helpful for decision-making in the construction LSCM system. It is of interest in both the academic and industrial spheres to investigate the applications of SCOs in supporting construction management in other scenarios, *inter alia*, safety management, construction procedure guiding, and facilities management.

Conclusions

This research is an in-depth exploration of smart construction objects (SCOs) focusing on their computational applications in construction logistics and supply chain management (LSCM). Instead of developing a completely new system that intrudes upon current LSCM processes, this research argues for the *concurrence of process and information*, i.e., managing information throughout the LSCM process to support decision-making. By augmenting existing construction resources with core smart properties including awareness, autonomy and communicativeness, SCOs represent a new way of capturing, processing, and communicating information. By connecting them to the smart management platform, a SCO-enabled LSCM system is developed. The system is further calibrated and validated in the rich context of offshore prefabrication housing production in Hong Kong. Anecdotal evidence has shown that the system is effective in terms of facilitating better LCSM decision-making.

The research makes several practical and theoretical contributions. Firstly, the SCO-enabled LSCM system can be implemented in real-life practice to alleviate many problems existing in construction LSCM. The multi-layer architecture of the SCO-enabled LSCM system developed in this study provides clear direction and sufficient detail for other researchers interested in replicating the work here. While questioning the ‘radical changes’ advocated by business process re-engineering (BPR), this research confirms that BPR is a very useful analytical framework for analyzing the LSCM process. The research also adds to the theoretical debate on decision-making by arguing the importance of process and information concurrence and trying to explicate it in construction LSCM. It provides a sound theoretical foundation for efforts to reengineer the LSCM process, but asserts that future research efforts should be devoted to better measure the *concurrence of process and information*.

It is acknowledged that there are numerous hurdles in the way of full operation of the SCO-enabled LSCM system. In addition to the construction industry’s notorious reluctance to embrace change, technical and economic challenges associated with the system are yet to be fully addressed. Future studies are thus recommended to solve the technical problems, as well as to find empirical evidence quantifying the costs and benefits of the LSCM system. It is also suggested that the canonical system based on SCOs should be customized and scaled up to other construction scenarios requiring better decision-making.

Acknowledgement

This study is jointly supported by the General Research Fund (Project No. 17205614) of the Hong Kong Research Grant Council (RGC) and the Innovation and Technology Fund (Project No. ITP/ 045/13LP) of the Hong Kong Innovation and Technology Commission (ITC).

References

Akanmu, A., Anumba, C., and Messner, J. (2014). “Critical review of approaches to integrating virtual models and the physical construction”. *International Journal of Construction Management*, 14(4), 267-282.

Amendola, A. (2002). “Recent paradigms for risk informed decision making.” *Safety Science*, *40*(1), 17-30.

Bankvall, L., Bygballe, L. E., Dubois, A., and Jahre, M. (2010). “Interdependence in supply chains and projects in construction.” *Supply Chain Management: An International Journal*, *15*(5), 385-393.

Behzadan, A. H., Aziz, Z., Anumba, C. J., and Kamat, V. R. (2008). “Ubiquitous location tracking for context-specific information delivery on construction sites.” *Automation in Construction*, 17(6), 737-748.

Bekker, H., Thornton, J. G., Airey, C. M., Connelly, J. B., Hewison, J., Robinson, M. B., ... and Pearman, A. D. (1999). “Informed decision making: an annotated bibliography and systematic review.” *Health Technol Assess*, *3*(1), 1-156.

Bhattacharya, A., Mohapatra, P., Kumar, V., Dey, P. K., Brady, M., Tiwari, M. K., and Nudurupati, S. S. (2014). “Green supply chain performance measurement using fuzzy ANP-based balanced scorecard: a collaborative decision-making approach.” *Production Planning and Control*, 25(8), 698-714.

Cachon, G. P., and Fisher, M. (2000). “Supply chain inventory management and the value of shared information.” *Management science*, 46(8), 1032-1048.

Census and Statistics Department (2007). “The Survey on Waiting List Applicants for Public Rental Housing.” *Hong Kong Monthly Digest of Statistics*, Feb, 2007.

Chan, A. P., Fan, L. C., and Yu, A. T. (1999). “Construction process reengineering: a case study.” *Logistics Information Management*, 12(6), 467-476.

Chen, K., Lu, W., Peng, Y., Rowlinson, S., and Huang, G. Q. (2015). “Bridging BIM and building: From a literature review to an integrated conceptual framework.” *International Journal of Project Management*, 33(6), 1405-1416.

Chiang, Y. H., and Cheng, E. W. (2010). “Construction loans and industry development: the case of Hong Kong”. *Construction Management and Economics*, 28(9), 959-969.

Choo, C. W. (2001). “Environmental scanning as information seeking and organizational learning”. *Information Research*, 7(1), 1-7.

Cooper, M. C., Lambert, D. M., and Pagh, J. D. (1997). “Supply chain management: more than a new name for logistics.” *The International Journal of Logistics Management*, *8*(1), 1-14.

CSCMP (2005). “Definitions of Supply Chain Management.” *Council of Supply Chain Management Professionals*, available at: www.cscmporg/AboutCSCMP/Definitions/Definitions asp (accessed January 2016).

Dainty, A.R.J., Millett, S.J. and Briscoe, G.H. (2001). “New perspectives on construction supply chain integration”, *Supply Chain Management: An International Journal*, 6(3/4), 163-173.

Davenport, T. H., and Short, J. E. (1990). “The New Industrial Engineering: Information Technology and Business Process Redesign.” *MIT Sloan Management Review*, *31*(4), 11.

Davis Jr, F. D. (1986). *A Technology Acceptance Model for Empirically Testing New End-user Information Systems: Theory and results*. Doctoral dissertation, Massachusetts Institute of Technology.

Dubois, A., and Gadde, L. E. (2002). “The construction industry as a loosely coupled system: implications for productivity and innovation.” *Construction Management and Economics*, *20*(7), 621-631.

Flanagan, R., Jewell, C, Lu, W.S., and Pekericli, K. (2014). “*Auto-ID – Bridging the Physical and the Digital on Construction Projects”*. Chartered Institute of Building, ISBN 1853800191. 1-38.

Fidel, R. and Green, M. (2004). “The many faces of accessibility: engineers' perception of information sources”. *Information Processing and Management*, 40(3), 563-581.

Gibb, A.G.F. (2001). “Standardization and pre-assembly: distinguishing myth from reality using case study research”, *Construction Management and Economics*, 19(3), 307-315.

Grant, R. M. (1996). “Toward a knowledge-based theory of the firm.” *Strategic management journal*, *17*(S2), 109-122.

Green, S.D., Fernie, S., and Weller, S. (2005). “Making sense of supply chain management: a comparative study of aerospace and construction.” *Construction Management and Economics*, 23(6), 579-593.

Hammer, M., and Champy, J. (1993). “Reengineering the corporation. A manifesto for business revolution.” *Wyvern Business Library, New York: HarperBusiness (A Division of HarperCollins Publ.)*, c1993, 1.

Handfield, R., and Nichols, E. (1999). "*Introduction to Supply Chain Management". Prentice-Hall, Upper Saddle River, NJ.

Kahn, B. K., Strong, D. M., and Wang, R. Y. (2002). "Information quality benchmarks: product and service performance." *Communications of the ACM, 45*(4), 184-192.

Kaiser, M. J., and Snyder, B. F. (2012). "Reviewing rig construction cost factors". *Offshore(Tulsa)*, 72(7), 49-53.

Kortuem, G., Kawsar, F., Fitton, D., and Sundramoorthy, V. (2010). "Smart objects as building blocks for the internet of things." *Internet Computing*, IEEE, 14(1), 44-51.

Koushki, P. A., and Kartam, N. (2004). "Impact of construction materials on project time and cost in Kuwait". *Engineering, Construction and Architectural Management*, 11(2), 126-132.

Lambert, D.M., and Cooper, M. C. (2000). "Issues in supply chain management." *Industrial Marketing Management*, 29, 65-83.

Lee, Y. W., Strong, D. M., Kahn, B. K., and Wang, R. Y. (2002). "AIMQ: a methodology for information quality assessment." *Information and Management*, *40*(2), 133-146.

Liu, D.D., Lu, W.S., Niu, Y.H., and Wong, H.D. (2015). "A SCO-based tower crane system for prefabrication construction." Proceedings of *CRIOCM2015 International Symposium on Advancement of Construction Management and Real Estate*, Hangzhou, China.

Lu, W., Chau, K. W., Wang, H., and Pan, W. (2014). "A decade's debate on the nexus between corporate social and corporate financial performance: a critical review of empirical studies 2002–2011." *Journal of Cleaner Production, 79*, 195-206.

Lu, W., Huang, G. Q., and Li, H. (2011). "Scenarios for applying RFID technology in construction project management." *Automation in Construction, 20*(2), 101-106

Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D. and Zacharia, Z.G. (2001). "Defining supply chain management". *Journal of Business Logistics*, 22(2), 1-25.

Moxham, C., and Kauppi, K. (2014). “Using organizational theories to further our understanding of socially sustainable supply chains: the case of fair trade.” *Supply Chain Management: An International Journal*, *19*(4), 413-420.

Movahedi B., Lavassani, K., and Kumar, V. (2009) “Transition to B2B e-Marketplace Enabled Supply Chain: Readiness Assessment and Success Factors.” *The International Journal of Technology, Knowledge and Society*, 5 (3), 75-88.

Niu, Y., Lu, W., Chen, K., Huang, G. G., and Anumba, C. (2015). “Smart Construction Objects.” *Journal of Computing in Civil Engineering*, 30(4), 04015070.

Rameezdeen, R. Chileshe, N., Hosseini, M.R., and Lehmann, S. (2016). “A qualitative examination of major barriers in implementation of reverse logistics within the South Australian construction sector”. *International Journal of Construction Management*, 16(3), 185-196.

Ray, R. (2012), “Deciphering Supply Chain Management and Logistics”, *APIC Magazine*, Retrieved from http://goo.gl/9kxuqM (accessed February 2016).

Reason, J. (2000). “Human error: models and management.” *BMJ*, 320(7237), 768-770.

Ruikar, K., Anumba, C. J., and Carrillo, P. M. (2003). Reengineering construction business processes through electronic commerce. *The TQM magazine*, 15(3), 197-212.

Saad, M., Jones, M., and James, P. (2002). “A review of the progress towards the adoption of supply chain management (SCM) relationships in construction.” *European Journal of Purchasing and Supply Management*, 8(3), 173-183.

Shin, T. H., Chin, S., Yoon, S. W., and Kwon, S. W. (2011). “A service-oriented integrated information framework for RFID/WSN-based intelligent construction supply chain management”. *Automation in Construction*, 20(6), 706-715.

Simon, H. A. (1976). “*Administrative Behavior*”. (3rd edition) New York: Free Press.

Sterman, J. D. (1989). “Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment.” *Management Science*, 35(3), 321-339.

Soroor, J., and Tarokh, M. J. (2006). “Innovative SCM: A wireless solution to smartly coordinate the supply processes via a web-based, real-time system.” *VINE*, *36*(3), 304-340.

Stock, J. R., and Boyer, S. L. (2009). “Developing a consensus definition of supply chain management: a qualitative study.*” International Journal of Physical Distribution and Logistics Management*, 39(8), 690-711.

Tennant, S., and Fernie, S. (2014). “Theory to practice: A typology of supply chain management in construction”. *International Journal of Construction Management*, 14(1), 56-66.

Vrijhoef, R., and Koskela, L. (2000). “The four roles of supply chain management in construction.” *European Journal of Purchasing and Supply Management*, *6*(3), 169-178.

Wang, L. C., Lin, Y. C., and Lin, P. H. (2007). “Dynamic mobile RFID-based supply chain control and management system in construction.” *Advanced Engineering Informatics*, *21*(4), 377-390.

Wieland, A., and Handfield, R.B. (2013). “The Socially Responsible Supply Chain: An Imperative for Global Corporations.” *Supply Chain Management Review*, 17(5), 22-29.

Woudhuysen, J. (2004). “*The Globalisation of UK Manufacturing and Services, 2004-24: Towards the Agile Economy”*. UK Trade and Investment

Ye, K., Lu, W., and Jiang, W. (2009). “Concentration in the international construction market.” *Construction Management and Economics*, *27*(12), 1197-1207.

Zsidisin, G., Jun, M., and Adams, L. (2000), “The relationship between information technology and service quality in the dual-direction supply chain.” *International Journal of Service Industry Management*, 11(4), 312-328.

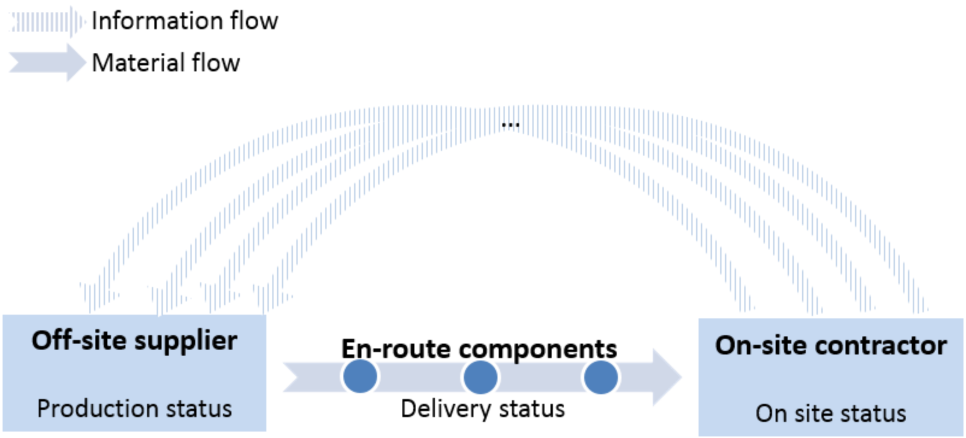


Fig. 1. Existing LSCM process in construction

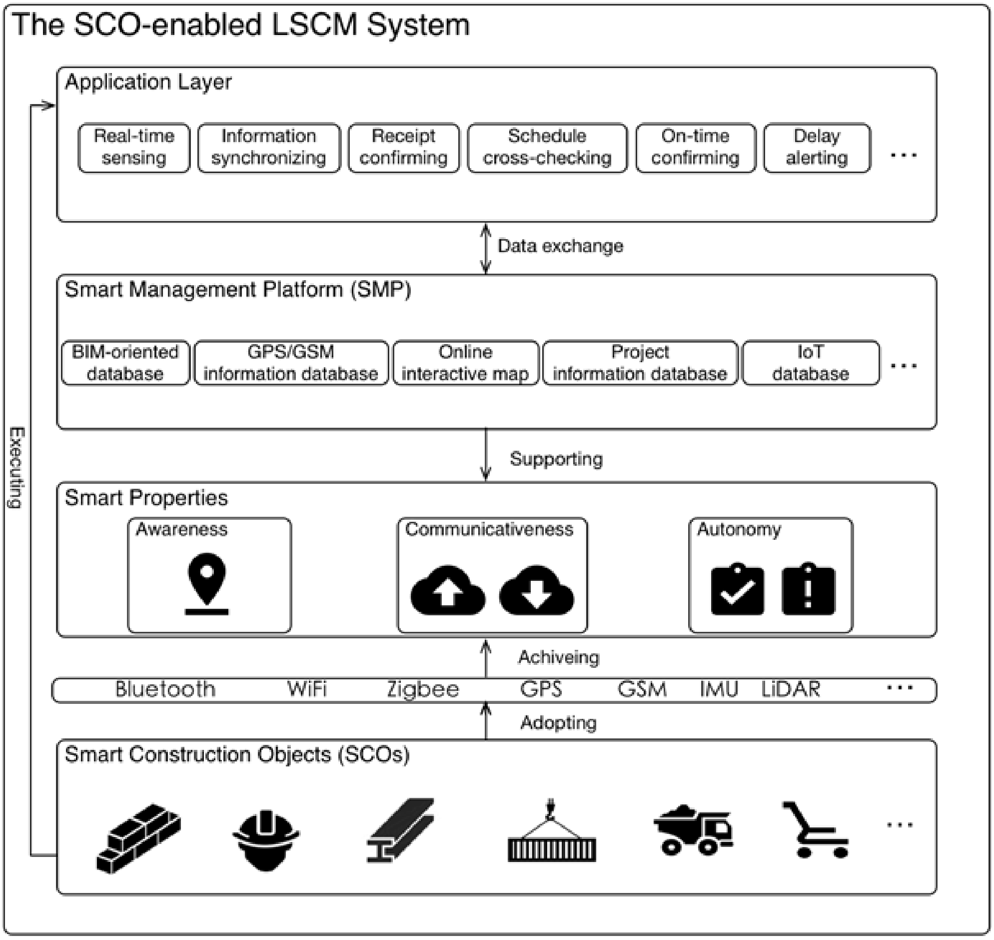


Fig. 2. The architecture of the proposed SCO-enabled LSCM system

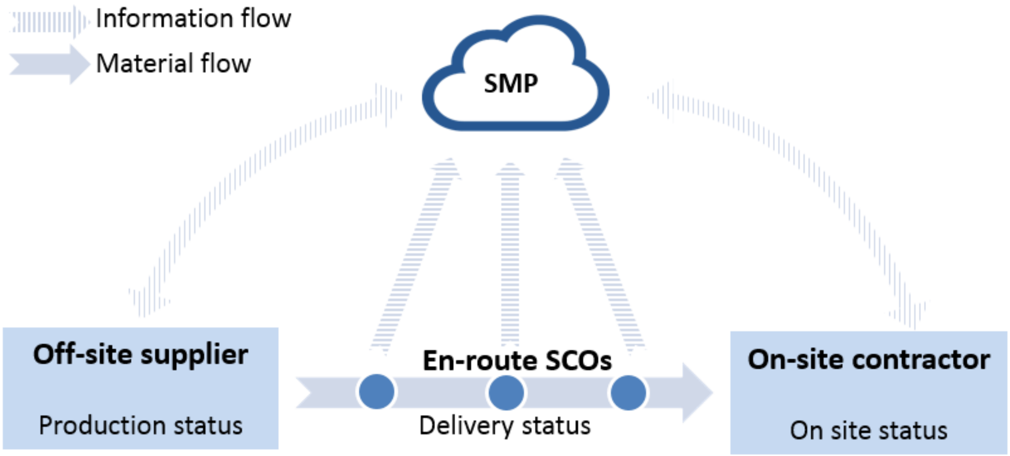


Fig 3. The proposed SCO-enabled LSCM process

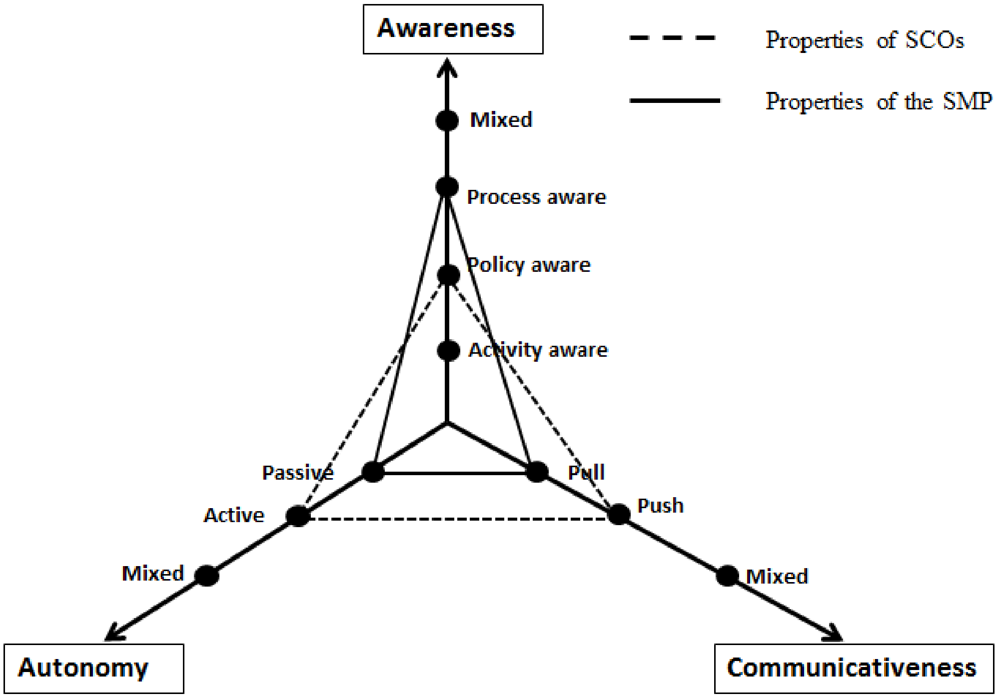
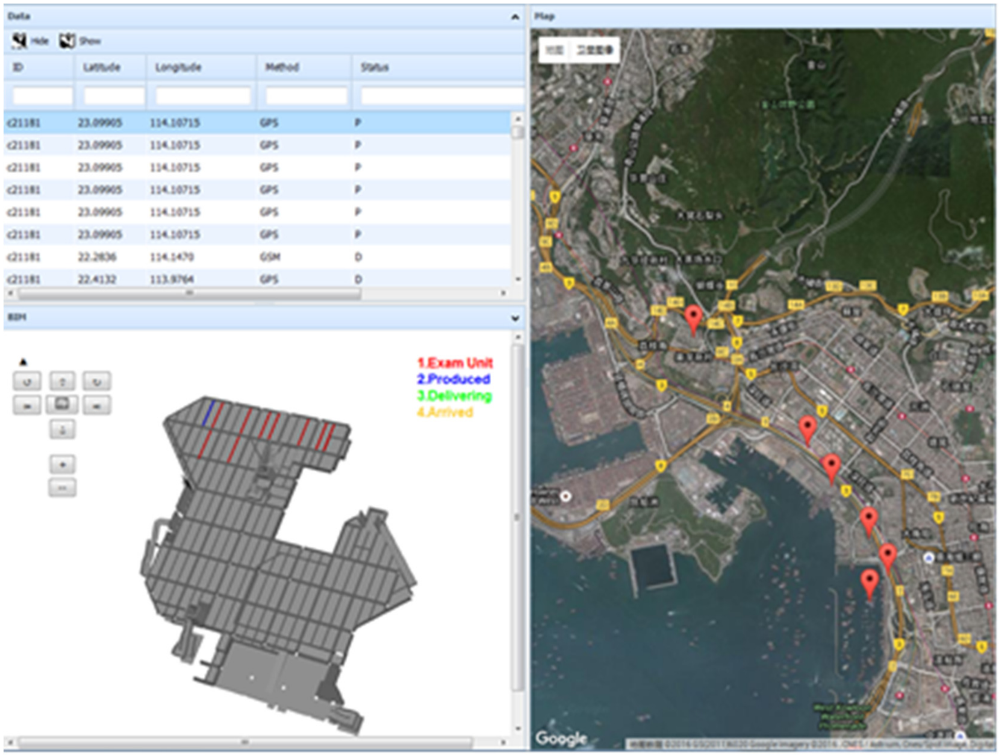


Fig 4. The property diagram of SCOs and the SMP



ID	Latitude	Longitude	Method	Status
c21181	23.09905	114.10715	GPS	P
c21181	23.09905	114.10715	GPS	P
c21181	23.09905	114.10715	GPS	P
c21181	23.09905	114.10715	GPS	P
c21181	23.09905	114.10715	GPS	P
c21181	23.09905	114.10715	GPS	P
c21181	22.2836	114.1470	GSM	D
c21181	22.4132	113.9764	GPS	D

1.Exam Unit
2.Produced
3.Delivering
4.Arrived

Fig. 5. The user interface of the Smart Management Platform (SMP)

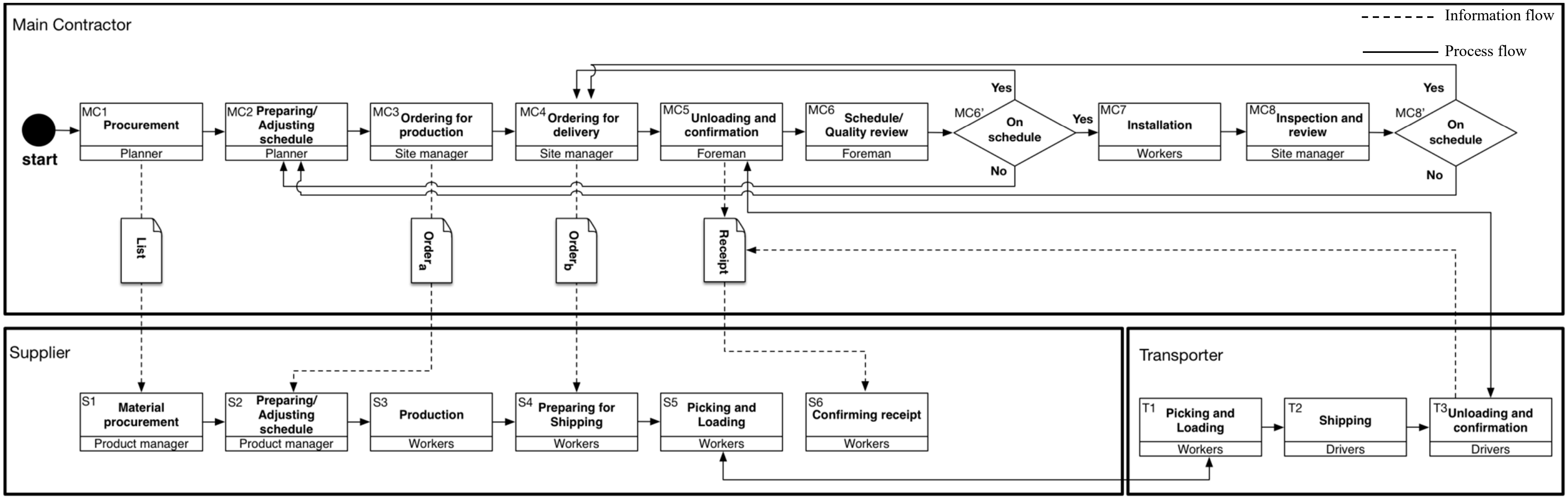


Fig. 6. The LSCM process map before the SCO-enabled reengineering

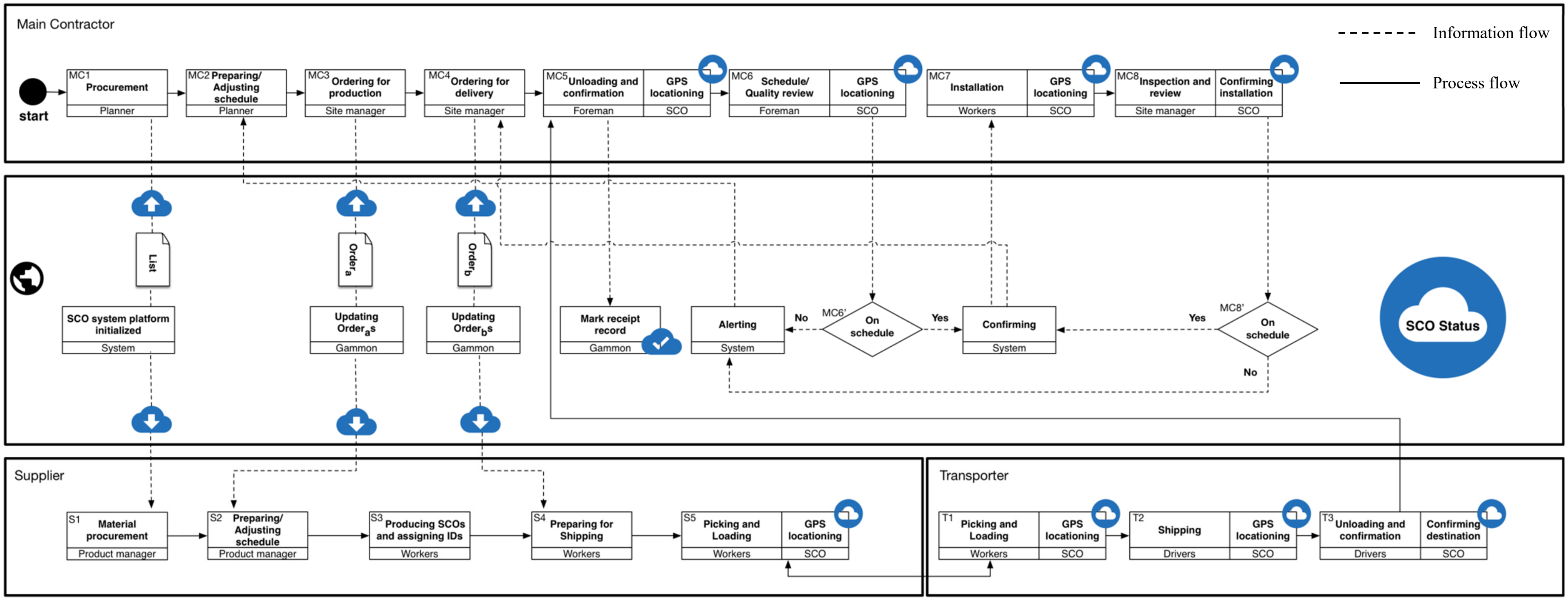


Fig. 7. The LSCM process map after SCO-enabled reengineering