SMART CONSTRUCTION OBJECTS (SCOS): A NEW THEORY OF SMART CONSTRUCTION IS BORN

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Abstract: Despite of the prolific development of smart systems in the construction industry, the theorizing work of 'smart construction' is rather stagnant. The fundamental concepts, definitions, and models of smart construction are yet to be fully explored. It is against this backdrop that this study seeks to advocate smart construction objects (SCOs) as an innovative concept and the basic elements to define, understand, and achieve a new theory of smart construction. It does so by adopting a mixed-method strategy at the kernel. It establishes the conceptual and deployment elements of SCOs and tests them in two case studies. This study reveals that the concept of SCOs can steer the field of smart construction towards a new theory by (a) enhancing the theoretical lucidity on smart construction, and (b) providing a generalizable framework for realizing it. One elegance of SCOs lies in that they can be adopted and implemented without radically changing the prevailing construction practice and process. Advancing smart construction through this direction can be expected to go more promisingly than existing directions.

Keywords: Smart construction, smart construction objects, theory.

1. INTRODUCTION

Smart construction has increasingly been advocated in recent years, with "*smart*" becoming a global buzzword. The enthusiasm for *smart* has infiltrated almost every aspect of life from the device level (e.g., smart phone and smart watch), the industry level (e.g., smart health and smart transportation), to the city or country level (e.g., the smart city initiatives in New York, Tokyo, Seoul, Glasgow, Ontario, and Singapore). The construction industry is no exception by strenuously exploring the concept of smart to solve its many chronic problems such as delayed delivery, escalating cost, unsatisfactory quality, and stagnant productivity.

Regardless of the growing interest, studies on smart construction, however, are stagnating at a primitive stage. "Smart construction" is conveniently used to refer to anything that is different from "traditional" construction. For example, there is a "smart construction site" where workers, materials, and machinery can be tracked and monitored (Hammad et al., 2012); 'smart building construction' as an indispensable element of the smart city (Angelidou, 2015); or "smart construction lift car toolkit" that allows automated recognition of the logistic items in construction (Cho et al., 2011). Likewise, with the resurgence of interest in artificial intelligence (AI) and robotics for construction, several AI - or robotics-based systems have been developed under the nomenclature of "smart construction". These include the sensing system to monitor workers' exposure to vibrations (Kortuem et al., 2007), the contour crafting system for automatic fabrication of building structures on site (Khoshnevis, 2004), or the mechanical arms to help worker handle heavy materials (Lee et al., 2006).

Despite the research efforts on smart construction by employing ideas from AI, robotics, and analogous concepts, there is still widespread frustrations in the industry in respect of smart construction. In contrast to the advanced development of smart systems in manufacturing, automobile, civil aviation, and logistics and supply chain management, the fundamental concepts, definitions, and models of smart construction are yet to be systematically explored. Successful cases of smart construction have emerged in a piecemeal fashion, hence having little generalizability. In addition, smart systems introduced from other industries have been disruptive to existing construction practice, resulting in practitioner reluctance to harness their potential. There is a need to develop a new theory to guide smart construction development, and it is against this backdrop that this study was initiated. Unlike most studies of this kind tending to develop a smart construction technology or system, this study takes the challenge to look at smart construction as a more general issue from a theoretical perspective.

Building on previous studies of smart construction objects (SCOs), this research argues that the development of SCOs is leading towards a new theory of smart construction. It demonstrates that SCO development offers a perspective from which to (a) systematically define, understand, and achieve smart construction; (b) provides a new perspective to solve problems beyond the scope of existing theories; and (c) address limitations in existing studies on smart construction, including lack of theoretical lucidity, and disruptive and piecemeal application with limited generalizability.

2. THE NEED FOR A NEW THOERY

According to Oxford dictionaries, a theory is a "supposition or a system of ideas intended to explain something, especially one based on general principles independent of the thing to be explained". There are two broad types of theory: explanatory theory and change theory. An explanatory theory is used as a plausible general principle or body of principles offered to explain a phenomenon. A theory is a model capable of predicting future occurrences or observations, being tested through experiment or otherwise verified through empirical observation (De Benetti, 2009). However, even the best explanations may not be enough by themselves to fully guide change, e.g., in smart construction development. Change models are desired in this case. Theories are by their nature abstract and not content- or topic-specific but they have empirical relevance.

There are non-negligible limitations in current studies on smart construction. First, it is lack of theoretical lucidity, meaning that the fundamental concepts, definitions, and models of smart construction have yet to be fully explored. Amid proliferating studies on smart construction, its definitions are still nebulous. Worse yet, research on smart construction is partitioned into isolated sub-disciplines, mostly too focused on technological tools such as sensors, networking, or automatic control. Smart construction is stuck in theoretical muddle and murk. Lucid theories on smart construction are necessary for its future research and development to proceed on a more solid footing.

The second limitation in existing smart construction studies is their piecemeal application with limited generalizability. Rooted in different theoretical bases from disciplines including computer science, information communication technology, and the manufacturing industry, most existing smart construction studies emphasize a cross-sectoral learning approach for achieving smart construction. Even though there are successful cases of smart construction application such as the application of expert systems in construction (Andersen and Gaarslev, 1996; McGartland and Hendrickson, 1985), the complex nature of projects, unique site conditions, non-repeatable construction processes, and heterogeneity and fragmentation of the construction industry all make it difficult to directly transplant well-developed smart systems from other industries.

The third limitation is rooted in the disruptive nature of current approaches for achieving smart construction. Notably, most smart systems introduced from other industries are intrusive to existing construction working practices. With a view to increasing the adaptability of smart systems to the construction industry, some studies advocate alteration of the traditional working environment or working procedures to accommodate new technologies, rather than integrating new technologies into the current working practices. Examples include the development of mobile platforms to cater for the operation of robots (Zied, 2007) and the strategy of robot-oriented design (ROD) (Bock and Linner, 2015). Consequently, the intrusive smart systems create reluctance on the part of workers and managers to harness their full potential while the industry is criticised for being 'notoriously slow' to embrace change (Liu et al., 2018; Woudhuysen and Abley, 2004). To date, not all smart systems have been treated not as a natural and endogenous ally, but instead some of them as a potentially disruptive adversary to construction.

These three limitations create a desire for a new theory of smart construction. Within the theory, ideally, conceptual elements of smart construction can be clearly defined to provide theoretical lucidity. Also required is systematic development of a generic system framework to enable the practical deployment of smart construction under the dynamic, sophisticated and diverse conditions of construction. More importantly, instead of continuously mandating construction personnel to change and adapt to new technologies, a non-disruptive approach that can innovatively accommodate the complex nature of construction is desired. Unlike similar studies which have developed a particular smart construction technology or a system, this study takes on the challenge of looking at the theoretical development of smart construction, seeking the fundamentally theoretical elements to define smart construction and the generalizable solutions in advancing the field.

3. RESEARCH DESIGN AND METHODS

This study adopts abductive reasoning logic for its research design. Based on a logic chain of exploration, modelling and production, experimentation, rectification and evaluation, abduction allows researchers to move between the creation of explanations and acquisition of knowledge from empirical phenomena (Downward and Mearman, 2006). This makes it particularly appropriate for a study in construction, which is primarily a practice-based research domain encompassing aspects of both natural and social science, and collaboration between academia and industry can lead to knowledge that is both academically insightful and practically actionable. The research design for this study and respective methods at each stage are elaborated as follows:

(1)Exploration stage: Literature review and industry engagement are conducted to understand the background, related concepts, and various models in construction. Based on the literature review and the reflection of the authors' industry engagement, the need for a smart construction theory and current limitations are identified, with initial findings summarized in Sections 2 and 3 of this paper.

(2)Modelling stage: Based on the understanding gained from the literature-based discovery, the conceptual and deployment elements of SCOs are systematically developed. This step involves desktop studies and discussions with practitioners and particularly with visionary scholars. In order to understand and define smart construction, the conceptual elements including the definition and core properties of SCOs are theoretically proposed, while taxonomic relationship with other concepts is also articulated. Besides, in order to apply SCOs in the, considerable efforts are paid to develop the deployment framework of the SCOs-enabled management system and technical solutions.

(3)Experimentation and rectification stage: In the experimentation and rectification stage, case study method is used to empirically test SCOs and the SCO-enabled smart management framework in context-driven and problem-focused project practice. This method is valuable in situations where existing knowledge is limited and shallow for more and deeper insights (Harris and Ogbonna, 2002). Prototypes of SCOs are developed and rectified to cater for practical needs and variance of contexts. By conducting two in-depth case studies, the understanding on the concept and framework of SCOs are substantiated in different application scenarios.

(4)Evaluation stage: Findings and reflections are provided with the theorizing and discussions in the evaluations stage. During the development of the theoretical elements of SCOs and the implementation of two progressive case studies, a continuous dialogue takes place between the author's pre-understandings and the empirical data. New insights are generated as an evolution of the authors' understanding, as summarised in the discussion section.

During the entire research study process, multiple data collection and analysis methods are applied, including interviews, direct observations and participatory-observations, documentation analysis, and theoretical debates. Certainly, it is not a linear process. Rather, the mixed methods approach unfolds in a reiterative fashion. Triangulations of literature-based discovery, theoretical debates, and co-production are repeated throughout the study, and are blended in narratives ensure a coherent argument for ease of reading.

4. SMART CONSTRUCTION OBJECTS (SCOS) AS A NEW THEORY

4.1 Conceptual elements

The concept of SCOs is developed as a basic element to define, understand, and achieve smart construction. Inspired by the concept of the smart object (SO) (Kortuem et al., 2010; López et al., 2012), SCOs is proposed as a step towards ubiquitous computing and smartness in the construction context. SCOs are defined as construction resources made 'smart' by augmenting them with smart properties (Niu et al., 2015). These resources could be machinery, tools, devices, materials, components, and even temporary or permanent structures. To explain the smartness SCOs could confer, three core properties of SCOs are proposed in Figure 2: awareness, communicativeness, and autonomy, denoting the sensing ability, data sharing ability, and autonomous action-taking ability of SCOs (Niu et al., 2015). Each of the three core properties is subdivided into several types, while they may function in cooperation depending on needs and requirements in different application scenarios.

As the basic elements of smart construction, SCOs offer a way to define and understand smart construction. Understanding of SCOs and smart construction are deepened when their taxonomic relationship with cyber-physical systems (CPSs) and the Internet of things (IoT) are elucidated (see Figure 1). Differences and similarities between the three concepts are articulated by Niu et al. (2018). For example, although the three concepts share similar underlying technology tools, each operates at a different level (SCOs at the component level, a CPS the system level, and the IoT the infrastructure level) (Niu et al., 2018). A synergetic deployment framework to integrate the three concepts has been proposed with the objective of harvesting the synergy between them when adopting smart construction.

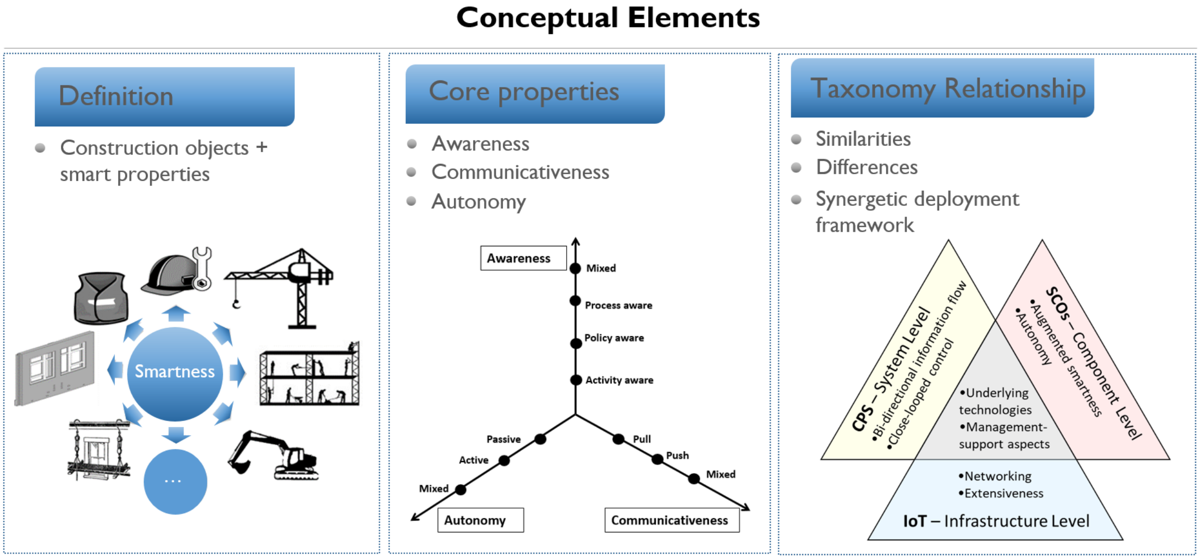

Figure 1. The development of conceptual elements of SCOs

4.2 Deployment elements

While flexible combinations of their three core properties (awareness, communicativeness and autonomy) enable SCOs to provide individual smart functions, the true power of SCOs lies in an integrated, responsive smart construction system in which they are linked. A generic framework for this SCO-enabled smart management system is developed for practical deployment (see Figure 2). By providing a multi-layered structure with the connecting relationships in between, the system framework for the SCO-enabled smart management system clearly illustrates the process of turning traditional construction objects into smart and customizable SCOs, the functions units to be included in the smart management platform (SMP), and the typical demand-oriented applications of SCOs. It demonstrates how SCOs could interact with people or each other to support construction management by enabling a more connected world of construction.

Whilst this study proposes SCOs as a paradigmatic development of smart construction rather than a technical solution *per se*, it is important to introduce the technical foundation of SCOs to demonstrate their feasibility for smart construction. Awareness, communicativeness, and autonomy of SCOs can be achieved by augmenting construction objects with various modules into construction objects, including computing, communication, sensing, and locationing modules (Liu et al., 2015). To encapsulate these modules in an integrated manner, a standalone, programmable, extendable integrated electronic chip, named i-Core, is developed in this study as one of the technical solution (see Figure 3) (Lu et al., 2016). Able to be implanted into machinery, devices, and materials, and similar to a computer central processing unit (CPU), the i-Core turns dumb construction components and plants into SCOs and makes smart construction possible. Implementation of the three core SCO properties relies on integration of various computing, sensing, and communicating modules into the i-Core. To meet changing needs of construction sites and achieve different functions, these modules are extensible and can be selected and customized case by case.

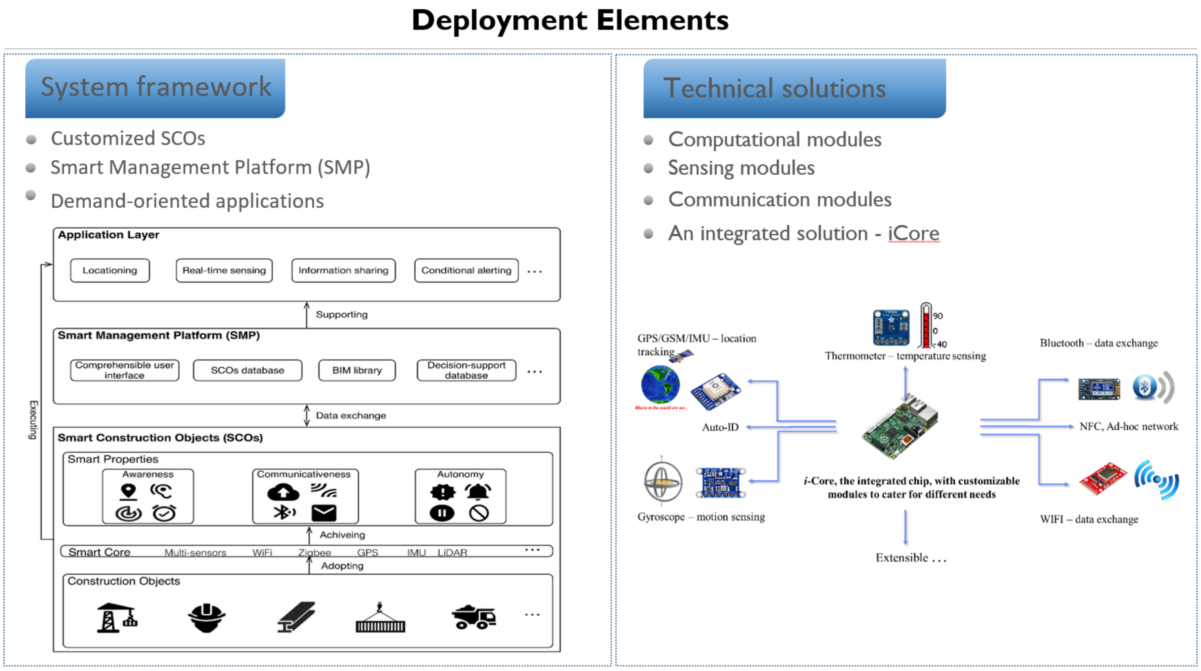

Figure 2. The development of deployment elements of SCOs

5. THE TESTING AND VALIDATION OF SCOS

5.1 Case A: SCOs for logistics and supply chain management (LSCM) in construction

In Case A, the first attempt to put the SCO concept and conceptual framework proposed in this study into practice, prefabricated beams were made into SCOs to support LSCM in a public housing prefabrication project in Tuen Mun, Hong Kong. The beams were enabled to sense real-time location, push the information to a cloud-based smart management platform (SMP), and update their LSCM status. With these functions, a real-time bi-directional information flow between SCOs and the SMP was achieved, along with concurrent information and material flow during the LSCM process (Niu et al., 2016).

The implementation of Case A validates the practicality and customizability of SCOs in achieving smart construction, demonstrating flexibility in property combinations, a customizable framework, well-performing prototypes of the i-Core, SCOs, and the SMP (see Figure 4), and the non-disruptive nature of SCOs. The collaborating practitioners, having used both radio frequency identification (RFID) tags and SCOs for LSCM, expressed a preference for SCOs because they require less manual work and fewer changes in working practice. These industry partners' interest in collaborating further lends support to the practicability of SCOs.

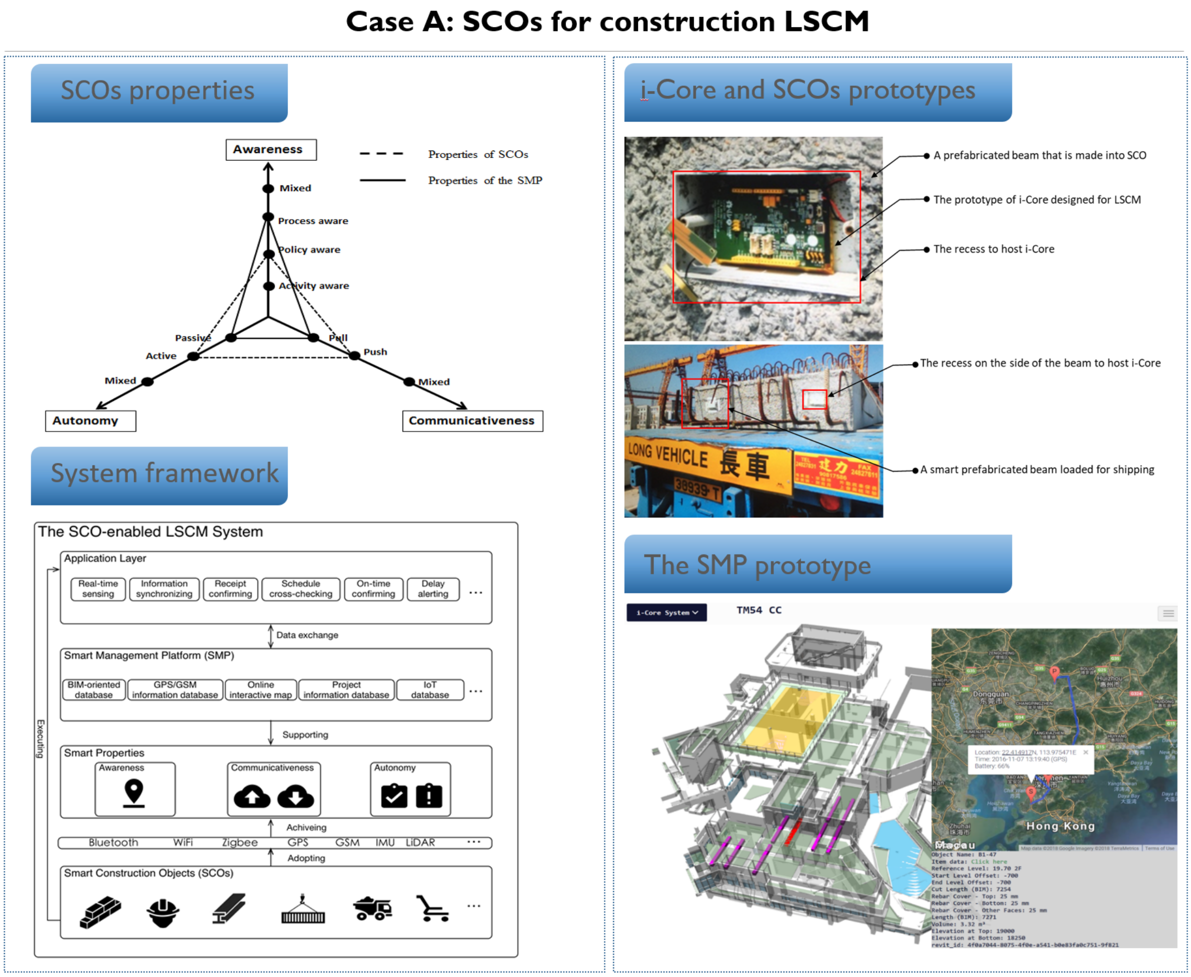

Figure 3. Testing and validation of SCOs in Case A

5.2 Case B: SCOs for construction occupational health and safety (OHS) management

With the unfailing support from the industry partners, Case B was conducted to enhance the validity and transferability of SCOs. While Case A involved the relatively new construction practice of prefabrication, Case B targeted conventional onsite tower crane operations and associated safety problems. By making a tower crane into a SCO and field testing it, Case B demonstrates that an SCO-enabled occupational health and safety (OHS) management system can support worksite monitoring, hazard detection, alerting, and data visualization to identify and respond autonomously to dangerous situations. Having validated the autonomy of SCOs in a controlled lab test, Case B demonstrates that SCOs could help control dangerous situations more quickly and with greater accuracy than human reactions by taking in-time, autonomous actions such as halting a machine (Niu et al., 2019).

The customizability of SCOs and the SCO-enabled smart management system was further substantiated in Case B when applied to suit a completely different application scenario. The different versions of i-Core developed for the tower crane and customized SMP also show the operability of SCOs for achieving smart construction (Figure 4). In addition, when looking the non-disruptive nature of SCOs in Case B, the AI-based solution provided by SCOs can be understood as an extra layer of protection. It does not require the crane operator or the safety manager to relinquish their existing OHS strategies such as wearing personal protective equipment (PPE) or conducting safety training, while reinforcing the OHS management from an additional perspective.

To sum up, the Cases A and B together deepen the understandings of SCOs towards a new theory of smart construction from an empirical perspective. By addressing each of the major limitations in existing studies on smart construction, including "lacking of theoretical lucidity", "piecemeal applications and limited generalizability", and "disruptive in nature", the in-depth explorations of SCOs in the two cases vividly demonstrate their practicality, customizability and non-disruptive nature in filling theses gaps.

6. FINDINGS AND DISCUSSIONS

6.1 Enhancing the theoretical lucidity of smart construction

The development of SCOs is definitely not the first study on smart construction. However, it makes a significant endeavour to enhance the theoretical lucidity. By systematically proposing the concepts, core properties, and system framework in smart construction, the development of SCOs has established the fundamental elements to define and understand smart construction. In this study, considering each SCO as a basic element of smart construction, the SCO-enabled smart management system and i-Core are developed to achieve smart construction by harnessing the synergetic power of SCOs. These conceptual and deployment elements serve as essential components in deepening understanding of smart construction.

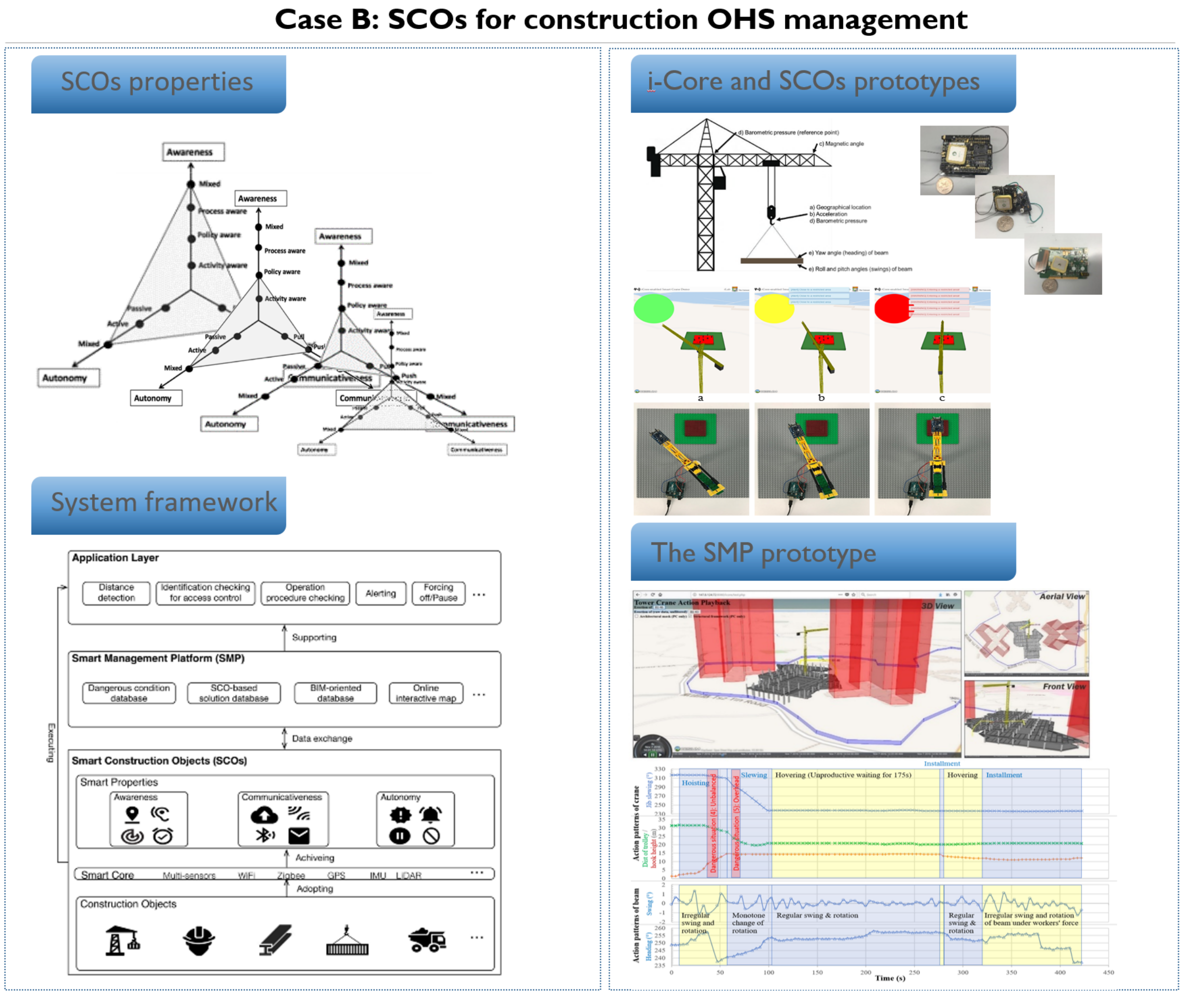

Figure 4. Testing and validating of SCOs in Case B

The theoretical lucidity of smart construction is further enhanced when understanding of the proposed concepts is substantiated in the context of industry practice. Applying the technical solution i-Core, an electrical circuit integrated with sensing, communication, and control modules, existing construction resources such as smart prefabricated beams and a smart tower crane (Cases A and B), are made into SCOs. These SCOs serve traditional functions while also behaving in a smarter way. The smart prefabricated beams, for example, still serve as the structural elements to take load in buildings, during the LSCM process, while they can sense and report their real-time locations to the cloud-based platform. When the conceptual elements of smart construction are understood not only literally but also from a practical setting, the move towards smart construction is improved.

The enhancement on the theoretical lucidity made by SCOs can also be perceived from the perspective that the deployment of SCOs are presenting management implications for the smart construction. By comparing the SCO-enabled LSCM with the traditional LSCM, it was found that SCOs can facilitate informed decision-making by providing real-time bi-directional information flow between SCOs and the SMP. Also, when compared with RFID-enabled LSCM, SCO-enabled LSCM is acknowledged by industry practitioners as a less disruptive approach since it requires less manual effort. Likewise, deployment of SCOs for OHS management reveals the ability of SCOs to support AI-based solutions and autonomous action-taking. Comparing the SCO-enabled smart construction model with the human-centric decision science model, SCOs could prevent dangerous situations from developing into fatal accidents by taking active and prompt actions in conditions that would overload human thinking and reacting abilities.

6.2 The generalizability and customizability of SCOs

The three core properties of SCOs, namely, awareness, communicativeness, and autonomy, are presented in a tri-axial diagram. Each axis carries one dimension of smart property that is divided into different types and levels. Different combinations of the core smart properties enable customization of smart solutions to almost unlimited construction scenarios as widely seen in construction. The tri-axial diagram is resilient and extendable, which is open to enrichment such as by adding a supplementary dimension of a particular type of smartness or additional smart properties. The resilience of the theoretical constructs can also be perceived in the framework of the generic SCO-enabled smart management system, which is not only generalizable but also customizable. The three layers comprising the SCOs, the SMP, and the application layer, were applied in both Cases A and B scenarios. The successful implementation of SCOs in both scenarios, together with practitioners' openness to SCOs as a means of achieving smart construction, reveal the practicability, generalizability, and customizability of SCOs towards the theory of smart construction. More importantly, the generic system framework also provides a clear direction and sufficient detail for the research community to replicate and enrich the work, serving as a classic element in supporting paradigmatic development.

From another perspective, the technical solution adopted in existing studies to bring SCOs to life, i-Core, can also be considered as a generalizable and customizable solution to achieve smart construction. Various sensors, location tracking modules, communicating modules, and control units can be integrated into the i-Core flexibly. Showing diverse traits and functions in different SCO application scenarios, the i-Core has the versatility to turn different construction resources into SCOs.

6.3 The non-disruptive nature of SCOs

Central to the new theory of smart construction through SCOs is the ideological shift from radical change to a non-disruptive approach, in achieving smart construction. The non-disruptive nature of SCOs is rooted in the rationale of ubiquitous computing from which SCOs are developed. Ubiquitous computing initiates the rethinking on a radical ideological departure from the tradition of putting intelligent machines out for use and having people adapt to them (Weiser and Brown, 1997). Notably, it advocates embedding of smart computing abilities in the environment, anywhere and everywhere (Weiser, 1999). For initiating this new perspective towards smart computing, ubiquitous computing is gaining acceptance as a new theory in the smart computing research community (Abowd and Mynatt, 2000; Greenfield, 2010). Likewise, developing SCOs is a step towards ubiquitous computing and smartness in the construction context. Instead of continuously inventing and bringing in new intelligent machines for construction personnel to learn, SCOs offer a new way of achieving smart construction by making existing construction resources and objects smart.

The development of SCOs should not be perceived as a technical solution *per se,* in contrast to most existing studies on smart construction applications. Instead, the aim is to promote an ideological shift towards the new theory of smart construction. In construction, the prevailing stagnant progress in innovation intake and technology acceptance suggest that the industry does not need or cannot afford radical change. The value residing in the non-disruptive nature of SCOs is clear from the positive response of construction practitioners in the case studies, in contrast with their resistance to other, disruptive smart systems.

Nevertheless, by arguing against radical change in established construction practice, this study does not assert that traditional construction practices should remain unchanged. It is a question of priority. The construction practice should be changed with the regard to improve performance and productivity, but not to make room for introducing new technologies. The motivations for the changes should always be enhancing productivity, quality, safety performance, and reducing cost. Likewise, the introduction of new technologies, innovations, should serve the same purpose of facilitating such improvement.

7. CONCLUSIONS

The global construction industry has long been plagued with problems such as delayed delivery, escalating cost, and unsatisfactory quality. Smart construction has attracted considerable attentions as a new direction to solve these problems while the understanding of smart construction is literally nebulous. By developing, prototyping, and testing the concept of smart construction objects (SCOs) in a systematic manner, this study argued that SCOs can be regarded as a new theory of smart construction. It demonstrated that SCOs, by providing the enriching conceptual elements for defining and understanding smart construction, as well as by offering deployment elements to achieve smart construction in industry practices, could foster a new theory of smart construction.

Linking the development of SCOs to the major limitations in smart construction studies, the elegance of SCOs were identified as threefold:

(a) SCOs enhanced the theoretical lucidity of smart construction by offering the theoretical concepts and framework to define and understand smart construction;

(b) SCOs allowed the generalizability and customizability of smart construction by providing resilient property diagram, system framework, and technical solutions to support implementation in diverse scenarios;

(c) SCOs provided a non-disruptive approach to smart construction that were more likely to be welcomed by the conventional construction practitioners.

With SCOs serving as the basic elements of smart construction, it is envisaged that their development will be further enriched in a variety of application scenarios and synergetic studies with other emerging technologies in construction.

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