Taxonomy and Deployment Framework for Emerging Pervasive Technologies in Construction Projects

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Abstract:

Managing complex and dynamic construction projects is challenging as it relies highly on the real-time communication and seamless coordination of numerous ‘things’ and people that are spatially and temporally distributed at a massive scale. To deal with the associated challenges, various concepts, including internet of things (IoT), cyber-physical systems (CPS), and smart construction objects (SCOs), have been explored in construction. Amidst the increasing overlap and merger of principles among these three pervasive technologies is that clearly narrow definitions and isolated development of each field are no longer appropriate. It is, therefore, opportune for this study to explore and propose a deployment framework that integrates IoT, CPS, and SCOs, with a view to achieving greater synergy that could expedite their holistic implementation. It does so by adopting a mixed methods approach with literature review, technological analyses, case studies, and action research at the core. This deployment framework encompasses the key components of each technology (i.e. the three core properties of SCOs, the bi-directional information flow in CPS, and the extensiveness of devices and networking in IoT) in an inter-connected structure while enabling the uniqueness of each technology to be evident. In addition, example application scenarios are described to demonstrate the applicability of the proposed framework in real-life practice. This study contributes to the body of knowledge by presenting a taxonomy that clarifies the similarities and differences between IoT, CPS, and SCOs when applied to the construction industry. The integrated deployment framework can be used to guide further theoretical explorations on the synergistic effects of IoT, CPS, and SCOs, and enriched with practical cases to facilitate construction project management.

Key words: Pervasive technologies; Internet of Things (IoT); Cyber physical system (CPS); Smart construction object (SCO)

Introduction

Managing a construction project involves utilizing various construction resources to achieve project objectives relating to such attributes as quality, duration, cost, function, and durability. Construction resources, including manpower, material and machinery, are usually diverse and scattered across locations and timespans. During the course of a construction project, occurrences such as misallocating funds, delayed or incorrect deliveries, and misplaced construction equipment are common. Many of these problems can be traced back to miscommunication, lack of coordination, and the deficiency in information timeliness and accessibility (Harris and McCaffer 2013, Niu et al. 2016). Despite the stereotype that construction is a traditional industry that is notoriously slow in innovation intake and reluctant to embrace changes, technology development has become a driving force in advancing construction (Stewart et al. 2004). This is particularly true for sophisticated construction projects where the execution of tasks requires multiple interdependent actors to work synergistically in the heterogeneous and sometimes hostile environments. The industry has recently seen the continuous introduction of emerging technologies such as Auto-ID (Jaselskis and El-Misalami 2003, Lu et al. 2011, Flanagan et al. 2014), laser scanning (Tang et al. 2010), senor networks (Kawakami et al. 2008, Kolba and Collins 2006), and automated control (Louis et al. 2014, Werfel et al. 2014) to tackle the maladies in construction.

Notably, the Internet of Things (IoT), a paradigm that has been permeating into several industries such as telecommunication, automotive, healthcare, and logistics, is starting to gain traction in the construction industry. IoT allows distributed objects, which are the so called 'things' in IoT, to be sensed and interconnected across the network infrastructure, thus enabling central monitoring and control of these 'things' (Miorandi et al. 2012). Usually, when the physical 'things' are linked to the cyber world, the interactions between the physical end and the cyber end can be achieved by bi-directional information flows. The system formed by seamless integration of physical 'things' with cyber components is termed Cyber-Physical System (CPS) (Lee 2006, Tang et al. 2010). Physical 'things' in either IoT or CPS are required to have smartness or be augmented with smartness so as to 'see', 'hear', 'think' and 'perform' jobs (Miorandi et al. 2012) – thereby making them "smart objects". As a step toward smartness in the construction context, smart construction objects (SCOs) are proposed to represent the construction resources that are made 'smart' by augmenting them with sensing, processing and communication abilities (Niu et al. 2015).

Sharing similar underlying technology tools, there is an increasing overlap and merger of principles between studies on IoT, CPS and SCOs in construction. However, research exploration and applications associated with these technologies are usually proposed and tested in isolation, lacking synergy and coherence. Niu et al. (2015) claim that SCOs are able to serve as the basic component of IoT but there is no discussion of how to SCOs fit into IoT. In the context of IoT, ‘things’ have been described to operate from embedded systems to CPS (Vermesan et al. 2011). Likewise, IoT has been interpreted as “CPS connected to the Internet” in the context of Industry 4.0 (Jazdi 2014). When the three concepts are mentioned together, the similarities, differences, and possible relationships between them have not been clarified. Narrow definitions and isolated development of each of these fields are thus no longer appropriate, as they do not allow the full potential of these technologies to be realized, especially when deployed in concert. Instead, this paper argues that greater interactions and synergy could speed up research progress and facilitate practical deployment from a holistic perspective.

The primary aim of this study is to develop a deployment framework that integrates various key components of IoT, CPS, and SCOs to achieve synergy in supporting project management throughout the whole life cycle of complex construction projects. It does so by adopting a mixed methods research approach under which literature review, technological analyses, case studies, and action research are triangulated. The theoretical perspective underpinning this framework is to view project management as making an array of decisions *per se* (Flanagan and Lu, 2008) and the concepts, including IoT, CPS, and SCOs are devised to support such decisions. Similarities and differences between IoT, CPS, and SCOs are then compared and analysed. Based on the comparison, a four-layered deployment framework that integrates the three concepts is proposed, followed by application scenarios that describe potential applications. The last part of the paper discusses the contributions of the framework, and draws some conclusions.

Related works

Internet of Things (IoT)

The definition of IoT has been evolving over the years in line with its ever-changing vision. The phrase 'Internet of Things' was first coined in the 20th century by Kevin Ashton, the executive director of the Massachusetts Institute of Technology (MIT)'s Auto-ID centre within the context of the widespread use of radio frequency identification (RFID) (Atzori 2010, Sundmaeker et al. 2010). In this sense, initially, 'things' in IoT referred mainly to RFID tags or the tagged objects. With the later prevalence of sensors deployment, the 'things' in IoT have been redefined to include sensing and actuating devices that are interconnected to share information across platforms (Gubbi 2003). Compared to RFID-tagged objects, sensors and actuators expanded the sources of data types in IoT while, in turn, the corresponding applications are constrained by the types and capacities of sensors as well. By fusing the paradigm of ubiquitous computing with IoT, the concept of 'things' in IoT has been further shaped into 'smart objects' that can be any ordinary object in contemporary life with the ability to see, hear, think and perform jobs by having them 'talk' to each other, to share information and to coordinate decisions (Miorandi et al. 2012). From this perspective, RFID tags, sensors, and actuators are often listed as the means to make these 'things' smart. The shift from interconnecting computing devices to more broadly interconnecting 'things' is enabling the rethinking of conventional approaches to networking, computing and service management (Vermesan et al. 2011).

Apart from the 'things'-oriented view, the IoT concept has also been explored and elaborated from a network-oriented view (Atzori 2010). IoT is regarded as a radical evolution of the current Internet (Gubbi 2003). Sundmaeker et al. (2010) define IoT as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual 'things' have identities, physical attributes, and virtual personalities that use intelligent interfaces, and are seamlessly integrated into the information network. Compared with the traditional network of websites, physical objects constitute the network terminals of IoT. The extensively-interconnected network enables every object to participate in the service flow to make the pervasive service intelligent (Ma 2011). The significance of IoT that surpasses the previous information communications technology (ICT) systems lies in the view that IoT itself, is beyond the individual application level. Instead, as a critical and integrated infrastructure upon which applications can run, services on IoT can be scalable from personalized (such as digitizing home appliances) to city-wide, such as delay-free traffic planning schemes (Stankovic 2014). While IoT caters for the interconnection and interaction between multiple systems, hidden values of domain-specific applications can also be harvested by interacting with domain-independent services (Al-Fuqaha et al. 2015).

Cyber-Physical Systems (CPS)

CPS are engineered systems that are built from, and depend upon the seamless integration of computational algorithms and physical components (NSF, 2016). A key aspect of the CPS approach is an effective mechanism for facilitating bi-directional coordination between the cyber and physical 'twins' (Lee 2008, Anumba et al. 2010). The concept of bidirectional coordination in CPS is used to describe the two-way integration of virtual models and physical assets such that changes in one are automatically reflected in the other (Anumba et al. 2010). The importance of CPS represents both philosophical thinking and a promising direction for technological system development: to represent and interact with the world through computation, communication, and control in cyberspace (Baheti and Gill 2011). CPS has been applied to smart grids, autonomous vehicle systems, medical monitoring, process control systems, robotics systems, and automatic pilot avionics (Khaitan et al. 2014). Advances in

CPS will enable capability, adaptability, scalability, and resiliency that will far exceed the simple embedded systems that are currently available.

To explore the potential of CPS in the construction industry, Akanmu et al. (2013b) refined its definition as “a tight integration and coordination between virtual models and physical construction/constructed facility so as to enable bi-directional coordination”. Likewise, Chen at el. (2015) addressed the similar needs in their concept of bridging building information modelling (BIM) and building (BBB), which emphasizes the connection of information contained in BIM with as-built situation in the ongoing, physical building processes. In construction, bi-directional coordination enabled by CPS aims at active monitoring and control of construction activities such as building components being erected on site, or the corresponding virtual model being updated to reflect the latest status of the component. Conversely, when design and other changes are made to the virtual models, appropriate updates can be automatically sent to the relevant physical assets in real time. The feasibility and versatility of CPS has been demonstrated by several cases in construction project management (CPM). For example, by developing the system architecture and prototypes, Akanmu et al. (2013a) proposed to use CPS to actively monitor and control light fixtures from construction to building maintenance phase. Yuan et al. (2016) further explored the application of CPS to the monitoring of temporary structures, demonstrating the potential of CPS for on-site safety monitoring.

Smart Construction Objects (SCOs)

If smart objects are the basic nodes of IoT, then smart construction objects (SCOs) serve as the fundamental element for IoT application in the construction context. For SCOs, the scope of ‘things’ is narrowed down from general objects to construction resources including machinery, tools, device, materials, components, and even temporary or permanent structures (Niu et al. 2015). The concept of smart objects in IoT is developing along with their unique properties, including possessing a unique identity, data collection and storage capacity, the ability to communicate and interact with other entities, and decision-making ability (López et al. 2013). As a step towards ubiquitous computing and "smartness" in the construction context, SCOs inherit the three core properties of smart objects, namely awareness, communicativeness, and autonomy (Niu et al. 2015). Awareness denotes SCOs' ability to sense and log their real-time condition and that of the surrounding environment; Communicativeness means the ability of a SCO to output information it has obtained through its awareness; and Autonomy refers to the ability of a SCO to take self-directed action or alert people for further action based on preset rules.

SCOs have demonstrated versatility and customizability in supporting various CPM applications. By making pre-fabricated components into SCOs, Niu et al. (2016) have proposed and tested a SCO-enabled logistics and supply chain management system to facilitate decision-making, which helps to achieve process and information concurrence. As a result, more informed and prompt decisions could be made. Similarly, SCOs always demonstrated potentials to assist on-site operations (Liu et al. 2017), safety management (Niu et al. 2018), and facility management (Niu et al. 2015). While these SCOs are still providing decision-making information to human decision-makers, what makes them different from conventional construction objects is that they can communicate with each other directly. In doing so, some routine or clearly rule-based decisions can be made by SCOs autonomously without necessarily involving human decision makers in the loop (Niu et al., 2015).

Methods

To reiterate, the deployment framework is developed to serve two purposes (a) to clarify the confusions surrounding the emerging pervasive technologies such as IoTs, CPS, and SCOs; and (b) to integrate them to achieve better deployment in supporting project management throughout the whole life cycle of complex construction projects. Nevertheless, there is no readily accepted methodology for developing a framework of this kind. The authors have thus referred to various methods as described in literature to develop ‘conceptual frameworks’, e.g., McGaghie et al. (2001), and Regoniel (2015). However, they did not provide a robust methodological approach either. Based on the research experiences in the UK, the U.S., and Hong Kong, the authors finally adopted a mixed methods research, which is a methodology for conducting research that involves collecting, analyzing and integrating quantitative and qualitative research (Teddlie et al. 2011; Halcomb and Hickman 2015).

To start, a comprehensive literature review is conducted to understand the works of IoT, CPS, and SCOs, with a focus on construction related literature. Efforts are paid to analyzing their research contributions, technology tools involved, and application scenarios/project stages, with a view to understanding their similarities and differences. The literature review is triangulated with the research conducted by the authors which has been funded by various funding regimes in the U.S. and Hong Kong. As a result, a figure is developed to illustrate their similarities and differences with detailed elaborations placed in a table.

Secondly, based on the understanding, a tentative deployment framework for IoT, CPS, and SCOs in construction is developed. Drawing upon previous experience, the framework is developed in a layered structure. Great efforts are paid to determining the variables, components in each layer, and the intra- and inter-layer relationships. This step involves literature review, desktop studies, and discussion with practitioners and particularly with visionary scholars before a final yet open deployment framework is determined.

Next, based on the deployment framework, prototypes and systems are developed. The purpose is to substantiate the framework and explore its application scenarios. With the ability of the developed prototypes and systems to facilitate real-life construction project management (CPM) practices, the efforts can arouse practitioners' interest to help carry out the field studies. The authors have conducted action research studies in three complex and dynamic construction projects in Hong Kong over the past four years. These are all typical cases including machinery management, logistics and supply chain management, and dynamic project progress control, which are to be elaborated later in this study.

Certainly, this is not a linear process. Rather, the mixed methods approach is unfolded in a reiterative fashion. Triangulations of literature, theoretical debates, and CPM practices are repeated throughout the research. In the next sections of the paper, they are blended together in narratives to ensure an uninterrupted reading journey for the readers.

Similarities and differences between IoT, CPS, and SCOs

Table 1 lists the relevant studies of IoT, CPS, and SCOs in the construction literature. Referring to their definitions and the listed studies, Figure 1 demonstrates the similarities and differences among the three concepts. The confusion relating to the three concepts usually arises from the common features they share. The most obvious common point is that the applications of IoT, CPS, and SCOs rely on similar underlying technologies including identification technology such as passive and active RFID tags, sensing technology such as global positioning system (GPS) units and various environmental-factor based sensors, and communication technology such as Bluetooth, WiFi, Zigbee, and traditional wired communications. When adopting the same range of technologies, the functions supported in these applications are alike. The applications of IoT, CPS, and SCOs assist construction managers in similar tasks including real-time monitoring, comprehensive data collection and retrieval, making context-aware alerts, and supporting predictive planning.

Topic	**Citation**	**Research contributions**	**Technology tools involved / mentioned**	**Application scenarios/stages**
IoT	Kortuem et al. (2010)	The study claimed that smart objects (SO) that are made into building blocks can cooperate and form IoT.	RFID, smart-object technology	Road construction; chemical storage etc.
	Ghimire et al. (2017)	This study provided a framework for efficient project management by using IoT-based tehcnologies to reduce the time for decision-making, which was validated in a construction project scenario.	Tags, sensor networks, Programmable Logic Controller (PLC) etc.	Project management
	Park et al. (2017)	This study explores the user experience of IoT in smart home appliance in the construction industry.	ZigBee, cellular networks (3G, and 4G), Bluetooth etc.	Smart home appliance
	Zhou and Ding (2017)	This paper proposes an IoT-based safety barrier warning system to achieve a safer underground construction site.	RFID, Ultrasonic detector, Infrared access device	Safety management for underground construction
	Ding et al. (2018)	This study proposed a smart steel bridge construction framework using Building Information Modeling (BIM) and Internet of Things (IoT).	RFID, Barcode, sensing networks, cloud computing, etc.	Project managament for steel bridge construction
CPS	Zhao et al. (2010)	This study proposed a conceptual framework for a cyber physical system for energy management in building structures.	Smart meter. Smart inverter etc.	Energy management
	Akanmu and Anumba (2015)	This paper demonstrated the potential value of CPS approach in enhancing bi-directional coordination through yhe development of system architectures, scenarios and prototype systems.	RFID, UWB, laser scanner, personal data assistant (PDA), Wi-Fi, Zigbee etc.	Steel placement; light fixture monitoring and control
	Yuan et al. (2016)	This study proposed a CPS-based temporary structures monitoring (TSM) system to prevent potential failure of temporary structures.	Load cells, switch sensors, accelerometer, etc.	Temporary structure monitoring
	Zhan et al. (2018)	This study focused on using CPS in smart building for energy-efficiency by proposing a novel error correction mechanism.	Zigbee	Energy management
SCOs	Niu et al. (2015)	This study articulated the concept of SCOs and their core properties, computing applications, and representations.	RFID, Bluetooth	Safety management, facility management, etc.

	Niu et al. (2016).	This study piloted the SCOs-enabled management framework in supporting logistics and supply chain management.	GPS, GSM, Arduino etc.	Logistic and supply chain management
	Liu et al. (2017)	This study developed a SCO-based tower crane system to provide reai-time component tracking and warning in prefabrication construction.	GPS, IMU, WiFi etc.	Profabrication construticon
	Niu et al. (2018).	This study developed a OHS management system supported by SCOs that could identify and respond to dangerous situations autonomously in tower crane operations.	IMU, barometers, GPS, etc.	Safety management

Table 1. Studies on IoT, CPS, and SCOs in the construction literature

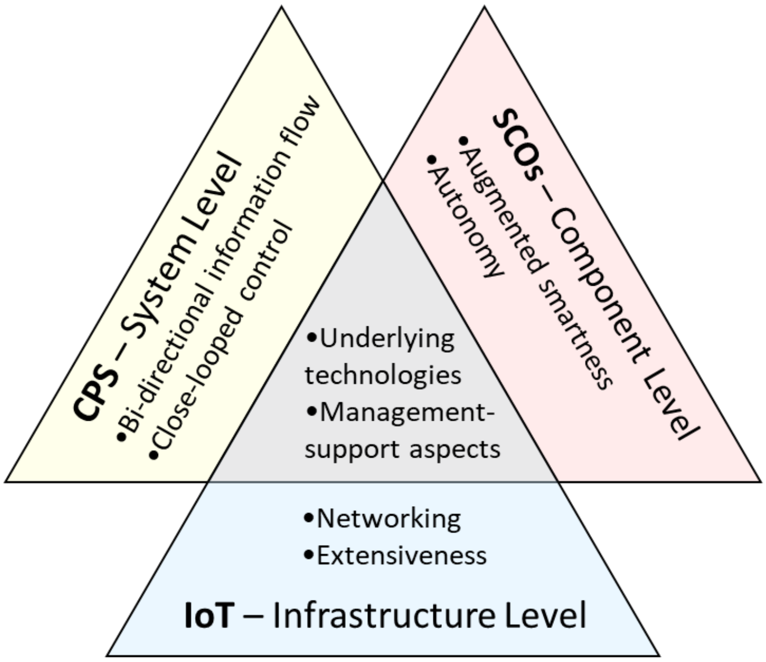


Figure 1. Similarities and differences between IoT, CPS, and SCOs

Meanwhile, the three concepts are as much different as they are similar. Fundamentally, IoT, CPS, and SCOs operate at different levels. SCOs refers to smart construction resources at the single component level. With their smartness to sense and communicate information, SCOs could serve as the physical part in CPS. Likewise, SCOs could serve as the elementary nodes in IoT. When smart objects are the basic building blocks by which IoT forms, SCOs can be regarded as the special group of smart objects in the construction context. Nevertheless, SCOs themselves, as an array of components, should not be confused with a system like CPS. CPS, literally, should be positioned on the system level. It contains not only components such as SCOs, but also computational algorithms and back-end platforms to support and control the physical components. As for IoT, it should not be seen as an individual system, but as a critical, integrated network infrastructure upon which many applications, services and systems can run (Stankovic 2014). As such, both SCOs and CPS may depend on IoT to utilize services and coordinate with each other. In addition, IoT can also host a wider range of 'things' including basic sensors and actuators.

The individual key features of IoT, CPS, and SCOs can be revealed in their distinct emphases as well. The quintessence of SCOs indwells in their customizable smartness (i.e. the three core properties that enable them to sense, communicate, compute and take actions while not compromising their original appearances and functions). In particular, the autonomy of SCOs could harness the power of artificial intelligence to take actions promptly and autonomously that equals or exceeds human intelligence with regard to specific tasks during the construction stage (e.g. to eliminate a hazard at source when a near-miss condition is detected by a SCO). The autonomy of SCOs are of help during the construction stage where the site environment is dynamic, complicated, and fragmented. In comparison, automation controls in most CPS and IoT studies focuses on the facility management stage or smart building appliance. To managing the complex on-site conditions, the intelligent capacity of 'things' in IoT and the physical component in CPS may be lower: for example, some RFID-tagged devices may not have the ability to take autonomous or reactive actions.

CPS emphasizes the bi-directional (cyber-to-physical, and physical-to-cyber) information exchange and feedback, where the back-end system should give feedback and control the physical world in addition to sensing the physical world, forming a closed-loop system. Compared with SCOs that may take rule-based actions on their own, the control and decision power in CPS largely relies on the cyber side. IoT emphasizes networking and interaction, aiming at interconnecting the miscellaneous 'things' in the physical world, which could include but are not limited to SCOs, CPS and other devices or sub-systems. Besides, IoT is characterized by the extensiveness in the quantity of devices, the type of devices, and the connection modes (Ma 2011). Compared to CPS or the SCO-enabled system, the amount of connected 'things' in IoT can sharply rise up to several billions. The devices may be connected in a wired or wireless mode, with strong state routing or statistical weak state routing in the large-scale heterogeneous network of IoT.

In summary, a closer examination of the similarities and differences between IoT, CPS, and SCOs shows that they obviously present their own strengths and fair share of weaknesses. They also present an opportunity to be integrated so that their strengths can be maximized while the weaknesses can be largely alleviated. This is particularly opportune when the three technologies are beginning to gain traction in the construction industry.

The integrated deployment framework for IoT, CPS, and SCOs in construction

A deployment framework is proposed that build on the similarities of these technologies to support their integration while preserving their individual characteristics. As shown in Figure 2, the structure of the framework is developed with reference to the basic three-layer architecture prevalent in existing studies of IoT, comprising perception layer, network layer, and application layer from a bottom-up approach (Al-Fuqaha et al. 2015). On top of the three layers, a business management layer has been proposed by Wu et al. (2010) and Khan et al. (2012) to host business models and analysis based on the received data. Similarly, a management-support layer is proposed in this integrated framework to assist management with different aspects. In addition, there have been studies proposing a processing layer (Wu et al. 2010) or information integration layer (Ma 2011) in between the network layer and the application layer to store and process data within the IoT framework. In this study, the ubiquitous data storage and process need is wrapped as cloud-computing service in the communication layer.

In addition to the IoT-based structural framework, the features of CPS and SCOs as highlighted in the box can also be revealed in the proposed framework. The virtual representations in the cyber application layer such as the BIM models or dynamic charts form the cyber parts of a CPS, whist their physical twins are the corresponding SCOs, sensors and actuators. Meanwhile, the bi-directional communication happens in the communication layer. To host the autonomy of SCOs and the actuators, a physical application dimension is added to the perception layer, making it a spectrum-like perception/application layer. Therefore, SCOs can be posited in the junction of the perception/physical application and communication layer, where its awareness, autonomy, and communicativeness are well hosted by the framework. From a holistic perspective, the four layers in the proposed framework with their functions are introduced and elaborated in detail below.

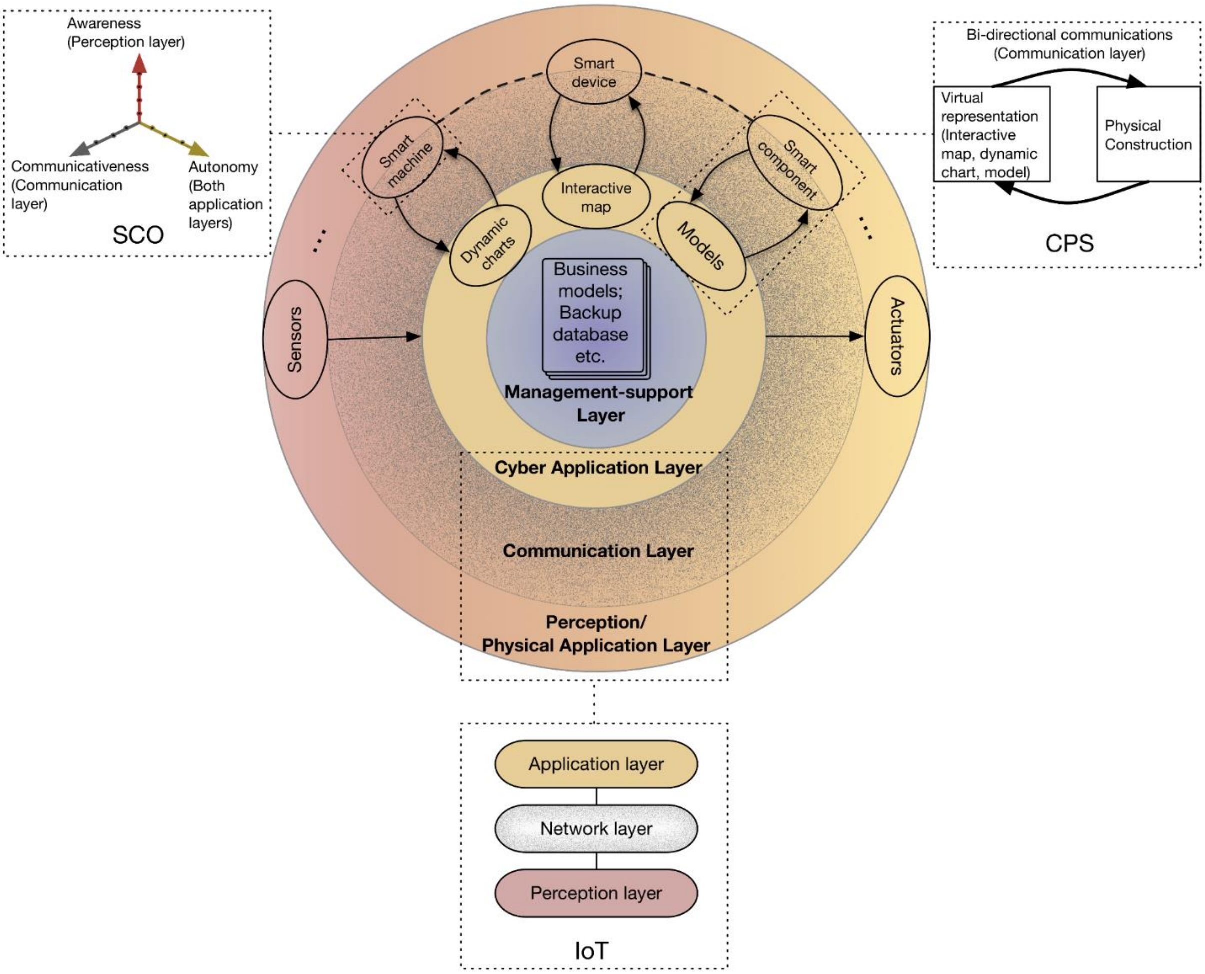


Figure 2. The deployment framework for IoT, CPS, and SCOs integration

The perception/physical action layer

The first layer, the perception/physical application layer, caters for the awareness of SCOs for capturing real-time data and autonomy of SCOs for taking reactive actions. In contrast to the perception layer in traditional IoT-based deployment framework, a physical application dimension is added, making it a spectrum-like layer that could support both perception and action-taking. Therefore, the near real-time action-taking ability of SCOs, based on the changing environment factors, can be well hosted by this layer. The reactive actions, faster and more precise than human intervention sometimes, could help prevent dangerous situations turning into accidents (Niu et al. 2018). For example, when a smart mobile crane detects that it is entering a restricted area, it could autonomously halt the motions to prevent further possible collisions.

Sensing and perception of the status of ‘things’ and their surrounding environment is the fundamental for an IoT-enabled system. The sensing ability of SCOs are augmented by embedded intelligence technology and nanotechnology. When microchip or nano-chip are embedded into existing construction objects with different types of sensors, they could collect real-time information on the progress of construction projects and real-time conditions of the environment without compromising their original functions. Besides SCOs, individual sensors and other data capture devices (e.g., laser scanners, photogrammetry devices, and human physiological status monitoring devices) should also be ensconced in the proposed framework. Pure actuators, such as control gates, warning lights, and alarm bells can be integrated on the actuators end.

The communication layer

The communication layer supports data transmission through various networks. There are three forms of data transmission. Firstly, it supports one-way data communication, including collecting data from sensors and conveying instructions to actuators. Secondly, local or regional data exchange among SCOs are supported to enable the communicativeness of SCOs. Thirdly, it bridges between the object/outer application layer and the inner application layer, supporting the bi-directional data flow between the physical objects and the associated virtual representation for CPS. The data can be transmitted through a wireless network, cable network, or the enterprise Local Area Network (LAN) by technologies including Fiber to the x (FTTx), universal mobile telecommunications system (UMTS), global system for mobile communications (GSM), WiFi , Bluetooth, Zigbee, and infrared technology.

The communication layer also stores and processes the data ubiquitously by providing the cloud computing service. The proposed framework is expected to handle big construction data that are generated over time from numerous sources at construction worksites. The data is also varied and could include activity workflows, asset inventories, as well as dynamic environmental conditions at the work sites. Due to the volume, velocity, and variety of data, traditional databases are inadequate to cater for the requirements and mobility required in the proposed deployment framework. In contrast, cloud computing bypasses the costly solution of establishing specific hardware platform at each work site. The ubiquitous storage and processing ability allows this cross-layer service to receive, deliver, exchange information over the network wire protocols. In order to coordinate numerous SCOs across the entire network, standardized communication and application interoperable protocols are needed. The Konnex (KNX) Protocol, the LonTalk Protocol, and the Building Automation and Control networks (BACnet) Protocol that have been commonly utilized to control devices for building automation especially for facility management. These protocols can be selectively adopted in the framework to coordinate the automation of SCOs across the lifecycle of building from the construction stage all the way to the maintenance stage.

The cyber application layer

While some of the applications can be executed autonomously by SCOs in the physical application layer, the cyber application layer is still an indispensable component in the proposed framework. Other than simple and rule-based actions that can be handled by the autonomy of SCOs in the physical application layer, there are always some more sophisticated decisions to be authorized by a human expert to ensure its accuracy and confidentiality, depending on the severity of the situation. In this case, decisions will be concluded in the cyber application layer and then sent back to the physical application later for appropriate actions.

The importance of the cyber application layer is also embodied in its ability to provide high-quality services to meet end-user requirements. The virtual representations of the “internet of construction things” are managed in the cyber application layer, which may have a variety of manifestations including dynamic graphs and charts, interactive maps, and 3D models such as BIM models. The form of representation is based on the services requested by end-users. For instance, data such as the current location and tracking path will be visualized in an interactive map if an end-user would like to inquire about the transportation and logistics status.

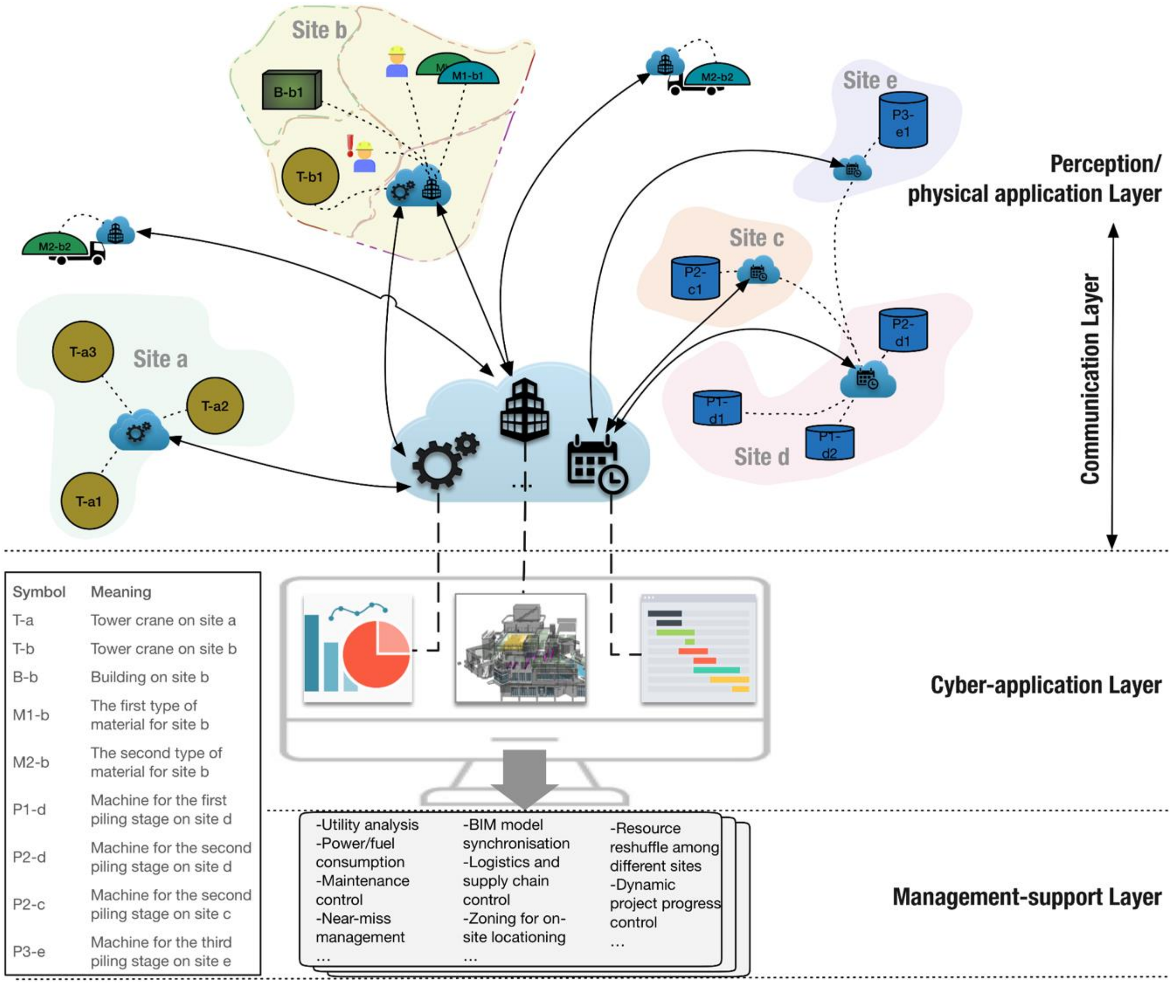
The management-support layer

On top of the applications in the cyber and physical application layers that are directly associated with project operation and management, the management-support layer provides a hub for more profound data analysis and feedbacks. Data collected from distributed sites and across timespans are compiled together for further analysis in the management-support layer. Decision-support models such as building energy models, and life-cycle assessment, risk management models, and models of corporate social responsibility etc. can be incorporated in the management-support layer to utilize the data in the system. The management-support also supports the management of the underlying three layers and the cloud computing services. System maintenance, upgrades, research and operation feedbacks are supported by this layer to ensure the service enhancement and sustainable development of the system.

The application scenarios of the proposed framework

Three example scenarios, which are frequently witnessed in CPM, are presented here to illustrate the potential of the proposed framework in practical applications. These scenarios are developed from the perspective of the main contractors, who commonly need to coordinate multiple parties including sub-contractors, suppliers, and different project teams of their own.

These scenarios, collectively shown in Figure 3, are developed to address the possibility of coordinating site-specific and cross-site machine management, organizing different prefabricated components in BIM with zone-based on-site positioning, and linking critical construction resources based on a dynamic project programme.



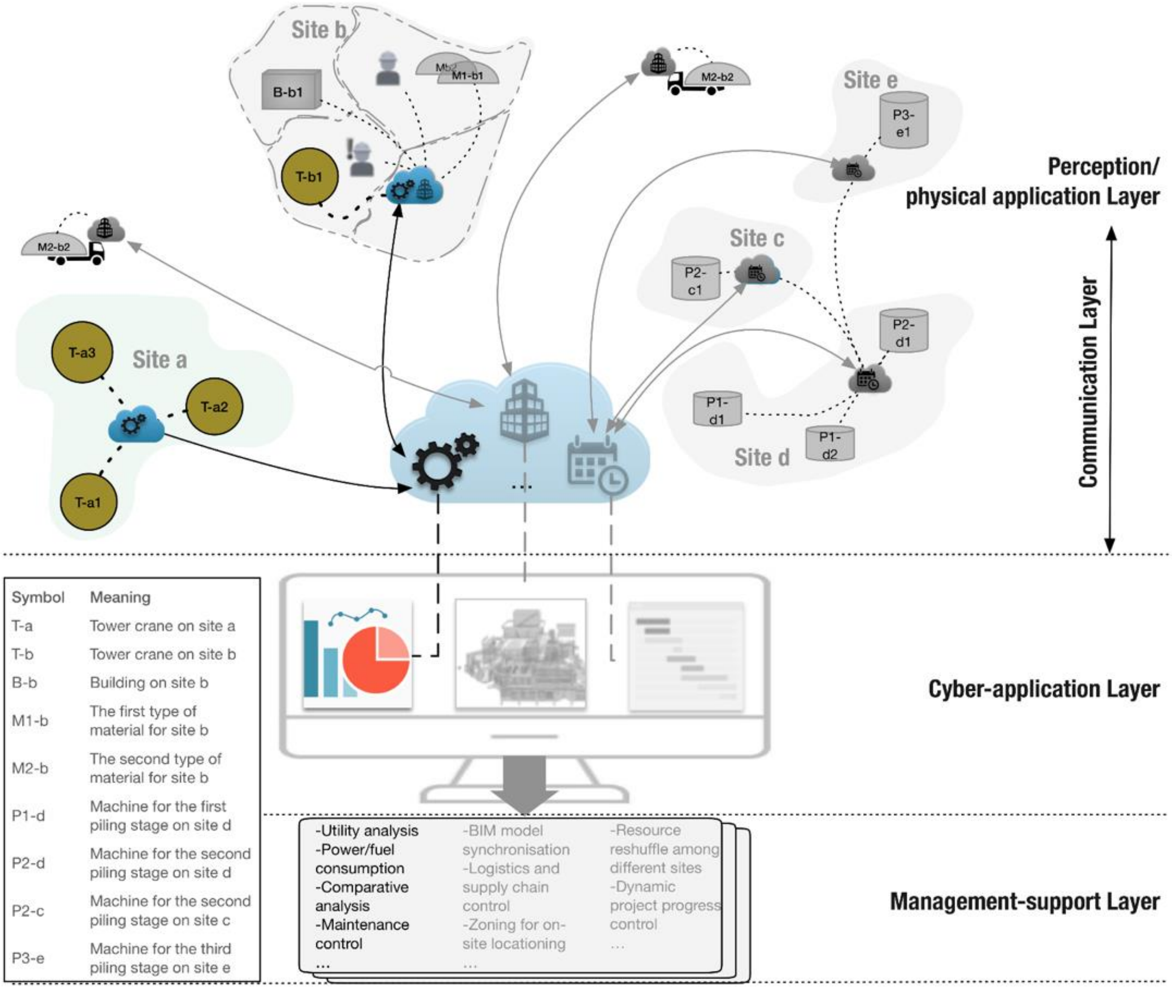
Symbol	Meaning
T-a	Tower crane on site a
T-b	Tower crane on site b
B-b	Building on site b
M1-b	The first type of material for site b
M2-b	The second type of material for site b
P1-d	Machine for the first piling stage on site d
P2-d	Machine for the second piling stage on site d
P2-c	Machine for the second piling stage on site c
P3-e	Machine for the third piling stage on site e

Figure 3. The application scenarios of the integrated framework

Scenario 1: Site-specific and cross-site machinery management

The previous study of Niu et al. (2018) has demonstrated that construction machinery such as tower cranes or excavators, when turned into a SCO, can help OHS management by detecting dangerous situations, making real-time alerts to people under hazardous situations, and taking autonomous actions to prevent accidents from happening under certain conditions. When connected to the smart management platform, the smart tower crane and the platform forms a CPS where every motion and operation of the smart tower crane is visualized and analysed to inform the management of safer and more productive operation of tower cranes (Liu et al. 2018). Similar applications of smart tower crane and the associated CPS can be hosted by the proposed framework, with the potential of providing a wider range of services when inter-connected.

In addition to the application supported by individual SCO or separated CPS, more insights can be gained from the interconnected SCOs and CPSs, either within the same sites or scattered on different sites. In the integrated framework, SCOs on the same site will be linked together to the cloud through an internet-connected mobile device or local workstation. When linked to the cloud, project personnel could use network-supported computing devices to access the cyber representations of SCOs in the cyber application layer where they could track, monitor, and control the SCOs, forming a closed-loop CPS system. For example, as highlighted in Figure 4, there are three smart tower cranes (T-a1, T-a2, and T-a3) on Site a, all connected together to the cloud. On one hand, by capturing and uploading the motion data of each smart tower crane, their working status (off, idling, on) can be monitored in real-time from the cyber application end. On the other hand, with the connection to the tower crane through the cloud, project personnel could remotely control the tower cranes without time and location constraints. Similarly, based on the idling time (which consumes power), the on and off periods can be adjusted without penalizing projects for energy-saving purposes. The data from T-a1, T-a2, and T-a3, together with data from other SCOs in the same site, could further be utilized in the management-support layer for analysis of power consumption, equipment usage patterns, and utilization rates on a site basis.



Symbol	Meaning
T-a	Tower crane on site a
T-b	Tower crane on site b
B-b	Building on site b
M1-b	The first type of material for site b
M2-b	The second type of material for site b
P1-d	Machine for the first piling stage on site d
P2-d	Machine for the second piling stage on site d
P2-c	Machine for the second piling stage on site c
P3-e	Machine for the third piling stage on site e

Figure 4. The application scenario on site-specific and cross-site machine management

Meanwhile, the same type of SCOs that are distributed on different sites will be linked together in the cloud and centrally managed in the back-end office to support comparative analysis. Similar to T-a1, T-a2, and T-a3, another smart tower crane on Site b (T-b1) in Figure 4 is also linked to the cloud. By processing the data sent back by the smart tower crane with a finite-state machine (FSM) model, six working states of each smart tower crane (idling, hoisting, slewing, hovering, installation, and resetting) can be identified and visualized in the dynamic line graphs (Liu et al. 2018). Compared to data analysis that relied on a single smart tower crane, data from an entire group of tower cranes on the IoT-based network could offer a larger sample, allow cross-site comparisons, and support more comprehensive analysis of different aspects including near-miss management, resource allocation, and productivity enhancement.

The network of the same type of SCOs also enables project personnel to centrally control the maintenance of SCOs for maximized utilization. By actively sensing and reporting the engine load, fluid temperatures and pressures, and other operational parameters of each type of SCO, their operating and maintenance cycle can be reflected on their cyber twins in real-time. Without the IoT-based network, a smart tower crane could autonomously alert people ahead of the time of breaking point. Thus, project personnel can wait for T-a1 to be maintained before putting it into usage again. In comparison, when T-a1 is incorporated into the IoT-based network, the proposed framework enables people to avoid or reduce the waiting time by pairing T-a1 with a back-up smart tower crane such ash T-a2 in case of breakdown or during maintenance. When T-a1 is approaching the time of maintenance, the work to be carried out by T-a1 can be passed on to T-a2 (as appropriate) while T-a1 is unavailable, enabling the tower cranes to be utilized at peak efficiency.

Scenario 2: Ubiquitous logistics tracking and on-site positioning

The proposed framework enables the ubiquitous locationing of construction personnel, components, machines and equipment in a dynamic manner. By making prefabricated beams into SCOs, Niu et al. (2016) demonstrated that the real-time tracking and updating of the locations of SCOs from the supplier site all the way to the construction site can be achieved with a cloud-based platform. The SCOs and the platform forms a CPS where the bi-directional information flow could improve the information accessibility, accuracy, timeliness and visibility during the logistics and supply chain management.

By applying the same principle to a web of prefabricated components required for a construction site, these components in various forms, from different suppliers, and with asynchronous delivery time can be carefully coordinated. As a simplified example highlighted in Figure 5, to construct the building B-b1on Site b, two kinds of prefabricated components (M1-b) and (M2-b) are procured from different suppliers. The real-time location of each batch of components is associated with a designated status during the entire logistics process including: *pre-shipment*, *en-route*, *arrived on site,* and *installed*. In Figure 5, the location of M1-b1 and M2-b1should be associated with the status of "arrived on site" while M1-b2 and M2-b2 should be '*en-route*'. The status information can be visualized in the BIM of B-b1 as colour changes or animations, allowing for real-time rendering of the building in progress, as well as establishment of project control.

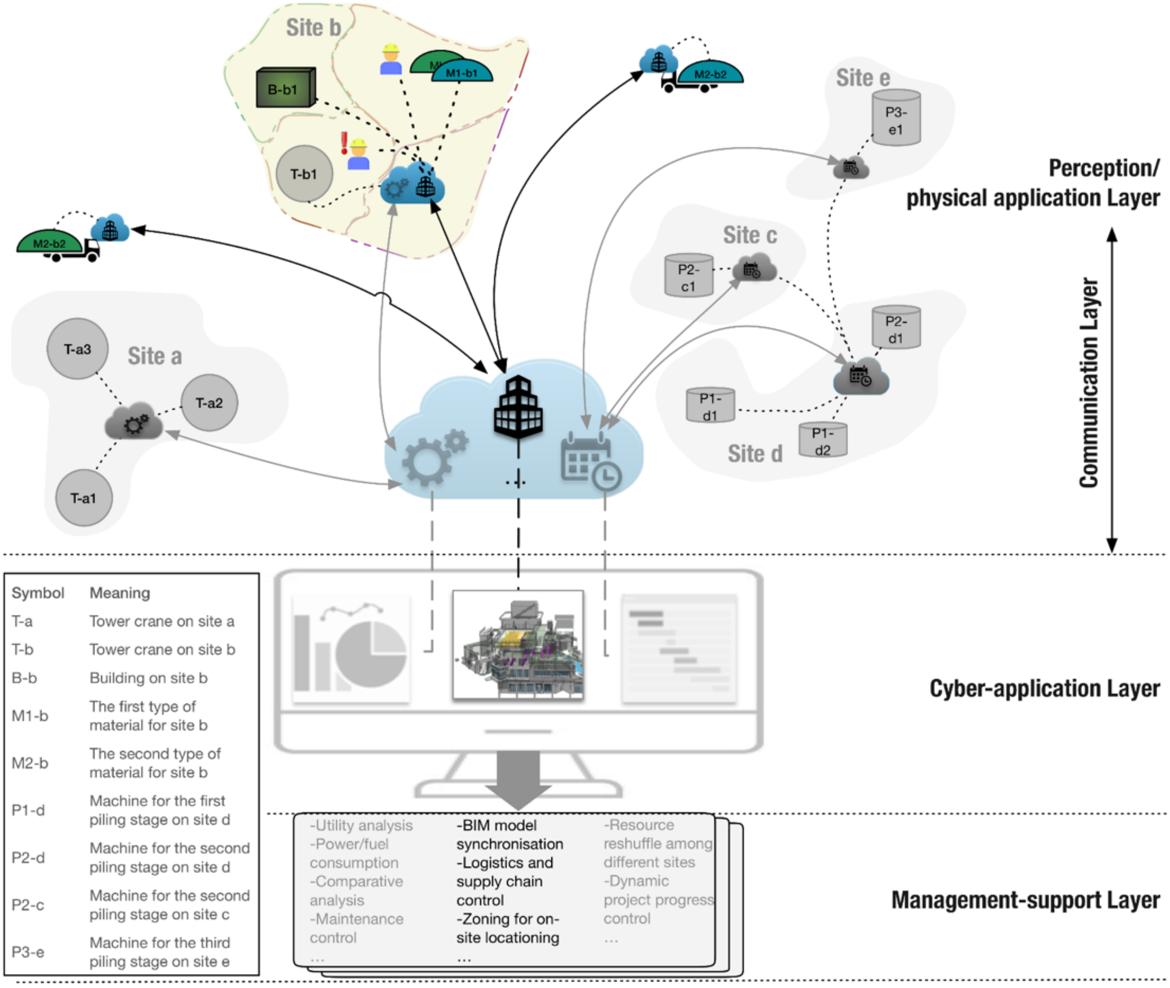


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Figure 5. The application scenario for ubiquitous logistics tracking and on-site positioning

Locating SCOs can be achieved by various tracking and positioning technologies, depending on the moving speed and range of the SCOs. For example, the en-route transportation of M1-b2 and M1-b2 are carried out by truck delivery, where they may reply on object-to-object (O2O) communication with the trucks so that the trucks could sense the real-time location by the embedded GPS sensors and update it to the cloud. For M1-b1 and M1-b2 that have entered the site gate, the more precise on-site locationing could further be assisted with RFID tags and readers or Bluetooth Low Energy (BLE) beacons. By installing the RFID readers and BLE beacons inside the infrastructure of the new buildings, in multiple secure turnstiles, and at the access points for each well-defined work zone, tagged objects can be tracked on a zoning basis (Costin et al. 2015).

By incorporating RFID, BLE, or other means of identification technologies into the IoT network, the on-site zoning could help locate key materials and personnel more efficiently. Construction sites receive miscellaneous shipments for different uses, many of which may be delivered to the wrong locations or get mixed up. By adhering identification tags to important shipments and high-value equipment, it could save time counting and looking for them in the relatively large construction sites, assisting in preventing theft and misplacement as well. Similarly, people on the construction site can be tracked on a zoning-basis when their personal protective equipment (PPE) such as safety helmet is linked into the IoT network, making it possible to warn people about entering restricted areas or dangerous zones.

Scenario 3: Ad hoc resource reshuffle for dynamic project progress control

A typical application scenario that utilizes the synergistic effects enabled by the integration of IoT, CPS, and SCOs is that the framework could support reshuffling construction resources among different project teams dynamically in line with the variances in project progress. Making a project programme is essential before the implementation of a construction project, with the sequence of tasks and recourses needed at each stage planned in advance. The sequential execution of tasks calls for high flexibility in resource arrangement and reallocation. Taking bored piling as an example, only when the holes in the subsurface have been created by a drilling machine, can the installation of the rebar-cage proceed using a crawler crane. Thus, if the crawler crane arrives at the piling site on time while the drilling machine has not finished the drilling job, the crawler crane needs to wait. Particular attention needs to be paid to machines that are small in number but highly coveted in demand, as their allocation can impose significant cost and time impacts.

Using the machine sequentially needed for bored piling as an example, Figure 6 highlights how the proposed framework could facilitate the dynamic construction resource re-shuffling between sites and projects for maximized efficiency. P1-d1 and P1-d3 represent two drilling machines used at the first stage of bored piling (such as rotary auger and vibrohammer) on Site d. When made into SCOs, their working status are synchronized to the cloud just like the smart tower cranes explained in the first scenario. Besides, as indicated in the project programme, they are also linked with the machine needed for the second stage of bored piling, which can be P2-d1 on Site d or P3-c1 on Site c. If P1-d1 and P1-d3 are originally linked with P2-d1but P2-d1 gets delayed in the working process, the priority of P2-d1 in the linkage would be decreased. Once the priority of P2-c1 outweighs that of P2-d1, with their availability and cost of transportation from Site c to Site d considered, P1-d1 and P1-d3 would automatically be linked with P2-c1 instead. The same practice could apply to the linkage between P2 and P3 as well, as long as they follow a strict execution sequence. When all the SCOs are connected in the cloud-based IoT network, the ad hoc adjustment for the sequential linkage between machines and other resources can be instantly visualized in the project programme diagram. In case there is not enough machine or materials to cope with the updated programme, the need becomes more clear and evident by deploying this framework, thus supporting the formulation of future renting or buying strategies.

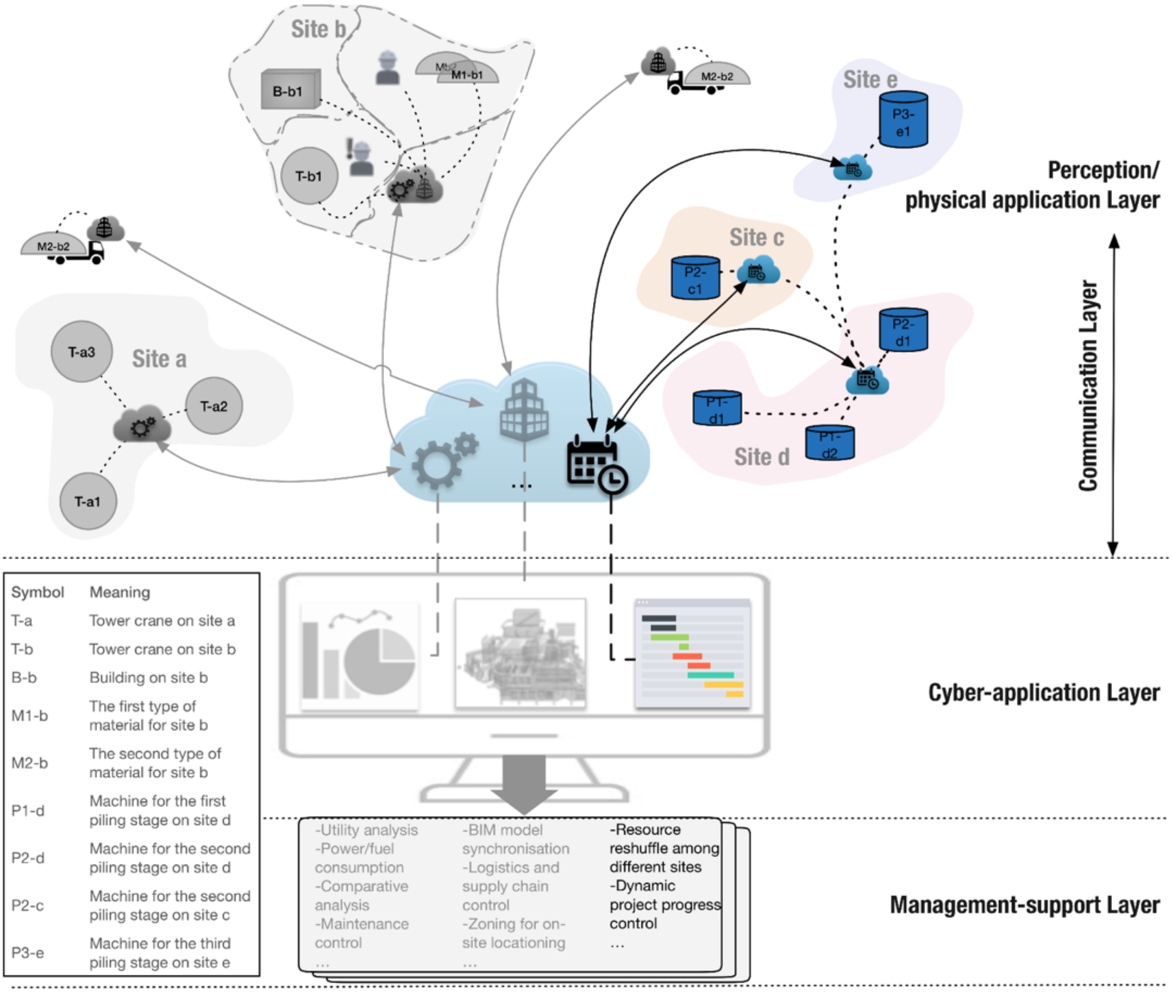

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Figure 6. The application scenario on dynamic resource reshuffle within a portfolio

Discussion

This study contributes to the body of knowledge by firstly clarifying the similarities and differences between IoT, CPS, and SCOs applied to the construction industry. A systematic review and comparison of the three concepts was lacking prior to this study. Repetitive explorations and synonyms have been misused due to the inexplicit relationships between them. Since the concept of IoT, CPS and SCOs share several common features, studies in the construction context that address them either individually or together may give rise to confusion. For example, the SCO-enabled management system is actually a CPS in essence. To this end, proposing the framework to integrate the concept of IoT, CPS and SCOs serves to clarify their differences and similarities, and to elucidate the intertwined terms. Based on the proposed framework, theoretical studies and practical applications of IoT, CPS, and SCOs could identify their corresponding scopes and emphasis, as well as their possible relationships with each other.

More importantly, the value of synergistic effects in supporting CPM is demonstrated by the proposed framework, which overcomes the limitations associated with the isolated development of IoT, CPS, or SCOs. For one thing, most existing studies on IoT in construction are still ‘internet of sensors’. Most of them rely on passive identification tags or simple sensors, mainly used for data collection with only a few actual ‘smart things’. Integrating SCOs into the studies of IoT enhances the level of smartness for the ‘things’ in IoT, while the integration of CPS reinforces the monitoring and control of these smart ‘things’. For another, existing applications on SCOs and CPSs are largely constrained by the scale, scope, and limited interoperability. For the empirical test of each case, the system framework with the hardware and software support needs to be designed and prepared from scratch. With the similar underlying technologies, the system structure, the supporting facilities, and the management-support service can actually be shared either at trial stage or when put into practical operation, enhancing the inter-connectivity and interoperability when a new device or system is added.

The integration of IoT, CPS, and SCOs also represents an important opportunity for implementing data-driven research studies and practical analysis. Using SCOs for data collection ensures the least interruption to existing construction processes, as less intrusive sensing devices will be introduced into construction sites if the existing construction objects are augmented with the sensing abilities. With the cyber representation of SCOs supported in each CPS, the managing of each SCOs and the collected data becomes accessible at the computer-end, ensuring the timeliness of the captured data. Given the inter-connected network support provided by the IoT to capture, store, process, and analyse large amounts of real-time data, the integrated framework can support data mining or even big data analysis for hidden patterns, unknown correlations and other useful information to facilitate better business prediction and decision-making.

When the three example application scenarios demonstrates the potential value of the deployment framework in assisting CPM mainly in the construction stage, SCOs that have been augmented with smartness and installed during the construction stage can be passed to the next stage to enhance facility management (FM). Especially for construction components that are made into SCOs, such as the prefabricated components and the heating ventilation and air conditioning (HAVC) devices, the awareness, communicativeness and autonomy could keep operating throughout facility's operations and maintenance phase of the structure to assist facility management. In this sense, the deployment framework has the potential value to the entire lifecycle management to accommodate various aspects of a construction resource and activities.

Conclusions

Managing complex and dynamic construction projects calls for technological assistance in coordinating the diverse and distributed construction resources and people at a massive scale. To respond to this call, many technologies including internet of things (IoT), cyber-physical systems (CPS), and smart construction objects (SCOs) are starting to gain traction in construction. By clarifying the similarities and differences between these concepts, this study sought to synergize them to serve construction project management (CPM) better than they can do in isolation. It was discovered that although the three technological instruments focus on different levels of analysis, they share common traits (such as sensing, identification, communication and auto-control technologies) for similar managerial challenges including real-time monitoring, comprehensive data collection and retrieval, making context-sensitive alerts, and supporting predictive planning. Each of the technological instruments has its own strengths (to be maximized) and weaknesses (to be mitigated) and these can be done by integrating them in a more synergic manner.

This study also developed a generic framework that integrates IoT, CPS, and SCOs for CPM. Four layers with appropriate technological tools are proposed in the framework to cope with the structure frame of an IoT network, the bi-directional communication required by CPS, and the three core properties of SCOs. In line with the proposed framework, example scenarios were presented to illustrate the potential benefits of integrating IoT, CPS, and SCOs in CPM. This study also demonstrated the versatility of the framework to cater for various needs in CPM. The proposed framework is also compatible with other research studies on data mining and big data analysis.

The main contribution of this study is twofold: (a) streamlined the three popular, yet easy-to-confuse conceptual ideas, namely, IoT, CPS, and SCO in the context of construction; and (b) integrated them into a generic, yet operable framework that can facilitate CPM. Certainly, the longevity of such frameworks lie in the extent to which they are adopted in industry practice. Future research is encouraged to turn the framework into real-life systems to facilitate real-life CPM practice, and empirically examine the synergistic effects of IoT, CPS, and SCO integration. The theoretical foundation of the framework can also be enriched with practical cases.

Data Availability Statement

No data were generated or analysed during this study.

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Reference

Akanmu, A., Anumba, C., and Messner, J. (2013a). Active monitoring and control of light fixtures during building construction and operation: cyber-physical systems approach. Journal of Architectural Engineering, 20(2), 04013008.

Akanmu, A., Anumba, C., and Messner, J. (2013b). Scenarios for cyber-physical systems integration in construction. Journal of Information Technology in Construction (ITcon), 18(12), 240-260.

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., and Ayyash, M. (2015). Internet of things: A survey on enabling technologies, protocols, and applications. IEEE Communications Surveys and Tutorials, 17(4), 2347-2376.

Anumba, C. J., Akanmu, A., and Messner, J. (2010). Towards a cyber-physical systems approach to construction. In *Construction Research Congress 2010: Innovation for Reshaping Construction Practice*, 528-537.

Atzori, L., Iera, A., and Morabito, G. (2010). The internet of things: A survey. Computer Networks, 54(15), 2787-2805.

Baheti, R., and Gill, H. (2011). Cyber-physical systems. The impact of control technology, 12, 161-166.

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.

Costin, A. M., Teizer, J., and Schoner, B. (2015). RFID and BIM-enabled worker location tracking to support real-time building protocol and data visualization. Journal of Information Technology in Construction (ITcon), 20(29), 495-517.

Ding, K., Shi, H., Hui, J., Liu, Y., Zhu, B., Zhang, F., and Cao, W. (2018). Smart steel bridge construction enabled by BIM and Internet of Things in industry 4.0: A framework. In Networking, Sensing and Control (ICNSC), *2018 IEEE 15th International Conference on (pp. 1-5)*. IEEE.

Flanagan, R., Jewell, C., Lu, W., and Pekericli, K. (2014). *Auto-ID — Bridging the Physical and the Digital on Construction Projects*. Chartered Institute of Building.

Flanagan, R., and Lu, W. (2008). “Making informed decisions in product-service systems.” Paper presented at the IMechE Conference, Knowledge and Information Management Through-Life, Institute of Mechanical Engineers, London.

Ghimire, S., Luis-Ferreira, F., Nodehi, T., and Jardim-Goncalves, R. (2017). IoT based situational awareness framework for real-time project management. International Journal of Computer Integrated Manufacturing, 30(1), 74-83.

Gubbi, J., Buyya, R., Marusic, S., and Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. Future generation computer systems, 29(7), 1645-1660.

Halcomb, E. and Hickman, L. (2015). Mixed methods research. *Nursing Standard: promoting excellence in nursing care*, 29 (32), 41-47.

Harris, F., and McCaffer, R. (2013). *Modern construction management.* John Wiley & Sons.

Jaselskis, E. J., and El-Misalami, T. (2003). Implementing radio frequency identification in the construction process. Journal of Construction Engineering and Management, 129(6), 680-688.

Jazdi, N. (2014). Cyber physical systems in the context of Industry 4.0. In *Automation, Quality and Testing, Robotics, 2014 IEEE International Conference* on (pp. 1-4). IEEE.

Kawakami, T., Ly, B. L. N., Takeuchi, S., Teranishi, Y., Harumoto, K., and Nishio, S. (2008). Distributed sensor information management architecture based on semantic analysis of sensing data. SAINT 2008, 353-356.

Khaitan, S.K., McCalley, J.D., and Liu, C.C. (2015). Cyber Physical Systems Approach to Smart Electric Power Grid.

Khan, R., Khan, S. U., Zaheer, R., and Khan, S. (2012). Future internet: the internet of things architecture, possible applications and key challenges. In Frontiers of Information Technology (FIT), 2012 10th International Conference on (pp. 257-260). IEEE.

Kolba, M. P., and Collins, L. M. (2006). “Information-theoretic sensor management for multimodal sensing.” Paper presented at the IEEE International Conference on the Geoscience and Remote Sensing Symposium, 2006. 3935-3938.

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

Lee, E. A. (2006). “Cyber-physical systems - are computing foundations adequate?.” Position Paper for NSF Workshop On Cyber-Physical Systems: Research Motivation, Techniques and Roadmap, 2006.

Lee, E. A. (2008). Cyber physical systems: Design challenges. In Object oriented real-time distributed computing (isorc), 2008 11th IEEE International Symposium on (363-369). IEEE.

Liu, D. D., Lu, W. S., Niu, Y. H., Xue, F., and Chen, K. (2018). Bridging the Cyber and Physical Systems for Better Construction: A Case Study of Construction Machinery Monitoring and Utilization. In *Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate* (393-399). Springer, Singapore.

López, T. S., Ranasinghe, D. C., Patkai, B., and McFarlane, D. (2011). Taxonomy, technology and applications of smart objects. Information Systems Frontiers, 13(2), 281-300.

Louis, J., Dunston, P., Martinez, J., and West, S. M. D. (2014). Automating construction operations using discrete event simulation models. In Construction Research Congress 2014, 1043-1052.

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.

Ma, H. D. (2011). Internet of things: Objectives and scientific challenges. Journal of Computer Science and Technology, 26(6), 919-924.

McGaghie, W. C., Bordage, G., and Shea, J. A. (2001). Problem statement, conceptual framework, and research question. Academic Medicine, 76(9), 923-924.

Miorandi, D., Sicari, S., De Pellegrini, F., and Chlamtac, I. (2012). Internet of things: Vision, applications and research challenges. Ad hoc Networks, 10(7), 1497-1516.

National Science Foundation (2016). Cyber-Physical Systems (CPS). https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503286.

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.

Niu, Y., Lu, W., Liu, D., Chen, K., Anumba, C., and Huang, G. G. (2016). An SCO-Enabled Logistics and Supply Chain–Management System in Construction. Journal of Construction Engineering and Management, 143(3), 04016103.

Niu, Y., Lu, W., Xue, F., Liu, D., Chen, K., Fang, D., and Anumba, C. (2018). Towards the "third wave": An SCO-enabled occupational health and safety management system for construction. Safety Science, in press.

Park, E., Cho, Y., Han, J., and Kwon, S. J. (2017). Comprehensive approaches to user acceptance of Internet of Things in a smart home environment. IEEE Internet of Things Journal, 4(6), 2342-2350.

Regoniel, P. (2015). Conceptual framework: A step by step guide on how to make one. Retrieved from SimplyEducate. http://simplyeducate.me/2015/01/05/conceptual-framework-guide. (Date of access: 03/09/2018)

Stankovic, J. A. (2014). Research directions for the internet of things. IEEE Internet of Things Journal, 1(1), 3-9.

Stewart, R. A., Mohamed, S., and Marosszeky, M. (2004). An empirical investigation into the link between information technology implementation barriers and coping strategies in the Australian construction industry. *Construction Innovation*, 4(3), 155-171.

Sundmaeker, H., Guillemin, P., Friess, P., and Woelfflé, S. (2010). Vision and challenges for realising the Internet of Things. Cluster of European Research Projects on the Internet of Things, European Commision, 3(3), 34-36.

Tang, P., Huber, D., Akinci, B., Lipman, R., and Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. Automation in Construction, 19(7), 829-843.

Tang, L., Yu, X., Kim, S., Han, J., Hung, C., and Peng, W. (2010). Tru-Alarm: Trustworthiness Analysis of Sensor Networks in Cyber-Physical System. In Proc. ICDM, 2010.

Teddlie, C., and Tashakkori, A. (2011). Mixed methods research. The Sage handbook of qualitative research, 285-300.

Vermesan, O., Friess, P., Guillemin, P., Gusmeroli, S., Sundmaeker, H., Bassi, A., ... and Doody, P. (2011). Internet of things strategic research roadmap. Internet of Things-Global Technological and Societal Trends, 1(2011), 9-52.

Werfel, J., Petersen, K., and Nagpal, R. (2014). Designing collective behavior in a termite-inspired robot construction team. Science, 343(6172), 754-758.

Wu, M., Lu, T. J., Ling, F. Y., Sun, J., and Du, H. Y. (2010). Research on the architecture of Internet of things. In Advanced Computer Theory and Engineering (ICACTE), 2010 3rd International Conference on (5, V5-484). IEEE.

Yuan, X., Anumba, C. J., and Parfitt, M. K. (2016). Cyber-physical systems for temporary structure monitoring. Automation in Construction, 66, 1-14.

Zhan, M., Wu, J., Wen, H., & Zhang, P. (2018). A Novel Error Correction Mechanism for Energy-Efficient Cyber-Physical Systems in Smart Building. *IEEE Access*.

Zhao, P., Simões, M. G., and Suryanarayanan, S. (2010). A conceptual scheme for cyber-physical systems based energy management in building structures. In Industry Applications (INDUSCON), *2010 9th IEEE/IAS International Conference on (pp. 1-6)*. IEEE.

Zhou, C., and Ding, L. Y. (2017). Safety barrier warning system for underground construction sites using Internet-of-Things technologies. Automation in Construction, 83, 372-389.