Taxonomy and Deployment Framework for Emerging Pervasive Technologies in Construction Projects

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Abstract: Managing complex and dynamic construction projects is challenging because 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 the internet of things (IoT), cyber-physical systems (CPS), and smart construction objects (SCOs), have been explored in construction. Amid the increasing overlap and merger of principles among these three pervasive technologies, narrow definitions and isolated development of each field are no longer appropriate. Therefore, this study proposes a deployment framework that integrates IoT, CPS, and SCOs to achieve greater synergy that can expedite their holistic implementation. It adopted a mixed-methods approach with a literature review, technological analyses, case studies, and action research at the core. This deployment framework encompassed the key components of each technology (i.e., the three core properties of SCOs, the bidirectional information flow in CPS, and the extensiveness of devices and networking in IoT) in an interconnected structure while enabling the uniqueness of each technology to be evident. Example application scenarios were 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 of the synergistic effects of IoT, CPS, and SCOs, enriched with practical cases to facilitate construction project management. **DOI: 10.1061/(ASCE)CO.1943-7862.0001653.**

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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 workerpower, materials, and machinery, are usually diverse and scattered across locations and timespans. During the course of a construction project, occurrences such as misallocated 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 deficiency in information timeliness and accessibility (Harris and McCaffer 2013; Niu et al. 2017). Despite the stereotype that construction is a traditional industry that is notoriously slow to innovate 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 in which the execution of tasks requires multiple interdependent actors to work synergistically in 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. 2010a), sensor networks (Kawakami et al. 2008; Kolba and Collins 2006), and automated control (Louis et al. 2014; Werfel et al. 2014) to address the maladies in construction.

Notably, the internet of things (IoT), a paradigm that has permeated 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 physical things are linked to the cyber world, the interactions between the physical end and the cyber end can be achieved by bidirectional 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. 2010b). 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 (SOs). 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 of 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) claimed that SCOs are able to serve as the basic component of IoT but did not discuss how 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

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(Jazdi 2014). When the three concepts have been 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, because 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 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 a 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 analyzed. Based on the comparison, a four-layer 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

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 twentieth century by Kevin Ashton, the executive director of the Massachusetts Institute of Technology (MIT)'s Auto-ID center within the context of the widespread use of radio frequency identification (RFID) (Atzori et al. 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 sensor deployment, the things in IoT were redefined to include sensing and actuating devices that are interconnected to share information across platforms (Gubbi et al. 2013). Compared with RFID-tagged objects, sensors and actuators expand the sources of data types in IoT while, in turn, the corresponding applications are constrained by the types and capacities of sensors. 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 also has been explored and elaborated from a network-oriented view (Atzori et al. 2010). IoT is regarded as a radical evolution of the current Internet (Gubbi et al. 2013). Sundmaeker et al. (2010) defined IoT as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols in which 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 the personal, such as digitizing home appliances, to citywide, such as delay-free traffic planning schemes (Stankovic 2014). Although IoT caters to the interconnection and interaction of 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 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 bidirectional 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. 2015). 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 et al. (2015) addressed the similar needs in their concept of bridging building information modeling (BIM) and building (BBB), which emphasizes the connection of information contained in BIM with as-built situations in the ongoing, physical building processes. In construction, bidirectional 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 using CPS to actively monitor and control light fixtures from the construction to building maintenance phases. 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

If smart objects are the basic nodes of IoT, then smart construction objects serve as the fundamental elements for IoT application in the construction context. For SCOs, the scope of things is narrowed 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. 2011). As a step toward 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 prefabricated components into SCOs, Niu et al. (2017) proposed and tested a SCO-enabled logistics and supply chain management system to facilitate decision-making, which helped achieve process and information concurrence. As a result, more-informed and prompt decisions could be made. Similarly, SCOs have demonstrated the potential to assist on-site operations (Liu et al. 2018), safety management (Niu et al. 2019), and facility management (FM) (Niu et al. 2015). Although these SCOs still provide 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

The deployment framework was developed to serve two purposes: (1) to clarify the confusion surrounding the emerging pervasive technologies such as IoTs, CPS, and SCOs; and (2) to integrate them to achieve better deployment in supporting project management throughout the whole life-cycle of complex construction projects. There is no readily accepted methodology for developing a framework of this kind. The authors thus referred to various methods as described in the literature to develop conceptual frameworks, e.g., McGaghie et al. (2001) and Regoniel (2015). However, those studies did not provide a robust methodological approach, either. Based on research in the United Kingdom, the United States, 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 and Tashakkori 2011; Halcomb and Hickman 2015).

To start, a comprehensive literature review was conducted to understand the works of IoT, CPS, and SCOs, with a focus on construction-related literature. Research contributions, technology tools involved, and application scenarios/project stages were analyzed in order to understand their similarities and differences. The literature review was triangulated with research conducted by the authors which was funded by various funding regimes in the United States and Hong Kong. As a result, a figure was developed to illustrate their similarities and differences.

Secondly, based on the understanding, a tentative deployment framework for IoT, CPS, and SCOs in construction was developed. Drawing upon previous experience, the framework was developed in a layered structure. The variables, components in each layer, and the intralayer and interlayer relationships were determined. This step involved a literature review, desktop studies, and discussion with practitioners and particularly with visionary scholars before a final yet open deployment framework was determined.

Next, based on the deployment framework, prototypes and systems were developed. The purpose was 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 field studies. The authors conducted action research studies in three complex and dynamic construction projects in Hong Kong over the past four years. These were all typical cases including machinery management, logistics and supply chain management, and dynamic project progress control, which are elaborated subsequently in this study.

Certainly, this was not a linear process. Rather, the mixed-methods approach unfolded in a reiterative fashion. Triangulations of literature, theoretical debates, and CPM practices were repeated throughout the research.

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, Fig. 1 demonstrates the similarities and differences of 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.

However, the three concepts are as 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 can serve as the physical part of CPS. Likewise, SCOs can serve as the elementary nodes in IoT. Whereas smart objects are the basic building blocks of IoT, 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 such as CPS. CPS 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. IoT 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 lies in their customizable smartness (i.e., the three core

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Table 1. Research studies relating to IoT, CPS, and SCOs in construction industry

Topic	Citation	Research contributions	Technology tools involved/mentioned	Application scenarios/stages
IoT	Kortuem et al. (2010)	Claimed that smart objects that are made into building blocks can cooperate and form IoT.	RFID, smart-object technology	Road construction, chemical storage, and so forth
	Ghimire et al. (2017)	Provided a framework for efficient project management by using IoT-based technologies to reduce the time for decision-making, which was validated in a construction project scenario.	Tags, sensor networks, programmable logic controller (PLC), and so forth	Project management
	Park et al. (2017)	Explored the user experience of IoT in smart home appliance in the construction industry.	ZigBee, cellular networks (3G and 4G), Bluetooth, and so forth	Smart home appliance
	Zhou and Ding (2017)	Proposed 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)	Proposed a smart steel bridge construction framework using BIM and IoT.	RFID, barcode, sensing networks, cloud computing, and so forth	Project management for steel bridge construction
CPS	Zhao et al. (2010)	Proposed a conceptual framework for a CPS for energy management in building structures.	Smart meter. Smart inverter, and so forth	Energy management
	Akanmu et al. (2013b)	Demonstrated the potential value of CPS approach in enhancing bidirectional coordination through the development of system architectures, scenarios and prototype systems.	RFID, UWB, laser scanner, personal data assistant (PDA), WiFi, Zigbee, and so forth	Steel placement, light fixture monitoring and control
	Yuan et al. (2016)	Proposed a CPS-based temporary structures monitoring (TSM) system to prevent potential failure of temporary structures.	Load cells, switch sensors, accelerometer, and so forth	Temporary structure monitoring
	Zhan et al. (2018)	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)	Articulated the concept of SCOs and their core properties, computing applications, and representations.	RFID, Bluetooth	Safety management, facility management, and so forth
	Niu et al. (2017).	Piloted the SCO-enabled management framework in supporting logistics and supply chain management.	GPS, GSM, Arduino, and so forth	Logistic and supply chain management
	Liu et al. (2018)	Developed a SCO-based tower crane system to provide real-time component tracking and warning in prefabrication construction.	GPS, inertial measurement unit (IMU), WiFi, and so forth	Prefabrication construction
	Niu et al. (2019).	Developed an OHS management system supported by SCOs that can identify and respond to dangerous situations autonomously in tower crane operations.	IMU, barometers, GPS, and so forth	Safety management

Note: OHS = occupational health and safety.

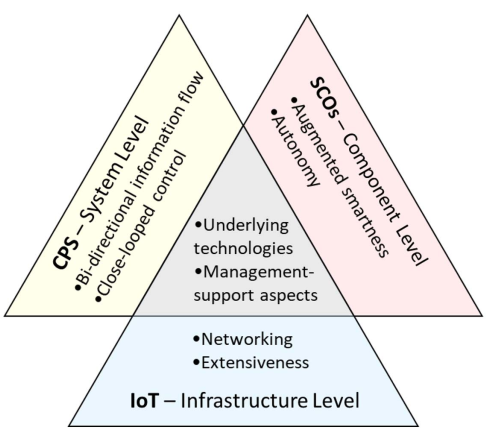

Fig. 1. Similarities and differences between IoT, CPS, and SCOs.

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 the source when a near-miss condition is detected by a SCO). The autonomy of SCOs is of help during the construction stage, when the site environment is dynamic, complicated, and fragmented. In comparison, automation controls in most CPS and IoT studies focus on the facility management stage or smart building appliances. To manage 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 bidirectional (cyber-to-physical, and physical-to-cyber) information exchange and feedback, in which 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, which 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 subsystems. Furthermore, IoT is characterized by the extensiveness of the quantity of devices, the type of devices, and the connection modes (Ma 2011). Compared with CPS or SCO-enabled systems, the number of connected things in IoT can sharply increase, up to several billion. The devices may be connected in wired or wireless modes, 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 and the weaknesses can be largely alleviated. This is particularly opportune when the three technologies are beginning to gain traction in the construction industry.

Integrated Deployment Framework for IoT, CPS, and SCOs in Construction

A deployment framework is proposed that builds on the similarities of these technologies to support their integration while preserving their individual characteristics. The structure of the framework is developed with reference to the basic three-layer architecture prevalent in existing studies of IoT, comprising a perception layer, a network layer, and an application layer in a bottom-up approach (Fig. 2) (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) 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 included as a cloud-computing service in the communication layer.

In addition to the IoT-based structural framework, the proposed framework includes the features of CPS and SCOs. The virtual representations in the cyber application layer are elements such as BIM models or dynamic charts form the cyber parts of a CPS, whereas their physical twins are the corresponding SCOs, sensors, and actuators. The bidirectional 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 spectrumlike 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 and their functions are introduced and elaborated in the rest of this section.

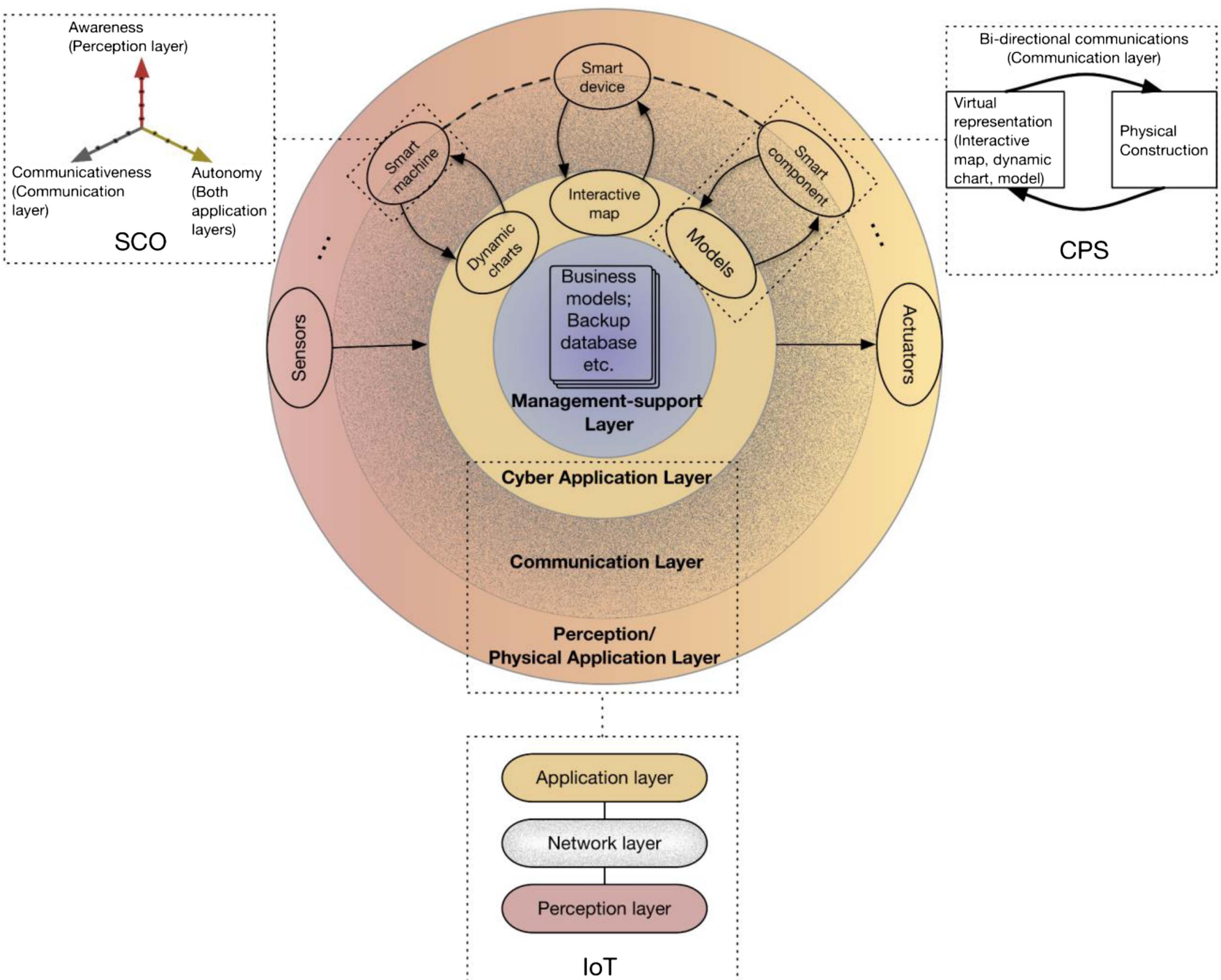

Fig. 2. Deployment framework for IoT, CPS, and SCO integration.

Perception/Physical Action Layer

The first layer, the perception/physical application layer, caters to the awareness of SCOs for capturing real-time data and autonomy of SCOs for taking reactive actions. In contrast to the perception layer in a traditional IoT-based deployment framework, a physical application dimension is added, making it a spectrumlike layer that can 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, which sometimes are faster and more precise than human intervention, could help prevent dangerous situations turning into accidents (Niu et al. 2019). For example, when a smart mobile crane detects that it is entering a restricted area, it could autonomously halt the motion to prevent possible collisions.

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

Communication Layer

The communication layer supports data transmission through various networks. There are three forms of data transmission. Firstly, this layer supports one-way data communication, including collecting data from sensors and conveying instructions to actuators. Secondly, local or regional data exchange among SCOs is supported to enable the communicativeness of SCOs. Thirdly, it bridges the object/outer application layer and the inner application layer, supporting the bidirectional 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 a 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 are also varied and could include activity workflows, asset inventories, and dynamic environmental conditions at the work sites. Due to the volume, velocity, and variety of data, traditional databases are inadequate 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, and 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, such as 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 the building from the construction stage all the way to the maintenance stage.

Cyber Application Layer

Although some of the applications can be executed autonomously by SCOs in the physical application layer, the cyber application layer is still an indispensable component of 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 more-sophisticated decisions that need to be authorized by a human expert to ensure 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 inquires about the transportation and logistics status.

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 feedback. Data collected from distributed sites and across timespans are compiled for further analysis in the management-support layer. Decision-support models such as building energy models, and life-cycle assessment, risk management models, models of corporate social responsibility, and so forth can be incorporated in the management-support layer to utilize the data in the system. The management-support layer also supports the management of the underlying three layers and the cloud computing services. System maintenance, upgrades, research, and operation feedback are supported by this layer to ensure the service enhancement and sustainable development of the system.

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 were developed from the perspective of the main contractors, who commonly need to coordinate multiple parties, including subcontractors, suppliers, and different project teams of their own. These scenarios (Fig. 3) were 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 program.

Scenario 1: Site-Specific and Cross-Site Machinery Management

Niu et al. (2019) demonstrated that construction machinery such as tower cranes or excavators, when turned into SCOs, can help

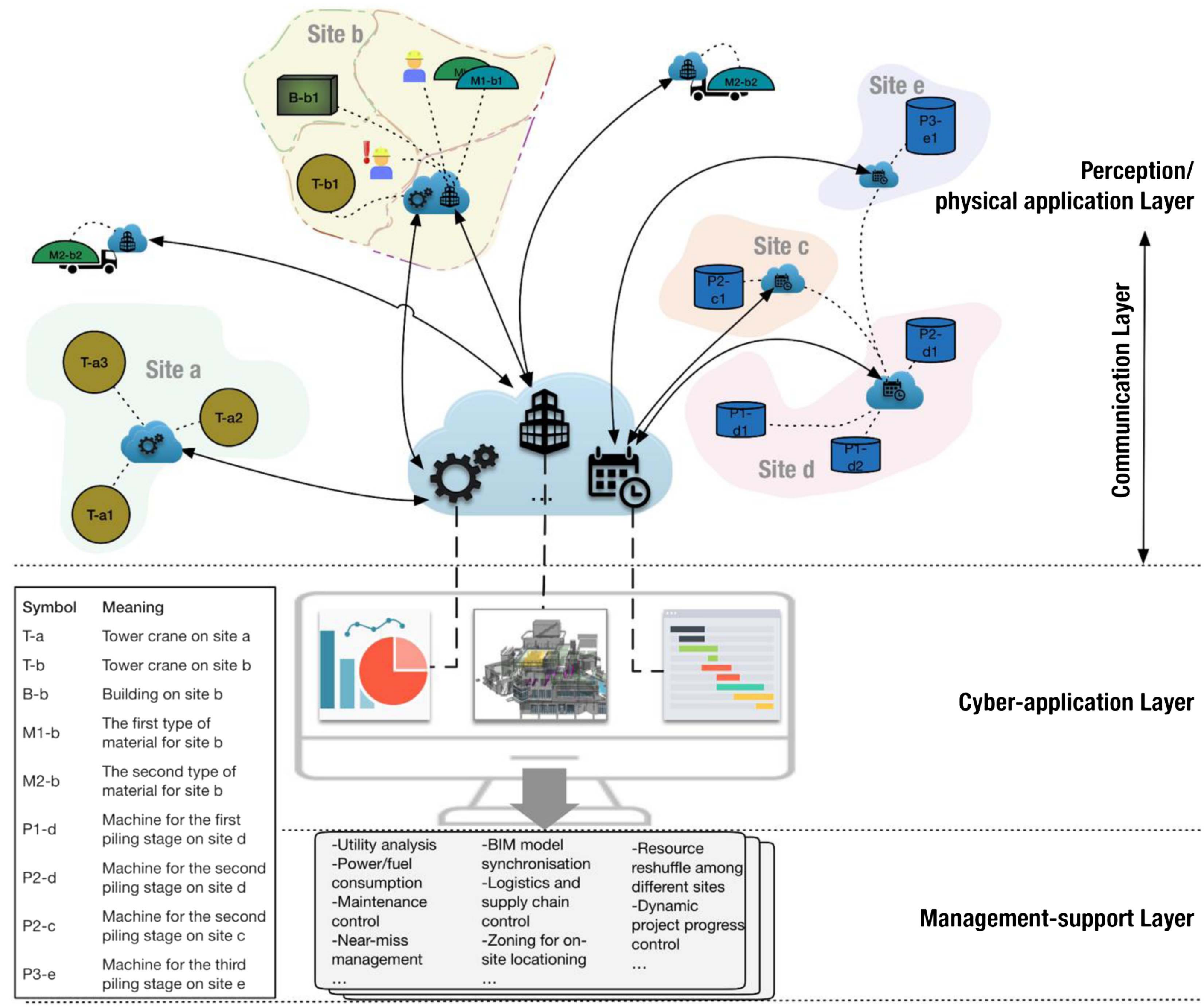

Fig. 3. Application scenarios of the integrated framework.

occupational health and safety (OHS) management by detecting dangerous situations, making real-time alerts to people in hazardous situations, and taking autonomous actions to prevent accidents from happening under certain conditions. When connected to a smart management platform, a smart tower crane and a platform form a CPS in which every motion and operation of the smart tower crane is visualized and analyzed to inform management of safer and more productive operation of tower cranes (Liu et al. 2018). Similar applications of smart tower cranes and the associated CPS can be hosted by the proposed framework, with the potential to provide a wider range of services when interconnected.

In addition to the application supported by individual SCOs or separate CPS, more insight can be gained from interconnected SCOs and CPS, either within the same sites or scattered on different sites. In the integrated framework, SCOs on the same site are linked together to the cloud through an internet-connected mobile device or local workstation. When SCOs are linked to the cloud, project personnel can use network-supported computing devices to access the cyber representations of SCOs in the cyber application layer, where they can track, monitor, and control the SCOs, forming a closed-loop CPS system. For example, Fig. 4, shows three smart tower cranes (T-a1, T-a2, and T-a3) on Site a, all connected to the cloud. On the 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 can 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 on the same site, can further be utilized in the management-support layer for analysis of power consumption, equipment usage patterns, and utilization rates on a site basis.

The same types of SCOs that are distributed on different sites are 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 Fig. 4 is also linked to the cloud. By processing the data sent back by the smart

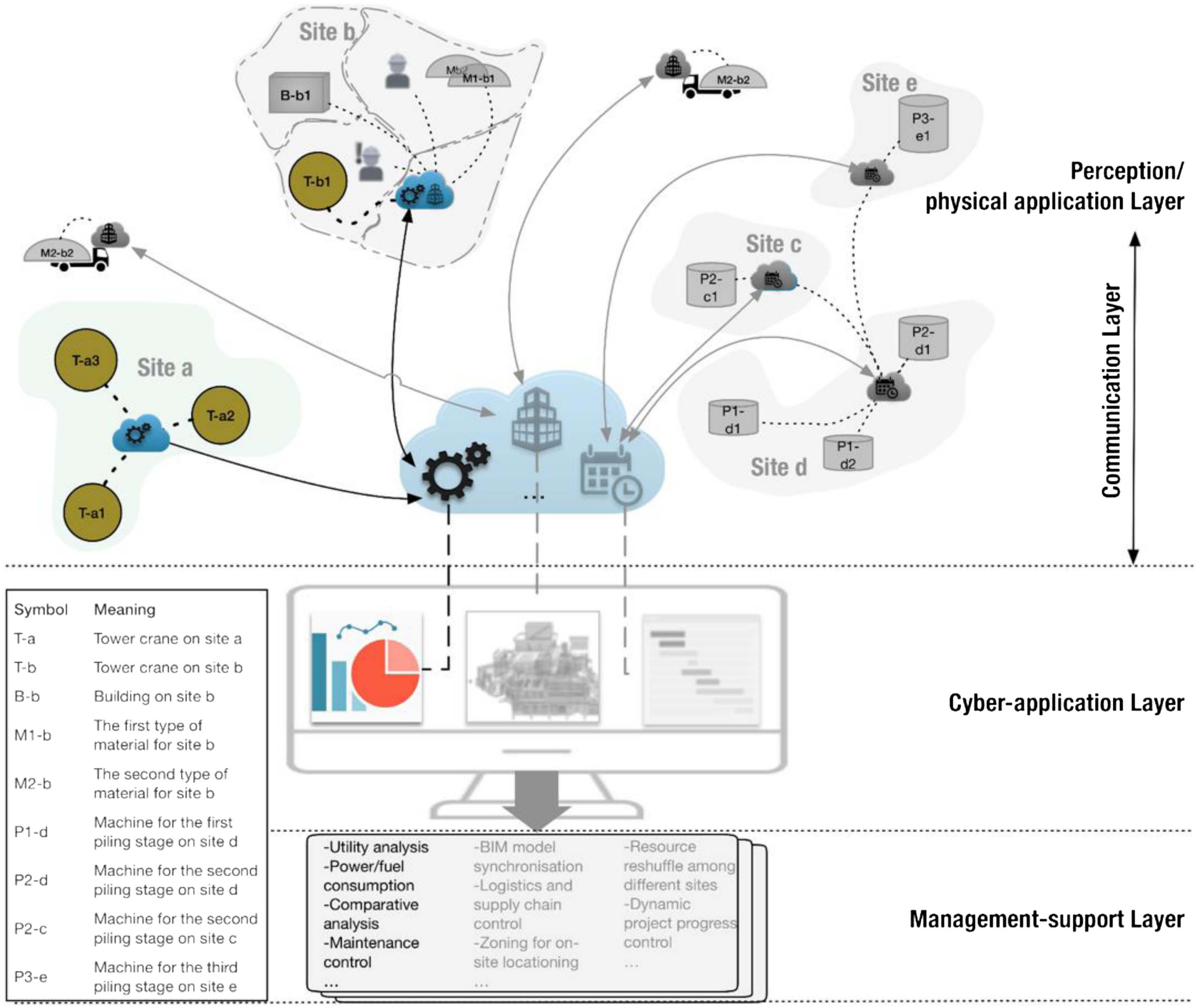

Fig. 4. Application scenario of site-specific and cross-site machine management.

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 with data analysis that relies on a single smart tower crane, data from an entire group of tower cranes on the IoT-based network can 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 use 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 the 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. (2017) 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 form a CPS in which the bidirectional information flow can 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 times, can be carefully coordinated. As a simplified example (Fig. 5), in order to construct Building B-b1 on 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 Fig. 5, the locations of M1-b1 and M2-b1 are associated with the status arrived on site, whereas those of M1-b2 and M2-b2 are en route. The status information can be visualized in the BIM of B-b1 as color changes or animations, allowing for real-time rendering of the building in progress, as well as establishment of project control.

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, during which they may reply on object-to-object (O2O) communication with the trucks so that the trucks can sense the real-time location by embedded GPS sensors and update it to the cloud. For M1-b1 and M1-b2, which have entered the site gate, more-precise on-site locationing can 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, on-site zoning can 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. Adhering identification tags to important shipments and high-value equipment could save time counting and looking for them on relatively

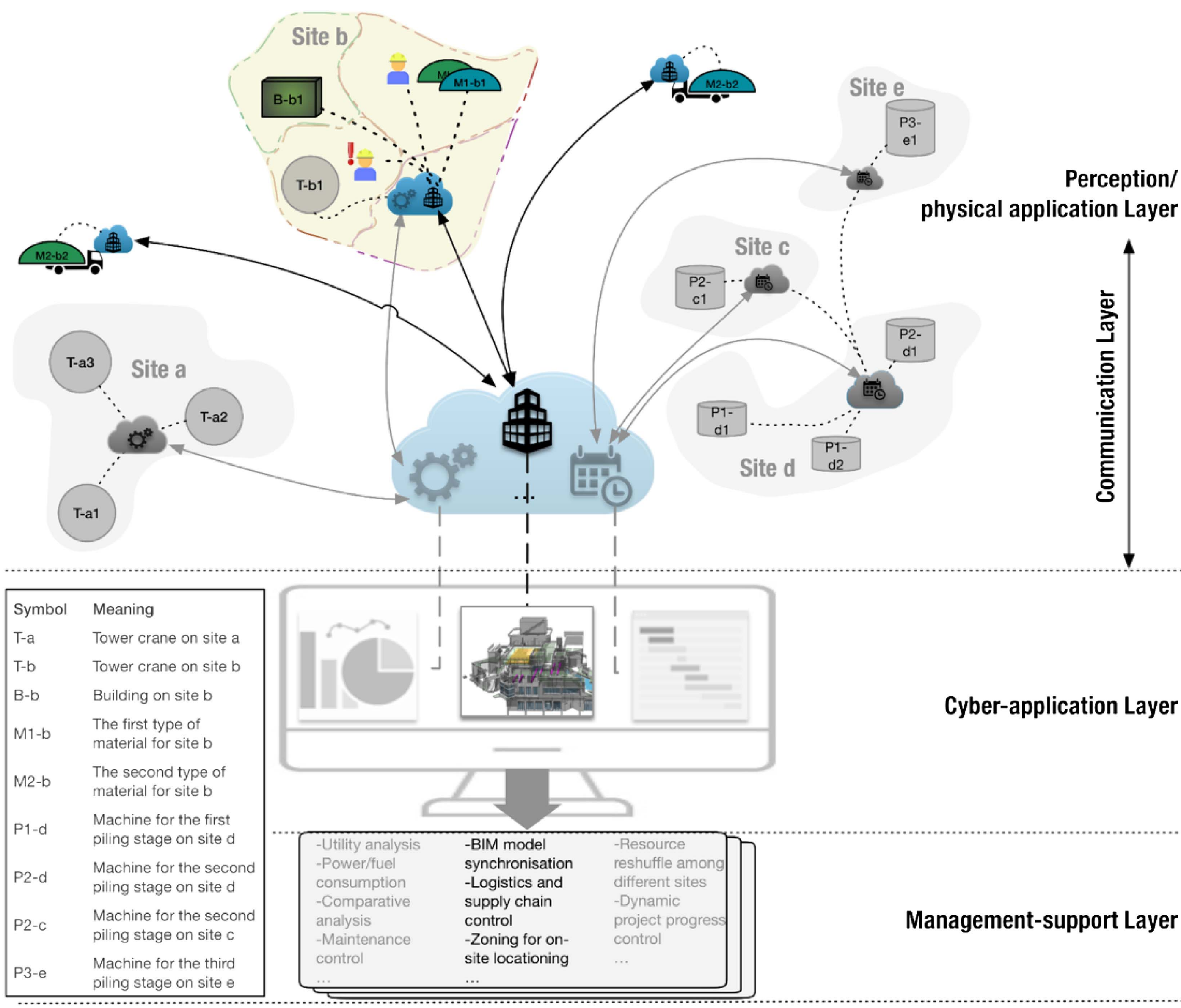

Fig. 5. Application scenario for ubiquitous logistics tracking and on-site positioning.

large construction sites, and assist 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 a safety helmet is linked into the IoT network, making it possible to warn people entering restricted areas or dangerous zones.

Scenario 3: Ad hoc Resource Reshuffle for Dynamic Project Progress Control

In a typical application scenario that utilizes the synergistic effects enabled by the integration of IoT, CPS, and SCOs, the framework could support reshuffling construction resources among different project teams dynamically in line with the variances in project progress. Making a project program is essential before the implementation of a construction project, with the sequence of tasks and resources needed at each stage planned in advance. The sequential execution of tasks calls for high flexibility in resource arrangement and reallocation. Taking bored pilings 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 but 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 high in demand, because their allocation can impose significant cost and time impacts.

Using the machines sequentially needed for bored pilings as an example, Fig. 6 highlights how the proposed framework can facilitate the dynamic construction resource reshuffling between sites and projects for maximized efficiency. P1-d1 and P1-d3 represent two drilling machines used at the first stage of bored pilings (such as a rotary auger and a vibrohammer) on Site d. When made into SCOs, their working statuses are synchronized to the cloud just like the smart tower cranes explained in the first scenario. In addition, as indicated in the project program, they are also linked with the machines needed for the second stage of bored pilings, which are P2-d1 on Site d and P3-c1 on Site c. If P1-d1 and P1-d3 are originally linked with P2-d1 but P2-d1 gets delayed in the working process, the priority of P2-d1 in the linkage is decreased. Once the priority of P2-c1 outweighs that of P2-d1, with their

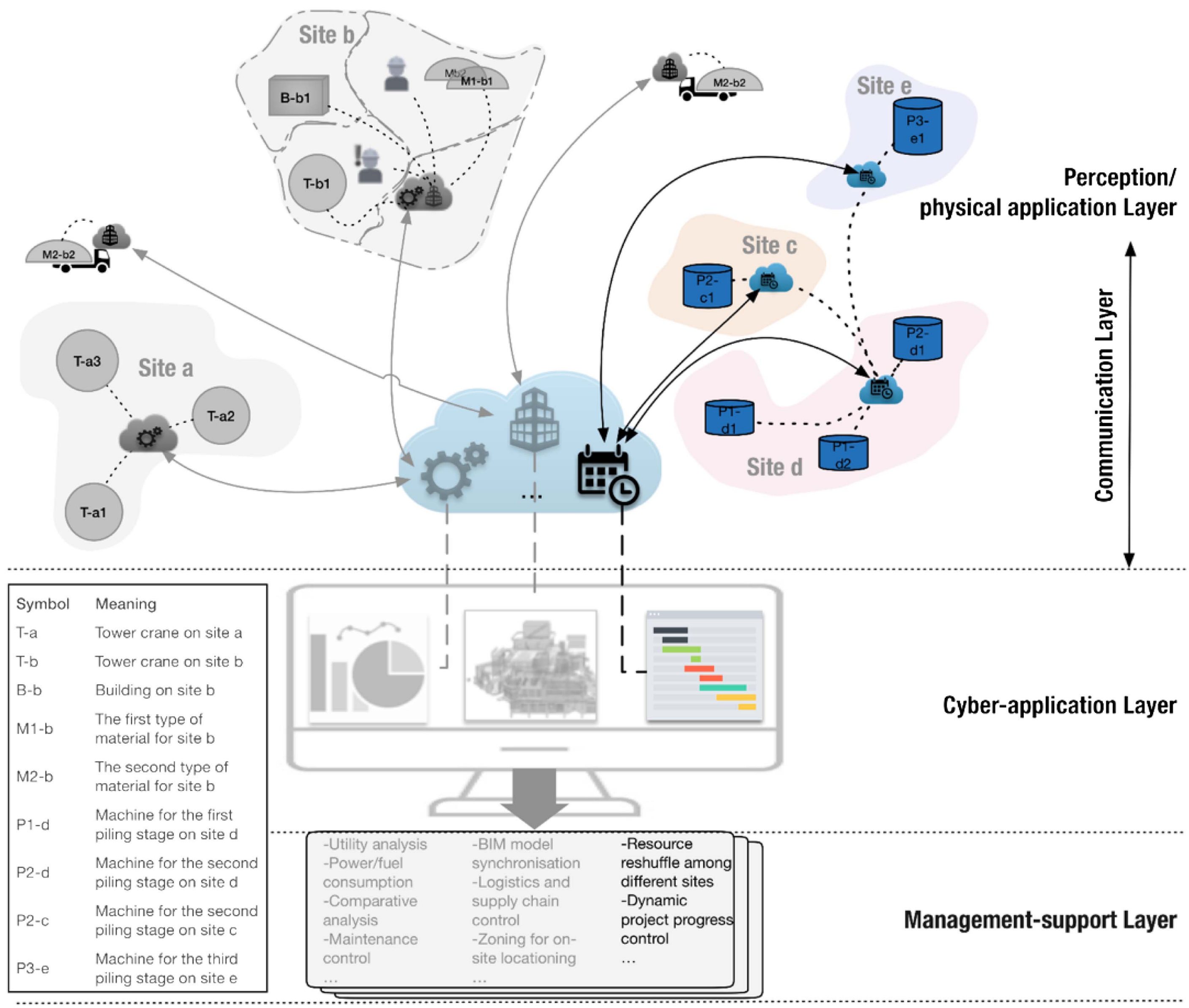

Fig. 6. Application scenario of dynamic resource reshuffle within a portfolio.

availability and cost of transportation from Site c to Site d considered, P1-d1 and P1-d3 are automatically linked with P2-c1 instead. The same practice can 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 of the sequential linkage between machines and other resources can be instantly visualized in the project program diagram. If there are not enough machines or materials to cope with the updated program, the need becomes clearer and more evident by deploying this framework, thus supporting the formulation of future renting or buying strategies.

Discussion

This study contributes to the body of knowledge by 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. Because 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 was 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 of IoT in construction still involve an 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 studies of IoT enhances the level of smartness for the things in IoT, whereas the integration of CPS reinforces the monitoring and control of these smart things. Furthermore, existing applications of 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 the trial stage or when put into practical operation, enhancing the interconnectivity 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, because 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 SCO and the collected data becomes accessible at the computer end, ensuring the timeliness of the captured data. Because of the interconnected network support provided by the IoT to capture, store, process, and analyze 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.

The three example application scenarios demonstrated 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. Especially for construction components that are made into SCOs, such as prefabricated components and HVAC devices, the awareness, communicativeness, and autonomy could keep operating throughout the facility operations and maintenance phase of the structure to assist facility management. In this sense, the deployment framework has potential value for the entire life-cycle management to accommodate various aspects of a construction resource and activities.

Conclusions

Managing complex and dynamic construction projects calls for technological assistance in coordinating diverse and distributed construction resources and people on a massive scale. To respond to this call, many technologies, including internet of things, cyber-physical systems, and smart construction objects are starting to gain traction in construction. By clarifying the similarities and differences between these concepts, this study synergized them to serve construction project management 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 autocontrol 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 were proposed in the framework to cope with the structure frame of an IoT network, the bidirectional 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 to 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: (1) it streamlined three popular yet easy-to-confuse conceptual ideas, namely, IoT, CPS, and SCO in the context of construction; and (2) it integrated them into a generic yet operable framework that can facilitate CPM. Certainly, the longevity of such frameworks lies 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 analyzed during the study. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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