Chapter 15

From Smart Construction Objects to Cognitive Facility Management

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15.1. Introduction

With ‘smart’ becoming a buzzword around the globe, the enthusiasm for smart has infiltrated almost every aspect of life from the device level (e.g., smartphone and smartwatch), the industry level (e.g., smart health and smart transportation), to the city or country level (e.g., the smart city initiatives in New York, Seoul, Glasgow, Ontario, and Singapore). The Architecture, Engineering, construction, and operation (AECO) industry is no exception. It is strenuously exploring the concept of smart to solve its many chronic problems such as escalating cost, delayed delivery, unsatisfactory quality, and stagnant productivity, as well as providing better services in the design, construction, installation, and operation stages. The smart era is driven by sensing, information and communication, computing, and automation technologies, which are becoming more powerful and pervasive than ever.

Pervasive sensing, information and communication, computing, and automation technologies make the bridge between the cyber and physical systems (CPS) buildable. Apart from the CPS, another dimension, the social dimension is also possible to be linked to form the cyber, physical, and social system (CPSS). CPSS tightly integrates sensors, actuators, data and information, computational resources, services, human beings, and so on from cyber, physical and social worlds (Somov et al., 2014). It extends the scope of CPS and takes the social characteristics of human beings into account to bridge the three worlds that have been largely isolated (Wang et al., 2017). As an emerging paradigm, CPSS has gained increasing popularity from the academia and industries by enabling deep fusion among social human beings, cyber computers, and physical things (Zeng et al., 2016b). To satisfy the requirement of human life, CPSS should contain handy sensing devices, networking facilities, computing facilities, actuating devices, and other equipment. The key techniques of CPSS include: (i) seamless migration technologies of various network, (ii) device management, (iii) context awareness, (iv) human-computer interaction, (v) user behavior based proactive service, (vi) social computing, and (vii) security and privacy (Zeng et al., 2016a).

Thanks to the progress in pervasive sensing technologies, Auto-IDs and sensors are getting more powerful in ability, cheaper in price and smaller in size, and has stimulated handling of the number of deployments (Sheth, 2016) and promoted the Internet of Things (IoT) (Xu et al., 2019a). IoT allows people and things to be connected with anything and anyone at anytime, anyplace, ideally using any network and any service (Vermesan et al., 2011). With the rapid expansion, there will be more than 25 to 50 billion IoT devices deployed and 17 to 32 percent annual growth before this decade is over (Sheth, 2016). It requires appropriate management for all these objects of IoT and their supporting technologies behind to overcome the technological heterogeneity and complexity, to better enhance situation awareness, reliability, and energy-efficiency in IoT applications (Foteinos et al., 2013).

Recently, there has been an emerging trend in cognitive IoT (CIoT). As a new network paradigm, CIoT is inspired by human cognition. In CIoT, real/virtual things are interconnected and interact as agents based on a situation-aware perception-action cycle (Wu et al., 2014). The things in CIoT are able to learn semantic and/or knowledge from kinds of databases, make intelligent decisions, and perform adaptive actions according to cognitive and cooperative mechanisms, with the objectives to promote smart resource allocation, automatic network operation, and intelligent service provisioning (Zhang et al., 2012; Wu et al., 2014).

The ability of CIoT is empowered by cognitive computing (CC), which can address interoperability and other aspects, such as hypothesizing correlations and validating them through evidence (Sheth, 2016). CC is an interdisciplinary product of human cognition and computing machines. It is different from artificial intelligence (AI) by its fuzzy computing ability by mimicking the human thinking process in a computerized environment. It aims to achieve the low power, small volume, mind-like function, and real-time performance of the human brain (Xu et al., 2019). With CC, a cognitive system can quickly learn and improve as it discovers knowledge and acquires profundity in complex environments (Xu et al., 2019).

Moreover, with the fast development of sensing and computing technology, communication, information, and actuation technologies are also high advance and pervasively used. For communication technology, LAN (local area network), WAN (wide area network), and WLAN (wireless local area network, including ubiquitously used WIFI, Bluetooth, Zigbee, and NFC), together forms a complete communication network that can connect everything to the Internet. Some other emerging communication technologies such as WPAN (wireless personal area network) and WiMAX (Worldwide Interoperability for Microwave Access) will make communication more convenient and efficiency. For information technology, computers and network systems, communication equipment and software, search engines, etc., are quite advanced to support FM. In the AEC/FM sector, BIM (building information modeling) is an emerging and increasingly popular information technology to support the management of buildings. As for computation technology, in recent years, technologies including big data, cloud computing, deep learning, machine learning, and cognitive computing are becoming more and more mature. Actuation technologies including wireless valve actuator, window opening/closing motors, relays for the HVAC (heating, ventilation, and air conditioning) systems are designed and produced and being pervasively used in daily life. With these supporting technologies, it is time to take a step forward to Cognitive FM.

The AEC/FM industry is embracing the rapid development of sensing, communication, information, computing, and actuating technologies to catch the fashion of “smart everything”. Among them, smart construction objects (SCO) (Niu et al., 2016a) and cognitive facility management (Cognitive FM) (Xu et al., 2019b) are proposed with a big blueprint. The concept of SCOs is developed as a basic element to define, understand, and achieve smart construction (Niu et al., 2016a). The aim of Cognitive FM is to enable FM objects to see, listen to, smell, and feel the physical space for themselves, have them interconnected to share the observations, and beyond that, empower FM objects with a “brain” to learn, think, and perceive both the physical and social spaces by themselves for high-level intelligence (Xu et al., 2019b). However, there is a gap between smart construction and cognitive FM, as their development has been focused on different scenarios and stages. For a smarter integration of different processes of AEC/FM practices, the two pioneering concepts should be bridged for the overall “smartness” of the built environment.

This chapter serves as an attempt to integrate SCO and cognitive FM by arguing that SCO will not only serve for smart construction purposes but can also remain in the objects for FM purpose; it is an enabler of cognitive FM. By their integration, information continuity and credibility, management continuity, and lifecycle management in AEC/FM projects for higher-level smartness. The rest of the chapter is organized as follows. Subsequent to this Introduction, Sections 2 and 3 will introduce the definitions, properties, and frameworks of SCO and cognitive FM, respectively. Section 4 will discuss the necessity and feasibility of integration construction and FM, as well as the integration of SCO and cognitive FM. Section 5 will propose a framework of SCO-enabled cognitive FM, followed by Section 6 which explains the implementation of the framework by two illustrative scenarios. Section 7 discusses the challenges and Section 8 concludes the chapter and proposes some works that can be performed in the future.

15.2. Smart Construction Objects

15.2.1. Definition of SCO

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

Despite the research efforts on smart construction by employing ideas from AI, robotics, and analogous concepts, there are still widespread frustrations in the industry in respect of smart construction. In contrast to the advanced development of smart systems in manufacturing, the automotive industry, civil aviation, and logistics and supply chain management, the fundamental concepts, definitions, and paradigms of smart construction are yet to be systematically explored. Successful cases of smart construction have emerged in a piecemeal fashion, having been developed for a specific trade and thus having little generalizability. In addition, smart systems introduced from other industries have been disruptive to existing construction practice, resulting in practitioner reluctance to harness their potential.

Based on previous studies of smart construction objects (SCOs), Lu et al. (2019) argue that the development of SCOs is leading towards a new paradigm of smart construction. It demonstrates that SCO development offers a perspective from which to (a) systematically define, understand, and achieve smart construction; (b) provides a new perspective to solve problems beyond the scope of existing paradigms; and (c) address limitations in existing studies on smart construction, including lack of theoretical lucidity, piecemeal application with limited generalizability, and the disruptive nature for deployment.

The concept of SCOs is developed as a basic element to define, understand, and achieve smart construction. Inspired by the concept of the smart object (SO) (Kortuem et al. 2010, López et al. 2012), SCOs are proposed as a solution towards cognitive computing and intelligence in the AEC/FM context. They are defined as “construction resources made ‘smart’ by augmenting them with smart properties” (Niu et al. 2016a). These resources could be materials, components, tools, devices, machinery, and even temporary or permanent structures. To explain the smartness SCOs could confer, three core properties of SCOs are proposed in a tri-axial diagram (Figure 15.1): awareness, communicativeness, and autonomy, denoting the sensing ability, data sharing ability, and autonomous action-taking ability of SCOs (Niu et al. 2016a). Each of the three core properties is subdivided into several types, while they may function in cooperation depending on needs and requirements in different application scenarios.

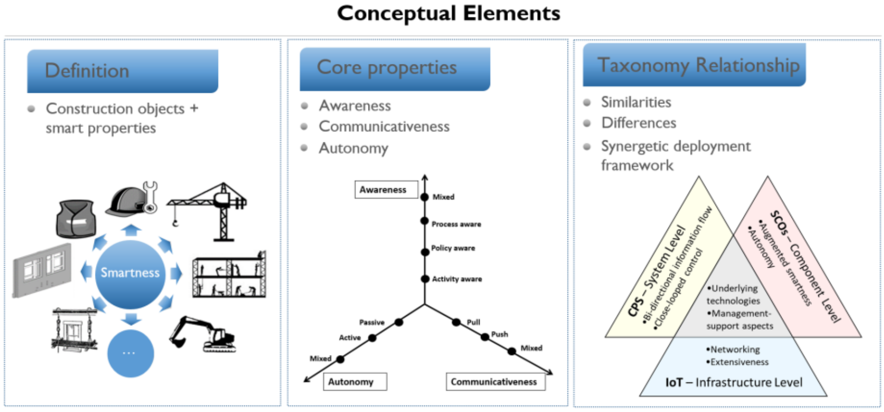

Figure 15.1. The development of conceptual elements of SCOs (Lu et al., 2019)

15.2.2. Properties and Framework of SCO

As the basic elements of smart construction, SCOs offer a way to define and understand the paradigm of smart construction. Smart construction can be perceived as a paradigm for construction management by leveraging SCOs with their smartness, including awareness, communicativeness, autonomy, and other potential smartness to be enriched. Understanding of SCOs and the paradigm of smart construction are deepened when their taxonomic relationship with cyber-physical systems (CPSs) and the Internet of things (IoT) are elucidated (see Figure 15.1). Differences and similarities between the three concepts are articulated by Niu et al. (2018). For example, although the three concepts share similar underlying technology tools, each operates at a different level (SCOs at the component level, a CPS the system level, and the IoT the infrastructure level) (Niu et al. 2018; Lu, 2018). A synergetic deployment framework to integrate the three concepts has been proposed to harvest the synergy between them when adopting smart construction.

While flexible combinations of their three core properties (awareness, communicativeness, and autonomy) (see Table 15.1) enable SCOs to provide individual smart functions, the true power of SCOs lies in an integrated, responsive smart construction system in which they are linked. A generic framework for this SCO-enabled smart management system is developed for practical deployment (see Figure 15.2). By providing a multi-layered structure with the connecting relationships in between, the system framework for the SCO-enabled smart management system clearly illustrates the process of turning traditional construction objects into smart and customizable SCOs, the functions units to be included in the smart management platform, and the typical demand-oriented applications of SCOs. It demonstrates how SCOs could interact with people or each other to support construction management by enabling a more connected world of construction. Awareness, communicativeness, and autonomy of SCOs can be achieved by augmenting construction objects with various modules into construction objects, including computing, communication, sensing, and location tracking modules (Liu et al. 2015).

Table 15.1. Properties of SCOs (adapted from Niu et al., 2016c)

Properties	**Sub-dimensions**	**Explanations**
Awareness - The ability of SCOs to sense and log the real-time condition of SCOs and the surrounding environment	Activity-aware	To understand and make record when certain type of activity or event is triggered
	Policy-aware	To understand to what extent the real-time condition or activity comply with rules and regulations
	Process-aware	To understand and recognize the workflow and transition between construction activities
	Mixed	To have more than one type of above awareness
Communicativeness - The ability of a SCO to share information with managerial personnel or other SCOs	Pull	To provide information on requests communicativeness
	Push	To proactively send updated information or make alert in a regular interval
	Mixed	To have both pull and push
Autonomy - The ability of SCOs to alert people for actions or to take autonomous actions	Passive	To make alerts to people and to assist people in making decision and taking actions
	Active	To take self-directed actions proactively based on change of conditions
	Mixed	To have both passive and active autonomy

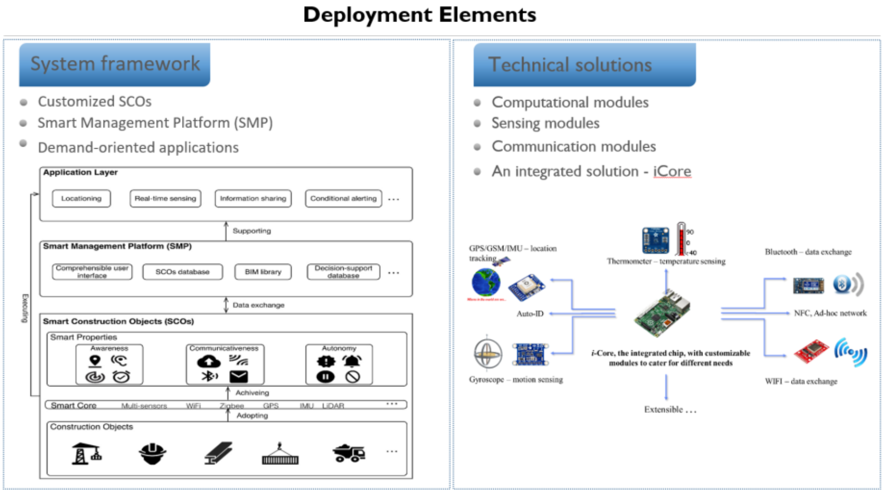

Figure 15.2. The development of deployment elements of SCOs (Lu et al., 2019)

15.3. Cognitive Facility Management

15.3.1. Definition of Cognitive FM

Cognitive facility management (Cognitive FM) is defined as "the active intelligent management of a facility, which can perceive through cognitive systems, learn in the manner of human cognition with the power of cognitive computing, and act actively, adaptively, and efficiently via automated actuators, to improve the quality of people's life and productivity of core business" (Xu et al., 2019b; 2019c). Cognitive FM proposes to shift the current predicament that a facility is often lagging in serving people, organizations, and businesses smartly (Wang et al., 2018). The tight spot is caused by the passiveness of current FM systems which cannot meet the changing and customized requirements of users in a facility. Most existing FM systems are passive ones with pre-programmed rules, failing to react to complicated, flexible, changing situations. Therefore, FM should and have to be updated with active intelligence mimicking human beings' cognitive capability (e.g., perception, learning, and action). Cognitive FM is a cyber-physical-social system (CPSS) where cyber (e.g., facility model, computer-aided FM system), physical (e.g., furniture, air conditioning system), and social (e.g., user behavior) information are integrated. The first step for cognitive FM to proactively perceive the requirements of users is to collect user behavior data, with which user preference and requirements can be learned.

The design of cognitive facilities management is to apply CIoT to FM with the consideration of integrating its cyber, physical, social systems (i.e., cyber-physical-social system, CPSS). The aim of Cognitive FM is to enable FM objects to see, hear, and smell the physical world for themselves, make them connected to share the observations, and beyond that, empower FM objects with a "brain" to learn, think, and perceive both physical and social worlds by themselves for high-level intelligence (Wu et al., 2014). Cognitive FM enhances the current FM by mainly integrating the human cognition process into the system design. The advantages are multifold, e.g., achieving situation awareness, increasing self-management, and enhancing service provisioning, to just name a few.

Cognitive FM aims to integrate physical space, cyber space and social space of a facility, as shown in Figure 15.3. In physical space, there are objects, including all types of facilities and their components, sensing devices like sensors, cameras, smartphones, and actuators, for instance, a piezoelectric actuator, pneumatic actuator, and hydraulic actuators. In cyber space, the major three components are database, computing algorithms, and different software. In social space, users and their behavior, as well as their digital twin, the social media, are the core elements. Physical and cyber spaces are connected with IoT, physical and social, networking, and social and cyber, human-computer interface. Physical flow, data follow and social flow from physical, cyber and social space respectively are integrated into Cognitive FM, which offers integration, interoperability, and cognition through computing. Cognitive FM will also give feedback to the three spaces to control actuators in physical space, update the database and enhance computing in cyber space, and affect user behavior. Finally, Cognitive FM achieves its three main purposes, sharing with the properties of SCOs, i.e., awareness, communicativeness, and autonomy.

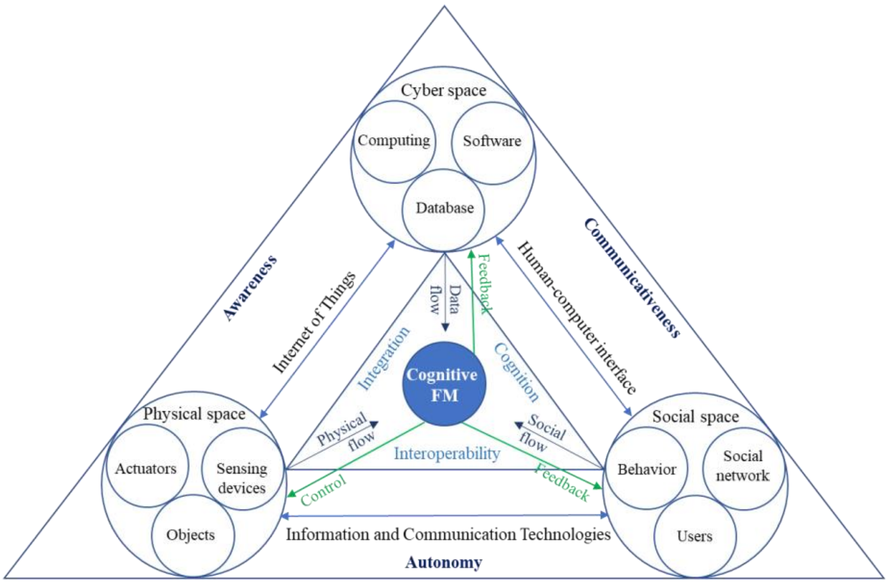

Figure 15.3. The integration of cyber, physical and social spaces in Cognitive FM

15.3.2. *Properties and Framework of Cognitive FM*

Perception is a primary property of cognitive FM. It is an active process of sensing the internal and external environments. By turning the stimuli from the environment into data, perception provides a system with information about the environment it inhabits (Russell and Norvig, 2016). Perception becomes accessible and extendible with the support of cognitive IoT. Sensors/sensor networks, Auto-IDs, cameras, and smart devices and their connected utilities are the ‘things’ that perceive the internal and external environments of the targeted facilities. Wireless sensor networks (WSNs) can enable real-time collection of sensory data in different types of facilities (Huang and Mao, 2017). Photogrammetry and videogrammetry are extensively utilized for movement and behavioral data collection, as well as the reconstruction of as-is and as-built digital models of facilities. Auto-IDs, including RFID and QR code, are largely adopted in empirical cases for real-time localization, tracking, and navigation (Xue et al., 2018). Smart devices are vital sources of ambient environment and user behavior information.

Learning is another important property of cognitive FM which distinguishes it from others. It consists of cumulating information as memories, acquiring access to the information, and discovering knowledge (Russell and Norvig, 2016). In a cognitive system, learning enables object recognition, categorizations, and action execution procedures (Franklin et al., 2014). For example, by learning historic records of indoor temperatures, air conditioning operation, and weather, cognitive

FM can realize customized indoor environment control based on occupant preferences, weather forecasting, and other possible factors. Learning is based on observation (watching other's performance and imitating), experience (concluding experiences and recognizing patterns), feedback (reflecting feedbacks and discovering knowledge), and reinforcement (reinforcing by punishment or rewards, respectively) (Illeris, 2004). It is a multimodal process in practices with an integration of multiple approaches.

Action is a third property that takes place between the cyber, physical, and social spaces. Simply being in action can facilitate perception and learning. In cognitive FM, actions may include but not limited to statistical analysis and visualization, model reconstruction, alert issuing, option recommendation, decision-making, device actuation, and a combination thereof. Action may execute in three ways, i.e., passively, semi-actively and actively (Casciati et al., 2012). Assisting people with decision-making is the passive action. A typical example would be sensing a notification for facility managers or workers. Semi-active action is the action collaborated by humans and machines. If a facility itself can execute the optimum plan it finds without human aid, then such action is active. A typical example of active action is the auto-control of the lighting system according to occupancy, natural light condition and the function it serves. The accomplishment of semi-active and active action largely relies on cognitive computing and automatic actuating devices.

Figure 15.4 shows the framework of cognitive FM. It has eight layers, i.e., the environment layer, perception layer, data layer, communication layer, computation layer, application layer, action layer, and evaluation layer. The eight-layer framework takes its three properties, i.e., perception, learning, and action, into its structure. It also put the integrating of CPSS into account. The framework can be customized based on different applications. The environment layer is the internal and external environment of the targeted objects. The perception layer should be developed based on data requirements. The data layer is dependent on the application and computing layer. The actuation and evaluation layer should be designed according to available actuating devices and evaluation requirements, respectively. Some technologies or devices may integrate different functions. The several layers of the framework may be integrated but none of them should be neglected in any form.

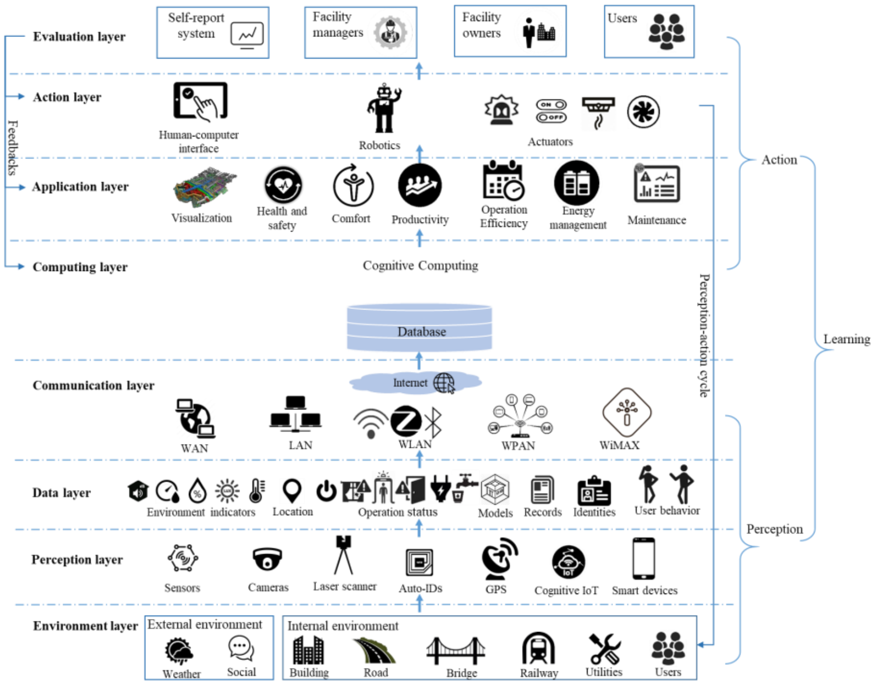

Figure 15.4. The system architecture of cognitive FM (Xu et al., 2019b)

15.4. The Need to Bridge Smart Construction and Cognitive Facility Management

Section 2 introduced the smart construction objects as a paradigm shift and a technical solution for the non-disruptive promotion of smart construction. Section 3 proposed a working definition, core properties, and framework for cognitive FM which aims to integrate physical space, cyber space and social space of a facility for proactive intelligence of FM. Although these two pioneering initiatives are far-sighted and share similar insights of integrating the cyber-physical system (CPS) in the built environment, there is a gap between them. They are isolated, only focusing on certain stages rather than the life-cycle of the built environment.

The isolation of construction and FM is am aeipathia in the AECO industry. Due to the complexity of construction projects, different technologies, professional knowledge, experts, and stakeholders are adopted and enrolled, which makes their coordination, cooperation, and communication hard and tedious. The common practice is that construction is mainly dominated by contractors under the management of clients, while FM is outsourced to professional FM companies. The gap between contractors and professional FM companies is always so insurmountable that they will lose precious data and information when transferring the project. Contractors have full records of every construction process and every component but hard to transfer all of them to professional FM companies. While FM companies need those records for better management of the facilities' lifecycle performance. Both academia and practitioners have long known this problem but cannot bridge the gap with a good approach. The research on smart construction is partitioned into isolated sub-disciplines, mostly too focused on technological tools such as sensors, networking, or automatic control. Meanwhile, there is also a divergent strand of research on FM focusing on the technical part, and just about the same attentions are attracted to the integrated system for FM. But construction and FM are rarely considered together.

It is important and urgent to integrate construction and FM in a loop because of the following four reasons.

Information continuity is the first that would be benefited from construction and FM integration. Data/information is the fuel and enabler of artificial intelligence (AI), cognitive computing, automation, and robotics. The integration of construction and FM will facilitate the continuous flow of information from construction to integration. For example, the production, logistics, and construction information of a beam component can be stored and transferred to the FM system for future monitoring and assessment. A complete record of information is also crucial for decision making. Due to the bounded rationality of human beings (Simon, 1972), necessarily integral information will reduce mistakes and save time with better-informed decisions to be made.

Information credibility is another benefit thus can also be achieved when construction and FM are combined. The reliability of information is another dimension that is imperative for decision-making and management efficiency. When facility/asset information can be traced back to the construction stage, credibility can thus be largely improved. With technologies such as Auto-ID, barcode, QR-code, and embedded sensors, information can be recorded and traced back to ensure the authenticity, completeness, and reliability can be promised. The blockchain, an emerging information encryption technology, will also help ensure the information credibility from construction to FM. Such technologies have been proved to improve trust and information credibility in the prefabricated component supply chain from production in the factory to logistics during transportation and finally to assembly on-site (Li et al., 2018).

Management continuity is another profit of construction and FM integration. The records of construction management, especially those related to quality management and safety management, are critical for FM. If a construction management system and an FM system share an interface, the management process, management personnel, and management approach can be shared. This is significant, on one hand, for FM, which is able to trace back the management problems should problems happen; on the other hand, for construction management, which can learn from FM requirements and feedbacks to better satisfy the operation and maintenance functions. The integration, moreover, will reduce the adding problem of different parallel management systems, decrease duplicated paperwork and confusion between different standards and formats. Furthermore, with sufficient, continued, and reliable information, AI-based management system will be conceivable, such a system will allow less error-prone decisions, autonomous and proactive actions that do not necessarily involve human decision-makers in the loop.

The integration of construction and FM also serves as a pipeline to respond to the call of life-cycle management (LCM), a flexible framework integrated of concepts, techniques, and procedures (Jørgensen, 2008). In a facility building project, life-cycle management includes design, construction, operation and maintenance (FM), and decommissioning stages (Labuschagne & Brent, 2005), among which construction and FM are the two longest and critical ones. LCM has a focus on both the production site and the product chain. In the built environment, the construction site and production chain from construction to operation should keep as the focus. Construction is the creation of value from design concepts while FM is the realization of value. The value chain flows from construction to FM should not be cut off.

Not only the integration of construction and FM is important according to the four reasons listed above, but also possible with SCO and cognitive FM as initiated. SCO can serve as a hardware foundation and software interface of sensing and computing to achieve awareness, communicativeness, and autonomy. It can be placed in the perception layer in Cognitive FM to collect data for awareness, it can meanwhile serve for the communication layer by its communicativeness, and computing layer with some edge computing capabilities, as well as the actuation layer with its autonomy. Cognitive FM, in turn, will be an integration platform for the implementation of SCOs. With the awareness, communicativeness, and autonomy of SCOs as a backbone, the perception, learning, and action of cognitive FM system will be better achieved. Individual customized SCOs will remain in the facility as smart facility objects and keep functioning as the cells of the cognitive FM. Meanwhile, the cognitive FM platform is the brain of sense-making and decision-making with the continuous information collected from the SCOs. The SCOs at the construction stage are now cognitive FM objects that can perceive their performance and surrounding environment for FM, which does not have to be only taken place after construction but also during it. Supported by the data collected from SCOs and other sensing technologies, the cognitive FM system can better perceive the condition of the facility, its environment, and its users; learn from the data and patterns; and, provide proactive intelligent action accordingly. Therefore, SCO and cognitive FM are mutually developed and supported. They should and they can be jointly built up for better integration of smart construction and cognitive FM.

15.5. The Framework of SCO-Enabled Cognitive FM

Cognitive FM aims to develop a CPSS of the FM system. It, therefore, needs to meet the following requirements: (i) human-centric, (ii) decentralized functions and distributed open systems with vague overall system boundaries, (iii) dynamical reconfigured internal structure and reorganized functions/behavior, and change boundaries, (iv) self-organizing, (v) reflexive interactions between system components and multi-constraint optimization, (vi) real-time operation and communication as well as synchronized manner, (vii) awareness of users and their social contexts, and adapt themselves accordingly, (viii) dependability, accountability, security, accessibility and maintainability, (ix)integration of various percepters and actuators, (x)interoperable components at multiple levels, (xi) knowledge-intensive components, (xii) components can make situated decisions, (xiii) components can memorize and learn from history and situations, (xiv) components can adapt to unpredictable or emergent states and proactively execute non-planned functional interactions, (xv) large volume of heterogeneous data from cyber, physical and social worlds, complex and dynamic user behavioral patterns (Horvath, 2012; Kuang et al., 2015).

An SCO-enabled cognitive FM will meet these requirements by adopting SCOs across different layers, as shown in Figure 15.5. SCOs will act as important components in the perception layer, communication layer, and actuation layer in the eight-layer framework. Each of the eight layers has their own functions and characteristics:

(1) The environment layer consists of the internal and external environments of a facility. The external environment, including natural and social components, forms the context which the facility is positioned in and exposed to. The facility as a whole is the object of cognitive FM, therefore its internal environment is the utilities and users within the facility. It is the layer where all commercial, residential, and social activities take place, and also the layer the system needs to perceive through sensing technologies. All the objects can be augmented by sensing, communication, and computation technologies to become smart objects.

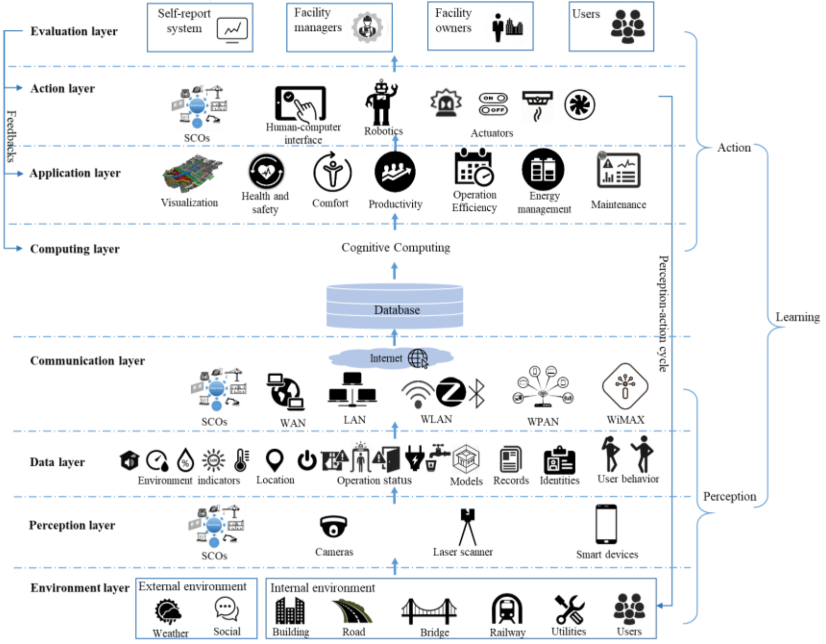

Figure 15.5. The framework of SCO-enabled Cognitive FM

(2) The perception layer entails SCOs and other devices that operate in a connected fashion to capture the features of the environment layer. SCOs as an integration of different sensors can sense the environment by processing the incoming stimuli and feeding observations to the upper layer (Jung et al., 2019). They can detect the status or characteristics of different objects. The information collected by SCOs is interpreted by the cognitive computing behind.

(3) The data layer means various data types generated after perception, including environmental indicators, such as temperature, humidity, luminosity, air pressure, or particulate matter density. It may also comprise pictures, video or 3D point cloud data of a facility or area, the identities of building components, furniture and users, location, operation status, user behavior, and other characteristics.

(4) The communication layer is in charge of uploading the sensing data to the database, mimicking the nerve system of human beings. There are various communication protocols available. Facility managers should choose the appropriate protocol based on their requirements and budget. Local and wireless communication protocols (i.e., LAN, WAN, and WLAN) are widely used in various current applications (Tolman et al., 2009). Personal networks (e.g., WPAN) and interoperable networks (e.g., WiMAX) are emerging and likely to popularize in online social communication. SCOs can also serve as a communication medium by integrating communication components such as Bluetooth, WiFi, or NFC.

(5) The computation layer is responsible for analyzing the data collected from the lower layers to support decision-making by harnessing the power of cognitive computing. SCOs with a computing board are also capable of doing some edge computing works and communicate the preliminary results to the cognitive computing system for further computation.

(6) The application layer makes use of the knowledge abstracted from the computation layer to facilitate multiple or even massive interactive agents (e.g., facilities or users) to support corresponding smart construction and cognitive FM applications.

(7) The action layer takes the decisions into actions by controlling the objects and changing the perceptron via the human-machine interface, robotics, or actuators. SCOs have the capability of issuing alerts or guidance that can also act as actuators from this aspect. Robots with caring, operation or maintenance abilities are also intelligent actuators with a promising future in cognitive FM.

(8) The evaluation layer is for the evaluation from stakeholders. It can share import interfaces with social network software for wider evaluation collection. Performance questionnaires will be designed to rate the services provided. More importantly, the evaluation results will serve as feedbacks to the application layer to improve application objectives and variables, or to the comutation layer to upgrade the learning algorithms, even to the perception layer to better customize SCOs and other devices for better perceptions.

As described, SCO can fit perfectly in the cognitive FM framework and work as an enabler by playing multiple roles across different layers. The SCOs in the form of construction components, machinery, and devices should be preserved, if necessary, for later operation and maintenance. To encapsulate these modules in an integrated manner, a standalone, programmable, extendable integrated electronic chip, named i-Core, is developed as one of the technical solutions (Lu et al. 2016). Able to be implanted into machinery, devices, and materials, and similar to a computer central processing unit (CPU), the i-Core turns deadweight construction components and plants into SCOs and makes smart construction possible. Implementation of the three core SCO properties relies on the integration of various computing, sensing, and communicating modules into the i-Core. To meet the changing needs of construction sites and achieve different functions, these modules are extensible and can be selected and customized case by case.

For example, a smart beam component object attached with an integrated chip (i-core) or an Auto-ID, manufactured either off-site or on-site, is a smart construction object at the construction stage and will keep as a cognitive FM object when the facility is finished and put in use. The data collected and stored from the construction stage can be kept and new data perceived during the operation stage will be added to construct a life-cycle dynamic dataset of the beam component. With many interconnected and intercommunicated objects turned into smart ones during the construction stage, the facility itself is a cognitive one which can perceive its internal and external environment, learn from historic data, and act proactively to meet customized and changing requirements of users and support the decision-making and management of facility managers in the changing environment.

15.6. Proposed Scenarios of SCO-Enabled Cognitive FM

To better illustrate how SCO can enable cognitive FM, two scenarios, proactive structure assessment, and life-cycle MEP system monitoring will be proposed and explained.

15.6.1. Proactive Structure Assessment

In this specific scenario, prefabricated beams will be turned into SCOs augmented by i-Core, not only to facilitate logistics and supply chain management in the construction stage but also to support proactive structure assessment during operation and maintenance stage. The customized i-Core in this scenario integrates an Arduino chip with GPS and GSM module, sensor network, and Auto-ID together (see Figure 15.6). GPS module enables the tracking of the beam during transportation. A customized sensor network with a gyroscope, thermometer, hygrometer, and pressure sensor will enable the perception of the internal and external environment. Auto-ID can store information such as manufacturing date, concrete and steel parameters, quality checking records, etc. A small smart chip with the ability of simple computing and communication will proactively send messages or report status of the location, transportation speed, and environment indicator records based on pre-set rules. The framework of the proactive structure assessment system is shown in Figure 15.7.

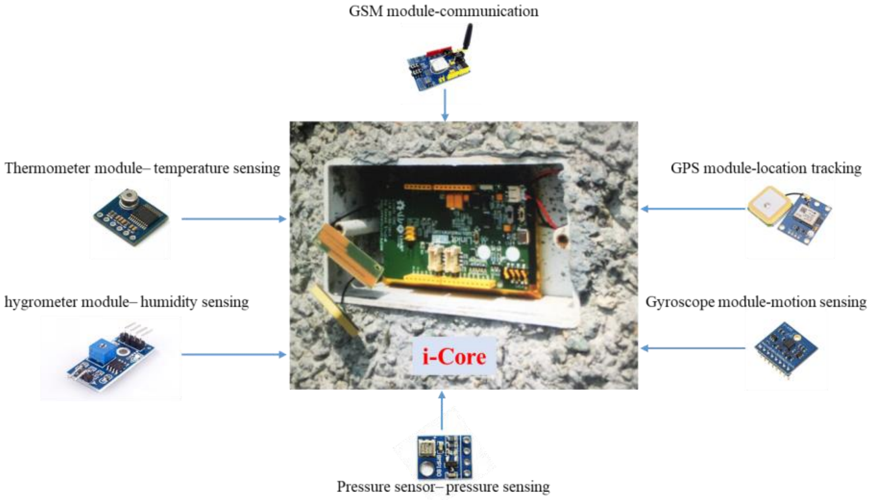

Figure 15.6. The customized i-Core design for smart prefabricated beam object

During the construction stage, it can support logistics and supply chain management (LSCM) via the cognitive FM platform. Augmented by the tracking and communication modules, real-time bi-directional information flow between SCOs and the platform (forming a CPS) will be achieved, along with concurrent information and material flow during the LSCM process (Niu et al. 2016b). Such a CPS will facilitate the real-time location checking of the prefabricated beam. The site manager can predict the arrival time of the truck and arrange transportation into the site. He/she can also plan for the temporary storage area or hoisting tower crane for the coming prefabricated beam. Once the beam arrived at the site, with a scanning of the Auto-ID, a receipt will be automatically issued to the manufacturer. To conclude, better and informed decision-making of material arrangement, labor and machinery planning, and construction progress management with less time lagging will thus be ensured for the procurement manager, material officer, and project manager.

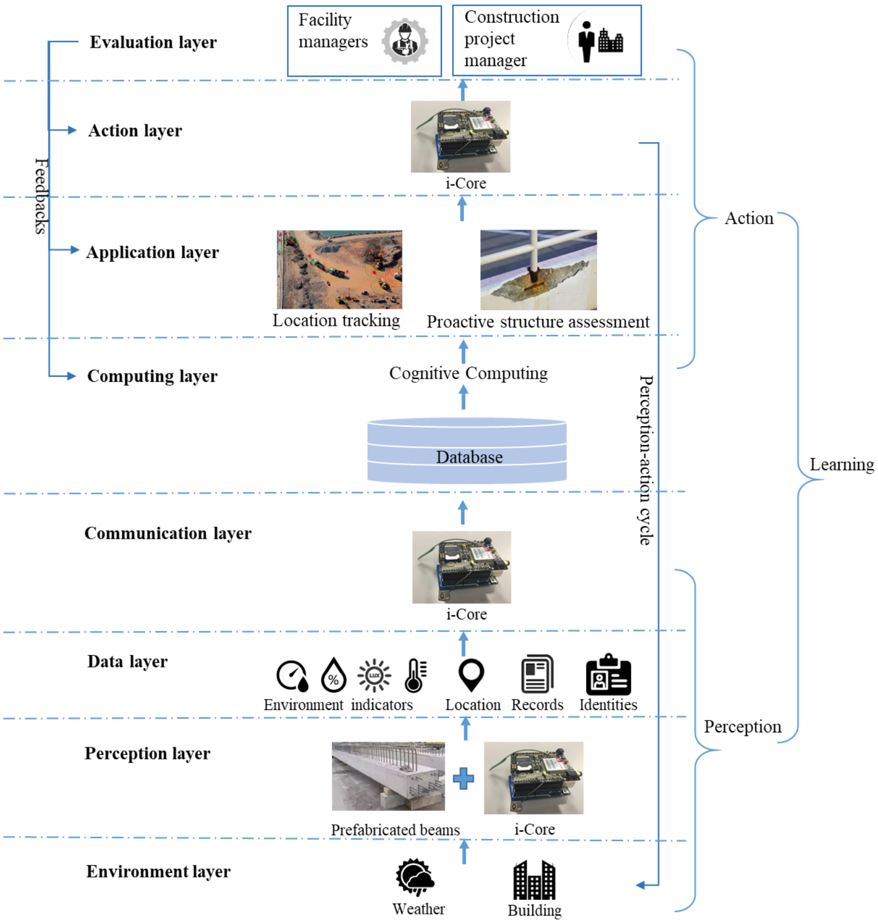

Figure 15.7. The framework of SCO-enabled proactive structure assessment

When the construction is finished, the i-Core embedded in the prefabricated beam object can be used for proactive structure assessment during the operation and maintenance stage. The framework of SCO (i.e., the smart prefabricated beam object) enabled cognitive FM is illustrated in Figure 15.8. With the sensor networks, the environment indicators including temperature and humidity, and the pressure loading on the beam can be collected. Auto-ID will store the identity of different components including beams, columns, plates. Such records stored in the database together will provide a foundation for proactive structure assessment. With cognitive computing, when the temperature, humidity, and other supporting indicators, are out of the normal ranges, alerts will be automatically sent to facility managers, asking them to check the status of the beam to see if there are abnormal situation happening to the beam. Also, when the loading pressure onto the beam is beyond the normal range, messages will be sent to them for a closer check. Moreover, such alerts and notifications are sent via the cognitive FM platform where it will keep a record of them and issue work assignments accordingly to maintenance stuff. The structure assessment is thus turned from passive by manpower to proactive self-report by the objects which are already augmented with smartness at the construction stage.

In this scenario, i-Core endowed SCO, the smart prefabricated beam component, is functioning as the integration of perception layer, communication layer, and actuation layer of cognitive FM. With other similar SCOs such as columns, plates, doors, windows, and other components all transferring to the FM stage, the facility per se is a network of smart objects, which lays a solid hardware foundation and software preparation for cognitive FM. By making use of the embedded technologies in the SCOs, the cognitive FM platform will cumulate rich big data for the nurturing of proactive intelligence. Such intelligence will not only serve for better physical facility management, but also better services provided for users and their customized needs.

15.6.2. MEP Auto-Monitoring

The second scenario illustrated is the MEP (mechanical, engineering, and plumping) monitoring. The MEP system is the kernel of modern facilities, especially for various types of buildings. However, due to its complexity and elusiveness, it is difficult to monitoring. Currently, it requires professional workers to check the components one by one. When partial failure happens, it is difficult to locate the part need to be fixed. An overall replacing to the whole system will be adapted during updating and renovation. All the current practices are quite tedious, error-prone, and expensive. SCO-enabled cognitive FM system may be a possible approach to relieve facility managers from their previous tedious routine work and save monitoring costs. The framework of SCO-enabled automatic MEP monitoring is displayed in Figure 15.8. The MEP objects are augmented with smartness by attaching sensor networks at the construction stage when contractors are installing the MEP system.

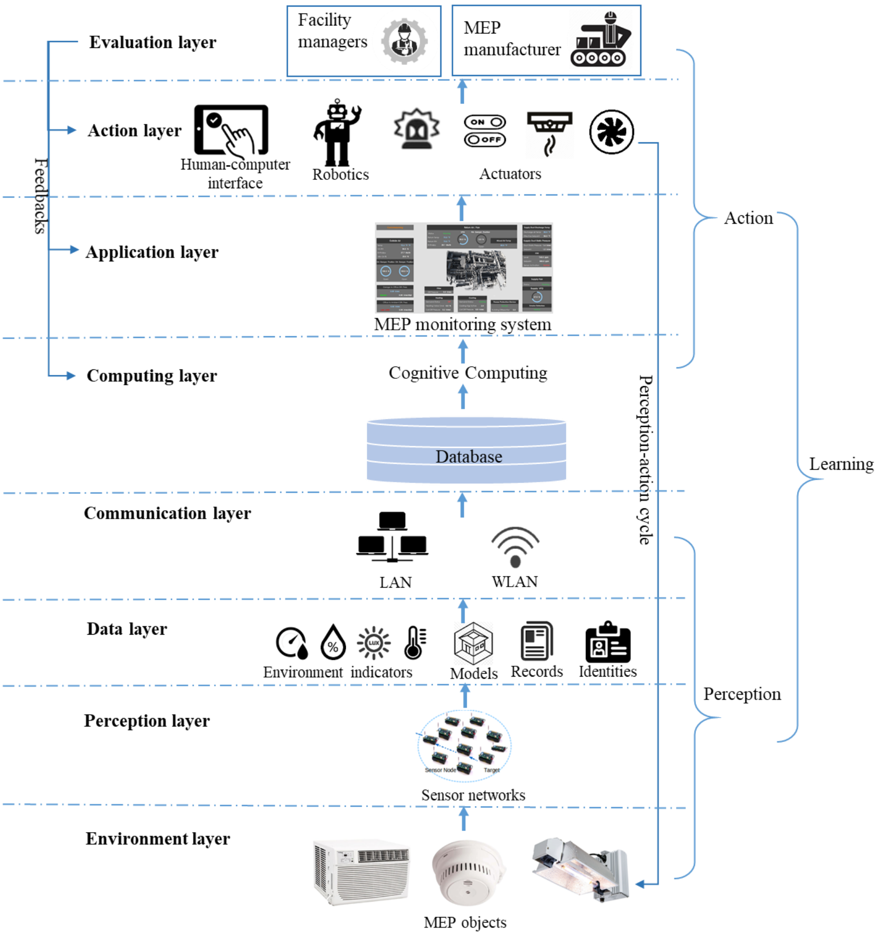

Figure 15.8. The Framework of SCO-Enabled MEP Auto-Monitoring

According to Figure 15.8, the MEP system is the major internal environment the cognitive FM investigates in this scenario. Sensor networks, be they wired or wireless, are attached to MEP systems and concealed by plates or walls at the construction stage. The sensor networks can be customized according to the monitoring requirements. Basically, thermometer, hygrometer, pressure sensor, sound sensor, and voltage sensor will be needed. Together they will be able to collect temperature, humidity, pressure, sound, and voltage of the MEP objects automatically. The sensing data thus will be uploaded to the database via LAN or WLAN. Cognitive computing modules will extract data from the databased for automatic analysis and monitoring. If cognitive computing of the temperature, humidity, pressure, sound, and voltage data detects any anomalies, notifications will be automatically sent to facility managers via the human-computer interface of the cognitive FM platform. The sensors are identified with numbers and located in a digital model, thus the notification of anomaly will be tagged with identification and location information. Therefore, FM staff can quickly find the failed object and fix it. Robotics can even be sent to fix the problems if possible. It is necessary when an emergency happens, or it is unsafe for workers to access. Under situations where residents need to be evacuated, alerts will be triggered, and messages will be sent to them via platform-to-person interface. For some other situations where actuations of the MEP system are needed, automatic control, e.g., turning on/off the power, resetting working temperature, opening fire-fighting system, can also be taken as responses. With the power of cognitive computing, the anomaly reasons can also be identified to support predictive maintenance. Facility managers can, therefore, plan the monitoring and maintenance to the point and avoid large scale failures. More importantly, the statistics of anomaly reasons and details can be reported to MEP manufacturers for their updating and optimizing the MEP objects from the design and manufacturing stage.

In this MEP auto-monitoring scenario, MEP objects (e.g., air conditioner, fire alarm, lighting devices) are turned into SCOs during the construction stage by embedding sensor networks, but their bigger value ia showing in the FM stage. By proactively collecting operation data through sensor networks, auto-monitoring of the MEP system is facilitated. It can meanwhile support emergency management, evacuation management, environment management, and energy management of cognitive FM. Passive monitoring by FM staff is replaced by proactive reporting with smart objects. Such a cognitive FM scenario will not only simplify the process of MEP monitoring, but also relieve FM staff from tedious and dangerous works. Therefore, the efficiency of FM will be improved, and the cost of monitoring will be reduced as well.

15.7. Discussions

The previous sections have introduced the SCO, cognitive FM, the framework and scenarios of SCO-enabled cognitive FM. The initiative is promising and feasible in the coming smart era. However, there are also some challenges ahead that should be discussed, including but not limited to power supply for SCOs, cost, data integration, and data storage.

At the technical part, the operability of the SCOs needs to be improved. Although pervasive sensing technologies are becoming increasingly accessible, one burning technical issue is the continuous power supply of the sensors. When the SCOs will be kept in the facility and operate for a long time, their power supply is a big and direct problem. Currently, some sensors/sensor networks rely on batteries for power, however, constrained by the duration of the batteries, they can only survive for days or months but incapable of working for a long period of time. Alternative methods offer rechargeable batteries or charging module for continuous power supply. However, the wiring, switching, and protection of such a complex system are also burdensome. Therefore, a better and smarter power supply for sensors/sensor networks is a tough problem to be overcome.

In the economic part, the cost is always the biggest concern. Although the prices of hardware such as sensors and integrated chips are declining quickly, the development of a platform that bridging the hardware and software is still relatively expensive. Besides, the cost of applying cognitive computing in such a platform is rather high. Patience should be paid for the maturing of algorithms and computing ability. The cost of adopting a new solution is, on the other hand, mainly contributed by managerial aspects. The training of new technicians, the changing of the organization, and the development of the new regulations at the initial stage will cost a lot of money. However, since the smart era is an irresistible trend, the upgrading of construction and FM is a must. From a long-term aspect, the investment at the initial stage can be compensated at later stages. The money will be saved by fewer manpower requirements, less routine and tedious works, less management expense, fewer errors, less repeated work, higher efficiency, more time saved, and better service provisioning. In summary, the benefits will offset the cost in the long-term.

The integration of data among different protocols is another challenging issue facing by most attempts of CPS development including in the built environment. Different sensors produce data with different formats, and different systems have different data requirements. The integration of data from different sources among different systems will inevitably cause the missing and garble of data. To share and communicate data among different hardware and software calls for a unified data protocol that is compatible. A unified data protocol is not only the gateway towards cognitive FM in the built environment, but also towards any IoT-enabled systems in the smart era.

With a large amount of heterogeneous data collected and cumulated, data storage is another issue with tremendous attention. Although the data storage capacity is increasing day by day, the accumulation of data increases even faster. Moreover, to avoid physical damage or failure of storage hardware, data backup is necessary but expensive. The cloud storage might be a feasible alternative but arguably because of being unsafe from attack and leakage. Consequently, a cheaper and safer data storage scheme is a non-trivial problem that should be seriously considered and discussed.

15.8. Conclusions and Future Work

This chapter proposed a new concept, together with a new framework, of SCO-enabled cognitive FM under the umbrella of the cyber-physical system (CPS) in the built environment. Based on two creative and futuristic concepts, smart construction object (SCO) and cognitive facility management (Cognitive FM) proposed by the authors, we take this chance to take a step further to integrate them for a bigger blueprint for the architecture, engineering, construction, and facility management (AEC/FM) industry. By integrating the two concepts, this initiative aims to enhance information continuity and credibility, management continuity, and life-cycle management in AEC/FM for better-informed decision-making and smarter services provisioning. The definitions, properties/key elements and framework/system architecture of SCO and cognitive FM are thus reviewed separately. After discussing the necessity and feasibility of integrating the two concepts, a framework of how they will be integrated is proposed. SCOs as the integration of sensing, communication, computing, and actuation technologies can work as smart objects during the operation and maintenance stage across different layers in the cognitive FM system architecture. SCOs are thus enablers of cognitive FM. To better illustrate the function of SCOs and their implementation in cognitive FM, two scenarios, i.e., proactive structure assessment, and MEP auto-monitoring, are briefly described.

Based on the discussion of challenges, there are plenty of works to be done in the future. Technically, in the meantime of developing higher performance sensors at cheaper prices, the power supply of the sensors should be paid more attention. A stable and durable power supply is the bottleneck of widespread SCO adoption and other IoT-related development. The integration of heterogeneous data is another burning issue, as well as the safe storage of increasing big data collected from different sensors and systems. Data, as the fuel of AI and robotics, is the fortune that should be carefully stored, protected, and utilized. On the economic aspect, empirical cases should be piloted and studied for a detailed cost-benefit analysis of the SCO-enabled cognitive FM. From the management perspective, how such an SCO-enabled cognitive FM system should be designed, organized, and managed is a primary issue to be attended to. Although there are a lot of future works to do, it is believed that SCO-enabled cognitive FM is a paradigm shift in the AEC/FM industry and will be accomplished in the near future.

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