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Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications

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ABSTRACT

The 21st century is witnessing a fast-paced digital revolution. A significant trend is that cyber and physical environments are being unprecedentedly entangled with the emergence of Internet of Things (IoT). IoT has been widely immersed into various domains in the industry. Among those areas where IoT would make significant impacts are building construction, operation, and management by facilitating high-class services, providing efficient functionalities, and moving towards sustainable development goals. So far, IoT itself has entered an ambiguous phase for industrial utilization, and there are limited number of studies focusing on the application of IoT in the building industry. Given the promising future impact of IoT technologies on buildings, and the increasing interests in interdisciplinary research among academics, this paper investigates the state-of-the-art projects and adoptions of IoT for the development of smart buildings within both academia and industry contexts. The wide-ranging IoT concepts are provided, covering the necessary breadth as well as relevant topic depth that directly relates to smart buildings. Current enabling technologies of IoT, especially those applied to buildings and related areas are summarized, which encompasses three different layers based on the conventional IoT architecture. Afterwards, several recent applications of IoT technologies on buildings towards the critical goals of smart buildings are selected and presented. Finally, the priorities and challenges of successful and seamless IoT integration for smart buildings are discussed. Besides, this paper discusses the future research questions to advance the implementation of IoT technologies in both building construction and operation phases. The paper argues that a mature adoption of IoT technologies in the building industry is not yet realized and, therefore, calls for more attention from researchers in the relevant fields from the application perspective.

1. Introduction

In the past decades, a great deal of research focused on smart buildings, communities, cities, and infrastructures [1,2]. Among others, one of the motivations behind these research activities is to develop an approach to provide reliable and energy efficient services without compromising the comfort and satisfaction level of people in the targeted contexts. However, until now, this topic is still being explored though researchers have studied related issues from different aspects [93–96], as the practical implementation plan is under investigation, and the topic involves an adaptation of technologies and knowledge from multi-disciplines. From the operational perspective, the current progress towards the development of smart buildings, communities, and cities may be described as isolated and segmented in terms of integration of technology and application development, mainly owing to the current IoT applications' limitations and sensor networks in buildings, cities, and infrastructures that are not seamlessly unified [3].

Buildings are one of the basic while crucial units for human's living environment. The concept of smart buildings originates with the increase in integration of advanced technology to buildings and their systems such that the buildings' whole life cycle can be remotely operated and controlled for convenience, comfort, and in a cost- and energy-efficient manner. It is widely accepted that the use of new technologies is a fundamental prerequisite to achieve the realization of smart buildings (also known as intelligent buildings), which includes, but is not limited to, sensor deployment, big data engineering and analytics, cloud and fog computing, software engineering development, and human-computer interaction algorithms, etc. Among these supporting technologies, one of the trending areas is the development of Internet of Things (IoT), as one of the challenges of smart buildings is to deal with a complex web of interconnected functional entities in different aspects of a building [4,5]. With the use of IoT, there is an

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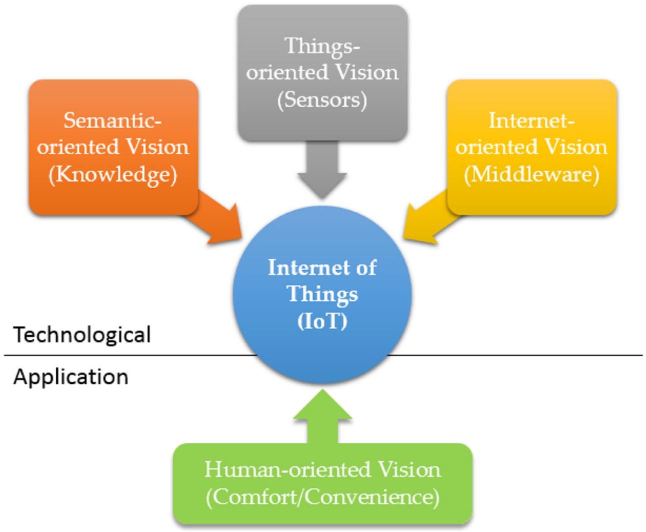

Fig. 1. Four main paradigms of IoT definitions.
(Adapted from [7]).

enormous potential to make considerable progress towards the envisioned goals. Given the diversity of the stakeholders and applications of IoT, a multitude of definitions for the technology are available in the literature [6]. On the technological side, IoT may be realized as the convergence of three major paradigms, namely: Things-oriented vision, Internet-oriented vision, and Semantic-oriented vision [7]. On this basis, the authors propose a Human-oriented vision to be incorporated as the fourth paradigm on the application side (Fig. 1).

The architecture of IoT is crafted to equip all objects with identifying, sensing, networking, and processing capabilities, so that these objects could exchange and share information with each other and develop advanced services over the Internet. Thus, the interconnection would further facilitate deeper insight of complex systems, provide dynamic context-aware decision-making capabilities and intelligent autonomy. These capabilities pave the way for achieving the goals in smart buildings which is integrated ambient intelligence by creating a global network supporting ubiquitous computing [8–10] as well as context-awareness among devices [11]. In 2008, the US National Intelligence Council envisioned IoT as one of the areas with potential influence on US comprehensive national power and included it in the list of six "Disruptive Civil Technologies" [12]. Not surprisingly, in the past five years, a speedy growth in number of connected devices has been observed. Cisco reported that in 2010, the number of connected devices per person is more than six considering those who use the Internet and estimated that the number of connected devices worldwide will rise from 20 billion today to 50 billion by 2020 [13,14].

The emergence of IoT is an evolutional outcome of a series of existing technologies such as wireless sensor networks (WSN), and machine-to-machine (M2M) communication, etc. The implications of IoT is two-fold:

- Integration of sensing, storage, network, processing, and computing capabilities into everyday objects (e.g. home appliances, door, window, lights, smoke detectors, etc.) and bringing them online, even though they might not be originally designed with these capabilities. This is contrary to most of the devices which are currently on the Internet and were originally designed to be part of it (e.g. smart phones, laptops, etc.).
- Integration of networks which include objects mentioned above. This would make them accessible via the network.

The ambient intelligence offered by IoT facilitates every object to understand their environments, establish meaningful interaction with people and assist people in decision-making. Although researchers are still facing technical challenges to develop, apply, and eventually maturing IoT [15], the technology has been given high expectation to be applicable to a variety of industries, such as healthcare, manufacturing, retail, farming, industrial automation, etc. [16,17]. Meanwhile, the Architecture, Engineering, Construction, and Operation (AECO) industry also attempts to adopt IoT to push the progress of connected informatization, which is one of the aims of smart buildings. However, the focus of researchers currently place on the development of application solutions of IoT in the building industry could be further strengthened. The reason is that, currently, most of the efforts are situated in the improvement of IoT technology itself, i.e., mostly concentrated in electrical engineering and computer science areas. Nevertheless, the collaboration of other disciplines including civil engineering or building technology is also required to identify the problems and challenges that would be solved or improved by using IoT and consequently facilitate the adaptability of IoT in smart buildings. Moreover, the research on application of IoT can conversely discover more potential problems and research directions on IoT development, both on the technological and methodological sides.

As a recent trend, IoT has started to penetrate in the building industry in the past years. Researchers and practitioners are both exploring the benefits and drawbacks of IoT through actual implementation. For example, several companies including IBM and Intel are already launching their products of smart buildings to the world [18], demonstrating the competitive edge and future tendency of IoT. Therefore, it is necessary to understand how to integrate IoT into this industry to benefit the development of smart buildings. However, to the best of the authors' knowledge, although surveys for IoT-based smart buildings exist (e.g. smart home technologies) [4,19], current literatures lack a comprehensive review and analysis of IoT applications to the overall fields for future building development. Furthermore, as the interest for interdisciplinary research continues to increase, an analytical review may be a new starting point for researchers in the fields of civil, construction, and architectural engineering. Hence, although the entire IoT sector is technology driven and suffers from a top down approach while the users are not the core that drives the change, a thorough understanding of the technical needs and potential application areas to the building industry is significant to help supplement improvement dimensions of IoT and expedite the development of smart buildings.

1.1. Research motivation and contribution

The motivation for this paper comes from the nature and requirement of smart buildings. A well-developed smart building contains extensive aspects of technical support, among which IoT is recognized as the crucial one. With the rapid pace of technology development and collaboration trends of different industries, this paper aims to guide stakeholders in the building industry of a better path to properly use IoT to address specific issues, and inspire researchers' thinking in the technology industry for future advancing. That said, this paper emphasizes the functionalities improved by IoT and the solutions of adopting IoT in buildings, instead of pointing out the technical defects of IoT itself.

In addition, this paper does not intend to discuss a single topic of smart buildings' multitudes of specifics that IoT can benefit, rather it aims to stand on a higher level to offer and deliberate a broad overview for researchers in relevant areas as a summary of the emerging literature targeting the application of IoT in the context of buildings. This paper can serve as an origin that leads to diverse tributary research questions for interested scholars.

Therefore, this paper is presented with a novel perspective and contributes in four primary aspects, namely: 1) to provide researchers and professionals in relevant fields of civil and construction engineering, building science, sustainability, etc., with holistic domain-related knowledge of IoT; 2) to fill the gap in the current literature by focusing on the current state and potential future of IoT in the building industry; 3) to discuss the current enabling technologies, applications, and recent developments of IoT, along with application recommendations for adopting IoT for the function improvement in buildings; and 4) to explore the challenges on the path of IoT for the building industry, including the whole building life cycle, i.e., cradle-to-grave.

A comprehensive survey of the literature was performed accordingly. Given that IoT is still in formative stages and has not yet been fully realized in the building industry, the reviewed literature included a diverse set of journal articles, conference papers, edited volumes, and technical reports in multiple fields such as computer science, or automation in construction, etc.

This paper is structured as follows: Section 1 introduces the concept of IoT and briefly reviews its potential in smart buildings. Section 2 discusses the generic architecture of IoT and enabling technologies as well as its connection to the building industry. Section 3 focuses on the current applications of IoT towards the implementation of smart buildings. Section 4 presents the development trends and elements to consider for IoT-based smart buildings. Section 5 discusses future requirements and development directions for application of IoT in the building industry. Finally, Section 6 concludes the paper.

2. Overview of IoT technology for smart buildings

From the users' perspective, a typical IoT system consists of five major components according to the components' contribution and function in IoT system, namely: 1) Devices or Sensors (terminal), 2) Networks (communication infrastructure), 3) Cloud (data repository and data processing infrastructure), 4) Analytics (computational and data mining algorithm), and 5) Actuators or User interfaces (services), as shown in Fig. 2.

The design of an IoT system architecture lies in the heart of enabling the functionality of an IoT system, which is interconnecting heterogeneous components anytime and anywhere through the Internet. The architecture of IoT system is typically divided on a layering basis, and many researchers have proposed their models to fulfill certain needs. Some common architectures include three-layer, SOA-based, middleware based, and five-layer; for additional details refer to [16,20–22]. For this paper, a more conventional architecture is adopted and discussed, namely three-layer architecture, along with its connection to smart buildings. Among others, one of the reasons to focus on this type of architecture is that the application layer is sub-divided into several sub-layers in other architecture types, while those sub-layers do not necessarily fit the scope and objective for smart buildings' development. Also, the three-layer architecture is more applicable for stakeholders from the IoT application perspective. Particularly for building industry researchers, a three-layer architecture is sufficient and suitable for an effective adoption of IoT for general functionality implementation.

The three-layered architecture of IoT consists of 1) Perception layer, 2) Network layer, and 3) Application layer. The perception layer which includes the perception nodes and perception networks is integrated into the target and is responsible for sensing and data collection. The network layer is responsible for data transportation, which is the most important layer in the architecture, as it is the convergence of various devices (e.g. gateway) and communication infrastructure. Finally, the application layer is the top layer which end users interact with. It receives the data transmitted and presents to users for further services. Fig. 3 shows the schematic view of the architecture.

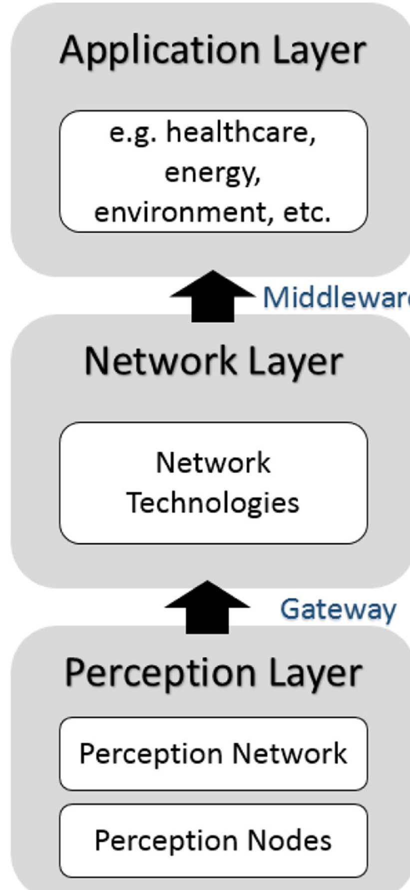

Fig. 3. Three-layer IoT architecture.

In each layer of this architecture, a wide range of technologies are available. In the following, some of the main enabling technologies and common standards/protocols are discussed.

2.1. Perception layer

The perception layer deals with data and information collection in the physical world and is usually represented by sensing and actuation

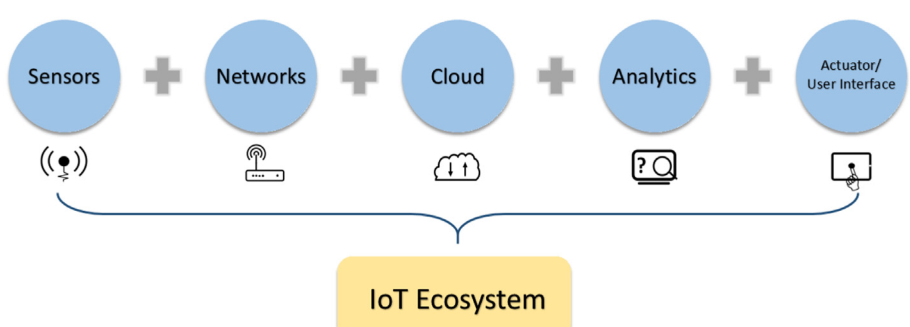

Fig. 2. Components of an IoT system.

Table 1
Challenges in sensing technologies commonly used in the building industry.

Technologies	Challenges
Wearable devices	1) Feasibility; 2) Privacy
Simple binary sensors	1) Power consumption; 2) Security; 3) Interoperability
Video camera	1) Storage requirements, 2) Information extraction, and 3) Social challenges around privacy
Bluetooth low-energy-based sensors	1) Sensing range limitations; 2) Costly, particularly for existing buildings
RFID	1) Reliability, 2) Stability
Infrastructure mediated systems	1) Insufficient detail on the activities, 2) Lack of contextual data collection capabilities

technologies. A sensor is a device that generates an electronic signal from a physical condition or event, while an actuator is a device that converts an electrical signal into action, often by converting the signal to nonelectrical energy, such as motion. Perception layer is mostly supported by the following technologies:

1) Wireless Sensor Networks (WSN): WSN consists of different types of sensors that automatically form a network following certain topology for communication purpose. Sensors can measure the physical world conditions such as position, occupancy, acceleration, velocity, motion, and temperature, etc. One of the benefits of WSN is the scalability and dynamic reconfiguration that allows remote monitoring through sensor node communication. WSN has been widely applied to the built environment area for monitoring parameters including ambient status, occupant behaviors, and energy use [23], for the purpose of monitoring indoor air quality and environmental health inside buildings.
2) Video cameras: video cameras could be considered as high-content sensors, with rich sources of information both for human observation and for computer interpretation. In comparison with other sensors, video cameras do not provide typical numerical or categorical data, but instead directly report the status of object or scenario, which sometimes accompany with social privacy issues. Besides, the storage requirements and information extraction process are more complex than simple binary sensors [17,24]. Video cameras can be used for building occupancy count and behavior to study energy use. Other approaches to building industry include the use of video cameras to monitor construction progress, manage building systems [25], etc. More prevalent are the use of Unmanned Aerial Vehicles (UAV)-based video monitoring for construction safety [26].
3) Radio frequency identification (RFID): RFID uses electromagnetic fields to automatically identify and track tags attached to objects. RFID tags usually come in two types, namely a) passive tags and b) active tags. Whereas passive tags are attached to an object for detecting users without any power source, active RFID tags are powered with a battery and create a greater range of service. RFID technology comes with some limitations such as limited reliability and stability mostly when the reading process happens through liquid or metals. Nevertheless, the ability of RFID tags to be placed out of sight and to track multiple objects or people make them a feasible choice for smart built environment applications [27]. In the building construction phase, one possible use of RFID is to track material transportation [28].
4) Others: besides the main technologies above, others include near field communication (NFC) devices, GPS [15], two-dimensional code [20], etc.

2.1.1. Standards

The standards of perception layer depend on the specific devices used in the IoT system. Organizations of ISO, IEC, IEEE created many world-wide standards to improve the level of compatibility. For example, ISO/IED 29182 formulates Sensor Network Reference Architecture (SNRA) for WSN [21]. The communication standard of WSN is usually represented by IEEE 802.15.4, a short-range communication protocol maintained by the IEEE 802.15 working group. For RFID, some standards are ISO 15459 which defines identification of individual transport product [29], ISO 11784 that regulates the data structure of RFID used in animal tracking, ISO 18047 for equipment performance testing and ISO 18000 for goods tracking [30].

2.1.2. Examples in the building industry on perception layer

In the research areas of built environment, the emphasis is usually placed on energy use, occupant activities, and environmental conditions. As a data sensing system, WSN attracts the interest of many scholars in the area, due to its low-cost and easy-to-deploy properties. Jang et al. [31] proposed a web-based WSN system for building environment monitoring. The system implementation starts from the sensor node design, which includes a microprocessor, radio hardware, sensor board, and power source. Temperature, light, acceleration, and magnetic sensors are embedded in the sensor node. Then, software was written to the on-board microprocessor to convert the sensors' signals to digital values. The system also involved data collection part using MySQL as the database. For the convenience at the user end, scripts were written in PHP to display the information needed on a webpage, so that the user will not be limited by skills in programming for access of data. The proposed system provided a potential path for engineers to use WSN for the whole building monitoring.

As concluded in [23], at the building level, the most common technologies of perception layer are: ambient sensors (e.g. temperature, humidity, CO_2), cameras, passive infrared (PIR), RFID, ultra-wide-band (UWB), and smart meters. In addition, infrastructure mediated systems could be another approach of sensing technology, which are distributed in target infrastructure [27]. Table 1 summarizes the categories of sensing technologies in the building scope and their current bottleneck.

2.2. Network layer

As the technical core of IoT system, network layer, which is also referred as transportation layer, is responsible for processing and transmitting the raw data obtained from perception layer. Network is defined as a mechanism for communicating an electronic signal. Moreover, this layer takes care of functions such as computing and data management processes. To transmit data among networks, there are two main ways of connection: wired and wireless communications. Due to the fact that wireless technology has more advantages over wired connection, and the future IoT will be expanded to the worldwide scale, the following only describes some main wireless technologies/media.

1) Wi-Fi: Wi-Fi is a communication technology that uses radio waves for local area networking among devices based on the IEEE 802.11 Standards. The most commonly used frequency is the 2.4 GHz UHF and 5.8 GHz SHF ISM radio bands. The technology is already used widely in personal computers, phones and tablets, smart TVs, and many other daily devices. One of the advantages of Wi-Fi is that any devices within the range of wireless modem can attempt to access the network. However, this is also a shortcoming due to security issues, as it is comparatively vulnerable to attack in contrast to wired cable connection.
2) Bluetooth: Bluetooth is another wireless communication technology for data exchange between devices over short distances. This

technology is initially invented by telecom company Ericsson [32], which overcomes the problem of data synchronization. It is now managed and maintained by Bluetooth Special Interest Group (SIG), with the newest version of Bluetooth 5, from the most-up-to-date announcement [33]. Bluetooth is suitable for physically smaller devices such as telephones, speakers, media players, personal computers, etc.
3) Zigbee: Zigbee is an IEEE 802.15.4-based specification designed for short-term communication with low-energy consumption. Therefore, it is used in many WSN systems at the network layer. Zigbee network layer support multiple topologies, namely star, tree and mesh networks. The worldwide approved ISM radio bands for Zigbee is 2.4 GHZ, while other frequencies are also available to use in different countries. The properties of the technologies are low-cost, low-power, low data rate, and self-organizing.
4) Long-Term Evolution (LTE): LTE is developed for high speed wireless communication based on GSM/EDGE and UMTS/HSxPA network technologies [34]. It is commonly referred as 4G LTE, while it is not exactly the 4G successor, as it does not meet some of the criteria of a 4G network. LTE has been going into service in the industry for mobile phones communication, due to its capability of providing multicasting and broadcasting service.
5) Other popular technologies at the network layer include *Z*-Wave, RFID, WAVE, IrDA, and USB (wired). The main enabling technologies are categorized in Table 2, according to the connection type and coverage range.

2.2.1. Standards/protocols

The transmission of data in the network layer must conform to communication protocols in support of IoT system. These protocols or standards are defined and proposed by different groups, such as IETF, IEEE, ETSI, etc., and are officially accepted in the industry for unified management. For example, ISO/IEC 8802 series include the international standards related to network layer of IoT for both local area networks and metropolitan area networks. Among the variety of existing protocols, a few commonly shared ones are presented as follows:

1) IPV6 (6LoWPAN): 6LoWPAN is designed by combining Low-power wireless personal area networks (LoWPAN) and IPv6. It is one of the infrastructure layer protocols that provides header compression for transmission overhead reduction. The advantages include high connectivity and compatibility with low-energy consumption.
2) MQTT: Message Queue Telemetry Transport (MQTT) is a message protocol for connecting remote embedded sensors and middleware. It is one of the application layer protocols. One advantage of MQTT is the adaptability for various platforms to connect things into the Internet.
3) CoAP: Constrained Application Protocol (CoAP) is also a messaging protocol that is based on REST on top of HTTP functionalities. The protocol is built for resource-constrained devices in the IoT due to the complexity of HTTP. Specifically, CoAP enables small devices with lower power, low computation and communication capabilities to use RESTful interactions.

In addition to the protocols above, others that are defined in different layers are HTTP, DDS, AMQP, XMPP. Note that in network layer of IoT, there are different sub-layers inside, and in general the protocols usually refer to the higher layers inside the network layer. Detailed introductions of the common network layer protocols could be referred to [15,16,20–22].

2.2.2. Examples in the building industry on network layer

A large amount of research has been conducted on the communication protocols for building automation IoT systems. On one hand, for larger scale systems, because of the complexity and variety of services, the development for specific network layer technologies or

Table 2
The enabling technologies for communication and their challenges.

Connection Type	Personal area network (PAN)	Local area network (LAN)	Wide area network (WAN)	Challenges
Wired connections	USB	Ethernet	Optic fiber, ADSL	1) Interconnections, 2) Network Penetration, 3) Security, And 4) Power
Wireless connections	Bluetooth, Zigbee, Wi-Fi, Wireless USB, IrDA	Wi-Fi & WiMAX	WiMAX and cellular technology 2G, 3G, 4G (LTE), and 5G	

standards are still at the research stage. For instance, Zanella and Vangelista [35] studied the existing IoT technologies that would be suitable for urban level. Their proposed architecture covers the 1) Web service approach for IoT service architecture which consists of possible samples of data format, application and transport layers, and network layer; 2) Link layer technologies; and 3) Devices that consist of backend servers, gateways, and IoT peripheral nodes. On the other hand, at the building level, although ongoing research is still being conducted, there are two standards employed in the industry as discussed below.

A network-based approach provides real-time monitoring and control along with the capability to gather, store, and analyze information related to the building [36]. However, different vendors provide solutions based on diverse network technologies. While gateways can solve some of the problems of integration, they cannot be considered as a long-term solution and hence there is a need for development of industry-wide communication standards. To address this issue, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) developed the Building Automation and Control Network (BACnet) which provides the necessary platform for integration. The protocol specifies rules for plenty sorts of building systems but is mostly dealing with electrical and mechanical systems in the building. The protocol stack of BACnet can be further referred in [36,37].

LonWorks, as a specific protocol developed by Echelon, is a name given to a group of technologies that are used to implement control networks. Each device in a LonWorks network is referred to as a node and each node consists of a “neuron chip” and a communication transceiver. The neuron chip has certain processing capabilities along with the ability to implement the LonWorks Protocol, which is the protocol standard used by LonWorks nodes. The transceiver provides an interface between the “Neuron” and the network field bus thus enabling connectivity to a number of transmission media. The LonWorks network also consists of repeaters, routers and the physical channel. A “segment” in the network is an uninterrupted piece of wire. A segment can sustain up to 64 devices [38]. The main advantage of LonWorks is that devices communicate with each other without the interference of an external “master”. The LonWorks protocol is also adopted under the BACnet standard and, hence, the LonWorks network can be incorporated into home networks that support BACnet.

2.3. Application layer

Although network layer can handle functions of data management and processing, these roles are mainly played in the application layer of IoT. In fact, application layer contains the most functioning modules in the IoT system. This layer serves as the front-end interface to provide analysis and decision-making results for users in related business or industrial domains. Therefore, it is the integration of IoT technology and any industry expertise for the specific intelligent application solutions [22]. In contrast to other IoT architectures, the application layer is in correspondence to business, application, and service management layers in the five-layer architecture, or service and application layers in the SOA-based architecture [16]. This reflects the broad services and requirements of this layer. Hence, the enabling technologies in the application layer vary based on the application domain of the IoT system. Thus, this section presents some popular and advanced technologies that are shared by different areas, from the perspective of information processing and analysis.

1) Augmented Intelligence: it is related to the analytical tools that ameliorate the capability to describe, predict and use relationships among phenomena. It is part of the conceptualization of artificial intelligence (AI), except that augmented intelligence emphasis more on enhancing human intelligence instead of replacing it. Generally, augmented intelligence program assists people to make decisions based on the statistical data so that the results are usually optimized to reach the application desire. Depending on the application areas, augmented intelligence is realized through different techniques and paths:

- Predictive Analytics & Machine Learning: machine learning is a method used to design complex models and algorithms that leads the computer to predict for humans, while in commercial use, it is also known as predictive analytics.
- Computer vision: computer vision is considered as an interdisciplinary field that focusing on digital images or videos to gain deep-level knowledge. The tasks include acquiring, processing and analyzing digital image data for related results derivation. This technique is often related to video cameras as the raw data source, which is mentioned in the previous section.
- Natural Language processing (NLP): NLP aims to interpret human (natural) languages to machine-understandable language, which combines the fields of computer science, linguistics, and computational mathematics. This technique will be widely used since most people do not have the expertise in communicating with computers directly. NLP will be involved as the bridge between human and computers.
- Speech Recognition: as the name indicates, speech recognition enables the recognition and translation of spoken language of human into text by computers. This technology has been studied by high-tech companies in the industry and is gradually integrated into smart built environment research.

2) Augmented Cognition: technologies and techniques that improve compliance with prescribed actions. Augmented cognition is more of a research task that focuses on environments where human-computer interaction exists. This concept leans on the human side with areas of psychology, cognition, and behavioral sciences that are associated with several high technologies:

- Big Data: this is a terminology that came in the early 2000s and the implication of “big” is three-fold including big volume of data, big velocity of data, and big variety of data. Big data can be further divided into two aspects, namely Big Data Engineering and Big Data Analytics [39].
- Cloud Computing: due to the fact of “big data”, corresponding computing ability is necessary to support data storage and analysis. Cloud computing is a form of Internet-based computing technique that provides shared computer resources for other devices on demand. Since average sensors/actuators do not always have a powerful computing capability, cloud computing will be playing the major role of data processing in the future.
- Cognitive Technologies: the ultimate goal of cognitive technologies is to make computers think as human beings. Most of the cognitive technologies are actually the integration of the concepts mentioned above rather than an independent field. These technologies have not been fully studied to be applied to building industry.

2.3.1. Standards

Due to the vast application areas of IoT, it is difficult to have a standard that governs every aspect of the layer. However, in terms of data format, there are certain standards including ONS (Object Name Service), Next-Generation Telematics Protocol (NGTP), Electronic Device Description Language (EDDL), M2MXML, BITXML, etc. [21]. The industry has already realized the importance of establishing IoT data standards and messaging protocols and has been seeking cooperation within industry-wide organizations, particularly for smart building development [40]. Furthermore, standards for data security of sensors and network systems exist. An example is ISO/IEC 29180, which constitutes clauses on security framework for ubiquitous sensor networks.

It should be noted that the application layer discussed in this section is different from other literatures on IoT which categorized the network layer into 5 sub-layers, with one of which defined as application layer. That "application layer" is within the scope of network communication levels, while the related standards are already involved in Section 2.2.

2.3.2. Examples in the building industry on application layer

According to [21], application layer is composed of two components: the computation layer and the domain application layer. Since this paper is expanded around the application of IoT in the domain of smart buildings, the latter component is presented in the following section (Section 3) while connections between computation layer and building industry are briefly discussed as the supplementary to the technologies described above.

For example, in the building industry, the dataset characteristics remarkably agree with the three pillars of Big Data: 1) As sensors are deployed in the building as well as on site, large volume of data will be easily collected; 2) in order to maintain a high-level service to humans, these data have to be transmitted, stored, and processed in short duration/granularity; and 3) different types of data will appear including environmental conditions, building energy use, occupant information, etc. In [41], the researchers proposed a benchmarking method for energy performance at the city-scale based on collected dataset of over 10,000 buildings in New York City. The researchers used coupled datasets of actual building energy use and building characteristics from the city for one calendar year, which involves an enormous amount of data.

Regarding algorithm design, Li et al. [42] proposed two indoor localization approaches for building emergency response, such as fire threat. Their approaches were based on RFID technology and achieved a room-level accuracy of above 80%. Although not a typical IoT application, that research shows a potential of IoT in future development orientation for building safety issues, which is also part of the smart building goals.

3. Opportunities of IoT in smart buildings

From Section 2, it can be observed that the connection between IoT and building industry exists at each layer of the technology. The integration opens the window for future evolution towards the goals of smart buildings. This section in turn provides a review of current IoT application cases, and categorized them based on the critical functionalities and objectives of smart buildings. Table 3 summarizes the selected examples.

Smart buildings encompass a wide variety of sensors, actuators, devices, and control systems that are interconnected and jointly function to improve the service for its occupants. A part of the concept of smart buildings involves integrating a communication network within the buildings' elements so that they can be manipulated or monitored remotely [43]. For example, before the air conditioner is turned on, an action that is triggered by temperature change, all the windows must be automatically closed. Thus, a sensor must trigger the air conditioner, and then information should be exchanged between the air conditioner and windows. From a technical interoperability perspective, it is more likely that the systems controlling the windows and the air conditioner are made by different manufacturers. This calls for an integration process for an automating control and management of the building. Besides this fundamental feature, Table 4 briefly presents the primary functional goals and technical requirements for smart buildings. In the following, a series of IoT enabled services and applications in smart buildings are discussed, which can directly or indirectly facilitate the achievement of these goals.

3.1. Localization for occupants and resources tracking

Indoor localization is of great value for improving building performance. For instance, occupants that are unfamiliar with a building could be provided with navigation to destination; the occupancy information acquired from localization information could be used to distribute resource in a balanced way; building managers could locate any equipment or facilities that needs maintenance or repair to increase their work productivity. Moreover, occupants' localization will help understand occupant behaviors and predict unique events inside buildings.

Currently, the role of building occupants has not been sufficiently taken into consideration and occupants' behavior is assumed to be static, and in some cases one or few representative profiles are used for building operation and management [44,45]. This causes consequences such as inefficient resource use or energy waste. To understand occupants' behavior is complicated while a challenging part is the ability to locate them while they are inside the buildings. Evidently, current GPS technologies do not possess desired accuracy inside the buildings as they are mostly designed for geo-fencing and zone-based services. A promising part of IoT is improvements in micro-location technologies which can locate any entity with a very high accuracy - possibly up to few inches. Essentially, micro-location is a geo-fence with high certainty, providing the ability to position and track any object inside the building, and consequently used for better and more efficient service provision (e.g. thermal comfort, lighting, preference-based services, etc.) [46].

There are five main technologies in the market for micro-location using IoT [46], namely: 1) Bluetooth Low-Energy (BLE)-Based Beacons/ iBeacons, 2) UWB-Based Micro-location (Ultra-wide band), 3) Wireless Positioning Systems, 4) Magnetic Field Mapping, and 5) RFID. Among them, BLE is becoming more and more popular due to its features of low power and ease of use, as they can be connected to handheld devices such as mobiles and tablets.

Specifically, Apple iBeacon protocol was introduced in 2013. A beacon-based BLE approach can be used to determine an occupant's location. For example, beacon devices can be configured to periodically send beacon signals that can be picked up by smart phones and to determine location. BLE is a low-power wireless technology that ameliorated existing Bluetooth technology to make it suitable for short-range control and monitoring [47]. A promising part of BLE is its capability to run over IPv6 [48] making it highly suitable for IoT enabled environments. An example of iBeacon-based localization is [49] that designed an indoor positioning system in hospital. In their study, the experiment users are carrying a mobile phone with iBeacon ID. When a user enters the hospital, iBeacon will send location information to the server through client end, and the server sends back a message directing a shortest path for the patient to his/her department through Wi-Fi, 3G, or 4G.

Alletto et al. [50] proposed a location-aware system for an IoT-based museum, which serves as a smart tourist guide for visitors. The visitor is equipped with a wearable device that combines capabilities of image recognition and location awareness. In this way, when the visitor reaches a place with certain artwork or historical context, the wearable device tracks the user by leveraging a BLE infrastructure and thus the processing center takes the information to interact with user and provide interesting contents for the user.

Besides BLE, other technologies are also useful for localization. Lee et al. [51] developed a home indoor positioning system that provides location information based on mobile phones. The novel part of the system is the use of a mobile vacuum robots for constructing the Wi-Fi radio map, so that Wi-Fi fingerprints labeled with their location information is available for positioning services. The high accuracy of the simple system could enable various location-based IoT applications in a home environment. Besides, RFID technology is used for asset and resource tracking by industry companies [52]. This solution can record location and usage of assets and generate reports for users, through RFID tags on corresponding objects.

On the technical side, there are some common issues for IoT-based localization technologies. The main challenges are 1) Interoperability,

Table 3
Review of application cases of IoT in smart buildings.

Building type	Application area	Academia/ industry	Country/region	Key technologies	Related data	Ref.
Hospital	Occupant localization for hospital department route direction	Academia	China	Mobile phone, tablet	iBeacon ID, user personal information	[49]
Museum	Occupant localization for artwork information access in museum	Academic	Italy	Wearable device, processing center, multimedia wall	User location, all sorts of content information of each artwork	[50]
Apartment	General localization, no application case	Academia	Korea	Intelligent mobile robot	Wi-Fi signals	[51]
General type	Tracking asset in buildings for physical equipment record	Industry	United States	Barcode tags, RFID	Location and usage of assets	[52]
Home and office building	Multi-source energy saving policy based on predicted arrival of occupants	Academia	United States	Smart phone with GPS, Cloud computing at server end	Distance to destination, appliance electricity use	[56]
General type	Energy consumption monitoring and energy-saving management system	Academia	China	Sensor networks	Building energy consumption data from HVAC, plumbing, power distribution systems, lighting systems; environment information	[57]
Residential building	Smart grid (energy control) system for residential building	Academia	Singapore	Smart plug, multi-purpose node, BLE sensor, smart gateway	Depends on different functions of the system, e.g. dynamic pricing information	[58]
Business building	Building maintenance applications for end users	Academia	Italy	Focusing on ontology design and application development	Equipment conditions (e.g. maintenance parameters, temperature of object), etc.	[63]
Educational buildings	Preventive maintenance of centralized HVAC systems	Academia	United States	Distributed acoustic sensing platform	Audio signals from HVAC systems	[64]
Office building	Smart facility management for different groups of people	Industry	Netherland	Sensors, cloud storage	CO2, temperature, occupation, humidity, light intensity, activity	[65]
Commercial building	Soft FM and hard FM	Industry	UK	Sensors, cloud platform for analysis	Different use cases have corresponding measuring parameters	[66]
Home building	Monitoring domestic housing conditions	Academia	New Zealand	Zigbee WSN, web interface at user end	Attributes of hot water, current and voltage of appliances, environmental conditions	[71]
General type	Integrating with Big Data platform for indoor environment analysis	Academia	Australia	Hadoop (for big data ingestion and analytics)	Oxygen level, luminosity, and smoke/hazardous gases	[72]
Office building	Intelligent building solutions (occupant comfort and energy savings)	Industry	United States	N/A	Indoor temperature	[73]
Healthcare-related buildings	Smart system for healthcare (cost-effective services)	Academia	United States	Cloud services, RFID/barcode, big data, web 2.0/3.0	Data selection depends on use cases (4 examples in the implementation part)	[75]
Commercial building	Smart meeting space with real-time room occupancy status and reservation facility	Academia	India	PIR sensor and Arduino Microcontroller, smart gateway (Raspberry Pi 3)	Room occupancy and environment	[79]
Parking structure	Automated parking systems	Industry	Taiwan	Camera sensors, card readers, smart gateways	Field data such as empty parking space, car information, maintenance request	[78]
General type	Smart grid system (Review of smart meters in power grid)	Academia	United States	Smart meters	N/A	[60]
Office building (six-story)	Structural health monitoring and early warning system for buildings	Academia	China	Sensing layer (pressure sensor), iDataBox (PC and wireless transmission units)	Steel stress, earth pressure	[81]
Residential buildings	Smart community (neighborhood watch and pervasive healthcare)	Academia	Canada	Body sensors, home surveillance systems	Body sensor readings and personal health information	[76]
General type (4 rooms)	Occupant safety and emergency management	Academia	Italy	Mobile devices, DangerCore, VirtualSensor, Wi-Fi, 4G, SMS	Feedback of users (noise, location, etc.)	[77]
Residential (smart home)	Remote monitoring of different home automation systems	Academia	Czech Republic	openHAB, Raspberry Pi (smart board), SNMP, HTTP (communication protocol)	N/A (this research focused on network communication development for the proposed system)	[80]
Dormitory and laboratory	Microservice-based IoT system (no specific application)	Academia	Russia	Raspberry Pi, SensorTags (CC2650), door sensor, human-trackers	Temperature, humidity, luminosity, pressure, door status, occupancy	[82]

Table 4
Major goals of smart buildings[a].

Goals	Descriptions	Technical Requirements
Location-based services	Identify building occupants or resources locations and movements for improving convenience of services in building	Track accurate position of targeted objects
Energy efficiency	Maximize the use of building energy, with the ideal condition to be a Net Zero Building (NZB), while keep a high level of service at the same time	Communicate with external elements (building-to-building, or building-to-infrastructure)
Proactive building equipment' maintenance (facility management)	Preventive maintenance and organized operation and control of building facilities and equipment to reduce operations and maintenance time and cost	Establish communication between building's equipment and devices
Indoor occupant comfort	Optimize ambient environmental conditions according to occupants' preferences for improving health and productivity	Understand occupants' behavior pattern

[a] Technically, the technical requirements should be integrated to realize the goals, while the separation here is for emphasizing the requirement of that particular goal.

which includes technologies, software development kits, and protocols. For example, a) a UWB-based micro-location system cannot be integrated with an iBeacon-based system, and b) within the iBeacon platform, there are different vendors that provide iBeacon-based micro-location enabling services that lack interoperability. Estimate-based iBeacon cannot be detected by Gimbal's mobile application and vice versa. 2) Stability. For example, the main issue with RFID technology is how collision is handled. If buildings are heavily populated, then the accuracy of such a method may be compromised [53].

3.2. Energy management

Building energy efficiency is among one of the most significant research topics so far, not only in smart buildings development, since buildings account for 40% of the total energy consumption in the world [54]. Yet, on the other hand, a smart building should not compromise the service level for building users or occupants to realize this goal, which calls for a solution to satisfy both sides. Some commercial Building Energy Management Systems (BEMS) [55] are already available that help control, monitor, and optimize building energy use currently. These systems normally installed non-intrusive meters at electric circuits to collect energy use data for users and managers. However, there is still much improving potential at this point. Smart buildings need to be configured according to specific requirements and this requires a certain level of context awareness. This means that the status of both the environment and the occupants plays a key role in how a smart building should operate. For example, the HVAC system needs to be set in accordance with the number of people in the room and the lighting system should monitor the lighting intensity outside of the building and set the lighting inside in accordance to that. With the support of IoT, this mechanism could be achieved, as studied by many researchers.

Pan et al. [56] first examined the statistical relationship between total energy use, heating and cooling energy use and environmental factors/occupancy status. Conclusion was drawn that energy is wasted although it was designed to be "green". To solve this problem, the researchers designed a location-based automated energy control framework. They used the cellphone of the experimental objects, with GPS location sensors and many other auxiliary facilities. Wi-Fi was used as the communication technology. The system stored map information and thus calculated the distance between the destination building and the mobile device and if the distance is less than a specific threshold, the energy policy plan will be updated, for example turn on/off air conditioning, to save energy use and still have the same level of service. They tested the result with electricity meter and simulated scenarios to demonstrate the effectiveness of the IoT-based framework.

Similarly, Wei and Li [57] proposed an energy use monitoring and saving system for smart building based on IoT. The system contains the traditional three layers, with sensors for all the subsystems in the building. The scale is limited to local area network, and the application layer oversees fault analysis, energy management, and equipment monitoring. The pitfall of the study is lack of actual implementation of testing cases.

Viswanath et al. [58] developed a system with IoT elements deployment and software designs on residential buildings. Each unit of their experiment has a set of sensors, actuators, smart plugs, smart meters, and a universal home gateway (UHG). The UHG is responsible for communicating with the other devices and a cloud server, where information-gathering and processing is done. This system allows a demand response adjustment of building systems to avoid high peak or high pricing period, for a more balanced load control. Plus, the application developed on the user end enables other functions including energy monitoring, home automation, and home security. Users could view dynamic pricing information to choose low load-consuming tasks for their preferences with the system.

IoT enables smart grid to manage energy use in a macro perspective with respect to building energy efficiency. The smart grid consists of computer networks that work along with the power infrastructure to manage and monitor energy use [59]. The traditional electric grids are incapable of adequately handling the rising and fluctuating energy demands. The smart grid establishes a two-way communication between the utility provider and customer that enables both information and energy transfer. One of the key elements of the smart grid that enables the two-way communication is the smart meter. A smart meter is an advanced energy meter that not just measures real time energy consumption but also additional properties such as voltage, phase angle and the frequency. Apart from this, they can also communicate diagnostic information and communicate with other smart meters [60].

The future of building energy efficiency will become more and more prominent as the industry around the world have been setting targets to promote this task. For example, United States Environmental Protection Agency (USEPC) is targeting a 20% of commercial buildings energy reduction by 2020 to 2030, and the government in Taiwan expects 33% by 2025 [61]. With the assistance of IoT, industry will have greater opportunities to realize these targets, and eventually benefit to global environment change and resource saving.

3.3. Facility management

In a building life cycle, operation phase takes up the longest period. Therefore, facility management is another goal of smart building, which integrates organizational activities to maintain efficient and effective services. Facility management (FM) requires timely preventive maintenance and malfunction detection of building equipment to ensure the facility's optimal condition. Traditional FM has problems of lower data quality, longer notification time, and delay in relevant operation and maintenance. Under this circumstance, IoT provides adaptive and real-time access to building facilities for relevant personnel. Efficient FM will bring many benefits, including potential to improve health and comfort of occupants, enhance quality of facility services overall, reduce cost of repair and building energy use, having means for efficient planning and resources use, etc. [62]. Several use cases of IoT in smart facility management are available, which are described below.

A smart building maintenance platform by D'Elia et al. [63] realized a set of context-aware smart maintenance applications that utilized environmental sensors to monitor related variables, such as temperature and humidity, and automatically report feedbacks. For example, if "temperature-out-of-range" message is generated, this platform is able to detect the location and the possible faulty equipment, HVAC in this case, and notify the corresponding human operator through personal device. Additionally, suggested corrective intervention instance will be provided to both the personnel and tenant as to facilitate the repair process. The idea of the platform could be extended to all building systems within a smart building, as well as building structure for automatic monitoring of the whole building. More recently, Srinivasan et al. [64] and Nirjon et al. [92] are developing an acoustic-based HVAC maintenance system by collecting, transmitting the audio signals via the Internet, processing, and characterizing the audio signature with corresponding HVAC system-related component data.

An exciting fact is that smart facility management based on IoT has been adopted by industrial companies. A Dutch company [65], launched a platform consisting of an application and data center to store sensor collected data of CO_2 levels, temperature, occupation, humidity, light intensity, activity (usage) in buildings. With cloud computing provided by Microsoft Azure, decisions are made based on the data and exhibit to the users with dashboard. A noticeable phenomenon is that the sensors are connected wirelessly via LoRa (WAN), and Netherlands was the first country to have full nation-wide LoRa coverage, which showed their strong potential for IoT applications.

In addition, Streather [66] listed several use cases of their IoT product for soft FM and hard FM. One example in soft FM is the hot desk monitoring, where presence sensors are installed under desks, so that people could remotely know any open spaces for them to book, and power or HVAC could be cut off for unoccupied desk areas; for hard FM, vibration/pressure differential sensors are used to monitor any assets such as air handler/fan units, thus it would be able to predict possible failure, and parts to be replaced to improve efficiency of an asset. In the US, IBM company [67] developed their own IoT system for facility maintenance and operations, which supports preventive and condition-based maintenance.

According to [68], a survey towards a number of facility managers in the industry showed an improving desire to investigate IoT technology to the buildings they manage. This is a sufficient proof that IoT plays an important role in FM. Although FM is facing several challenges such as no unified interface for FM system and inability to store and process large volumes of data [69], the development of IoT and other technologies (e.g. Big Data processing) will deliver real value to the industry for FM in buildings.

3.4. Indoor comfort enhancement

Same as energy efficiency, occupant's comfort is another primary concern of smart building in that it is the basic requirement of buildings to maintain comfortable ambient conditions for building users/occupants. Furthermore, people on average spend 80% of their lifetime in buildings [70], therefore a healthy and comfortable indoor environment is important for occupants' well-being and productivity. A robust monitoring and control of the indoor built environment is necessary and must be realized in real-time. On a more advanced level, the future building systems, such as HVAC, would be integrated with sensor and actuators, so that the temperature settings could be automatically adjusted according to the occupants' preference and requirement based on historical information through empirical learning. All these intelligent features will be developed on the basis of IoT system, for data collection, decision making, and sending commands, etc.

Smart home is usually the first building type to start with occupant comfort research using IoT system. Kelly et al. [71] implemented an IoT system for indoor environmental condition monitoring and utility usage for residential buildings. This system used ZigBee WSN that comprises of XBee-S2 modules to form the sensing network, and a gateway is the key to bridge information transformation between ZigBee and IPv6. The main contribution of this system is to demonstrate the interconnection ability with the WSN and the IPv6, so that a low-cost while flexible system is available for integrating IoT with home monitoring systems.

Bashir and Gill [72] proposed an integrated framework of IoT big data analytics (IBDA) for monitoring and controlling the building in real time. They simulated three environmental data including oxygen, smoke/hazardous gases, and luminosity in five different zones, and fed the data to Cloudera Hadoop Distributed Files system to make control decisions when the data value is out of the pre-defined comfortable range. Some pitfalls of the research are: 1) no energy concern, as the control strategies only care about occupant comfort; 2) no real IoT system test, since the researchers focused on real time data analysis and visualization.

Similarly, industry also have related solutions for the purpose of human comfort in smart buildings. Talon and Goldstein [73] presented how the IoT system developed by Intel corporation could be partnering with other domain experts to change experience for different stakeholders. One possible use of the system is to make people the sensors in a commercial building, by providing user interface on smartphones that allows office dwellers to send hot or cold complaints to the analytics engine. Optimal temperature settings are tuned based on the feedbacks across different zones in the office, and the HVAC system executes the mission to maximize occupant comfort.

It is worthy to mention that occupant comfort and building energy saving sometimes stand on the adversarial sides, therefore it is always meaningful to address both issues together when designing intelligent solutions for buildings. In fact, it turns out that this balance could be achieved with the use of IoT. Hence, the authors claim that occupant information should be involved in any comfort versus energy efficiency research, which requires the identification of useful parameters and the development of IoT technologies. [74] is a trial for this concern, which tested three buildings for results comparison.

3.5. Others

Apparently, smart buildings include plenty of aspects in addition to the main topics above. These smart features are usually in accordance with the special scenario or building type. Several case studies are presented in this sub-section as additional specifications.

3.5.1. Occupant safety and health security

Indoor safety and healthcare is valued by most building occupants, and this concern can also be improved by IoT implementation. [75] is an example for healthcare systems that is automated, intelligent and sustainable. Unobtrusive sensors that monitor the environment as well as the patient condition are linked to wearable interactive devices to enable a thorough evaluation of the health of a particular space as well the people in them. The IoT features that enable the smart healthcare systems are: 1) Portability and unobtrusiveness: Small devices that are embedded in the environment or unobtrusively on patient bodies to monitor patient health and communicate wirelessly; 2) Ease of deployment and scalability: a large number of devices will be deployed; 3) Real-time and always-on: Both the environment and the patient need to be continuously monitored so that response to any kind of emergency can be immediate; and 4) Reconfiguration and self-organization: Sensors can be removed or added any time by medical professionals. These changes should be accommodated easily and the sensor network should be self-organizing.

On a wider scale, Li et al. [76] formed the architecture of smart community on three domains, and also introduced the application of IoT on healthcare. Wireless body sensors are deployed around human body, so when a health emergency occurs, it will be reported by the

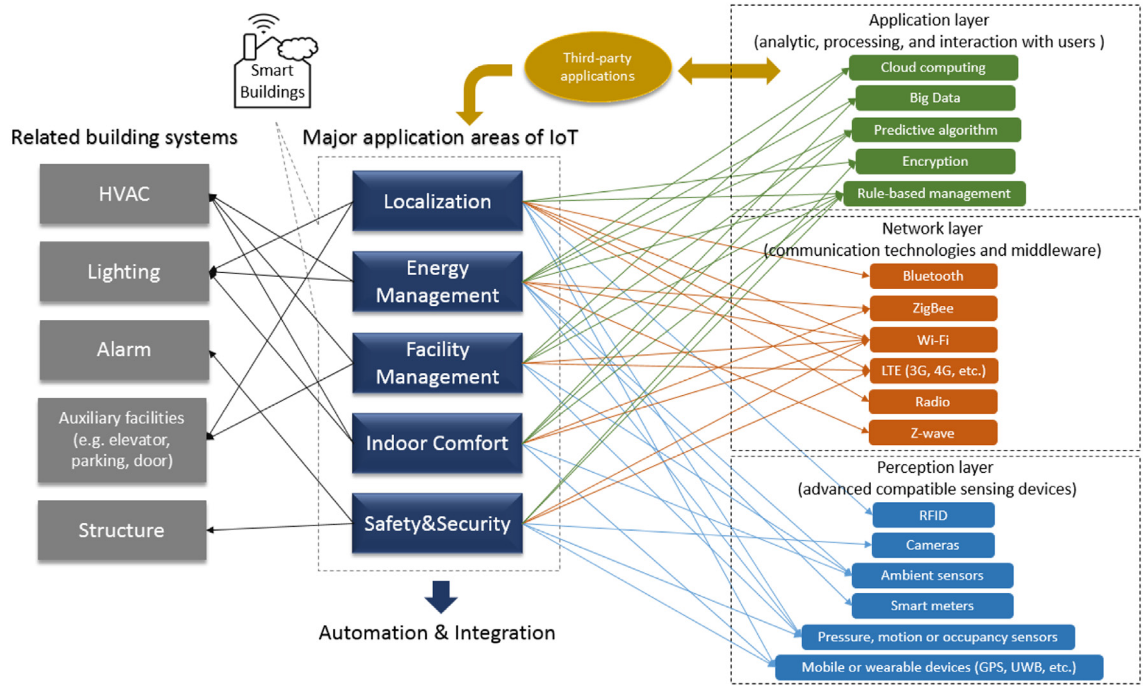

Fig. 4. Summary of application of IoT on smart buildings (goals, technologies, and related building systems).

sensors or home surveillance systems, so that the readings and personal information could be immediately sent to healthcare place for first time aid.

Piscitello et al. [77] proposed a Danger-System which is able to detect safety-related emergency and provide alert and rescue solutions for building occupants. The system utilized the application installed in users' smartphones to detect events such as user running or loud noise, and aggregate all the information to generate potential emergency activation. After the message is confirmed by building manager, notifications are sent to all users according to their current situation (e.g. location) and the building alarm is switched on.

3.5.2. Efficient resource management for convenience

IoT is able to increase convenience and efficiency in a building via resource management. Incorporating IoT into parking structures is applied in the industry, for the purpose of reducing unnecessary search of parking. An example of smart parking systems was proposed by [78] in which an automated parking structure can be equipped with integrated electromechanical transmission control, security control, detection systems and automated placement systems. The systems support features such as 1) vehicle measurement, 2) image analysis, 3) electronic payment scanning, and 4) automatic retrieval. According to [78], using a specific IoT gateway to connect the processing micro-computer, sensors, and other devices, field data in the parking system can be collected, stored and analyzed through the cloud. With the IoT system, the control center is able to remotely monitor and control the parking structure in real-time for a more efficient and smooth management for parking vehicles. The parking system could expand by linking the micro-system with the main control system that allows administrators to acquire important information of the parking structure. Thus, the operating status of the parking structure is always under control, which could facilitate solutions to emerging problems and potentially reduce the possibility of system failure. Furthermore, useful data could be transmitted through Wi-Fi or Ethernet connection to mobile devices such as cellphones, which provides information such as empty spot locations for drivers.

In respect to the meeting room availability issues in office buildings, the system by Patel and Panchal [79] reflected occupancy status via PIR sensors and a web server, where user can remotely enjoy booking services on their end devices through GUI. The advantages of the systems are three folds: 1) traditional meeting rooms in companies are becoming more manageable; 2) the sensors are small in size that are easy to hide in a room without creating spacing problems; 3) the system is simple to setup but effective to use.

Kovac et al. [80] implemented a smart home gateway to enable home automation systems and actuators including smart meters, alarm systems, lighting controls, etc. In this way, home owners can remotely monitor all the interconnected communication systems as a whole. The open Home Automation Bus (openHAB) platform is the core of the system that serves as an integration hub among devices.

3.5.3. Building health control

For health monitoring of building structures, Wang et al. [81] proposed an IoT-based integrated information system with early warning function. The system architecture incorporate sensor data collecting layer, data management layer, and structural health monitoring service layer. For the sensor data collection layer, steel stress gauge, inclinometer, and earth pressure cell sensors were employed at the pivotal locations of monitoring target, and multi-standard communication was applied for data transfer and processing. The system also had a module for uniform data parsing to abstract the different message formats of heterogeneous devices for data integration. Finally, the structural health monitoring layer directly linked to supervision department to inspect potential failure conditions.

3.6. Summary of current application of IoT on buildings

Based on the review of existing use cases of IoT for smart buildings development, the authors proposed an outline which summarizes the most common technologies and building systems that are relevant and necessary to enabling critical functions of smart buildings (Fig. 4). Although not a definitive depiction, the outline can assist engineers or researchers for future development and adoption of IoT systems. In addition, it is emphasized that the future IoT systems of smart buildings should implement the major functions in an integrated way, while not focus on only one aspect separately.

4. Discussion

Smart buildings are the product of integration of modern science and technology. Although smart buildings have been proposed for years, there is no upper bound for the development of this concept. As the technologies improve, more generations of definition and idea will be incorporated in smart buildings. From the literature review and the availability of popular technologies, it is concluded that the current and short-term future trends of smart buildings will be primarily based on IoT. Among others, the authors have identified three major trends as follows:

1. More types of buildings and more sophisticated functionalities are being implemented.

Initially, smart homes are the most frequent focus as a major component of the smart buildings. However, more types of buildings are being studied and tested with the sophistication of IoT-relevant technologies. Correspondingly, diverse functionalities need to be achieved that are built on the basis of the fundamental requirements of smart buildings mentioned above such as safety, energy-efficiency, convenience, and health, etc. For example, the implementation of smart sensors entirely built within the roofing or wall components will transmit the net energy transfer data; besides general information, these sensors can alert any thermal bridging issues as well as degradation overtime for optimal replacement to conserve energy.

2. IoT is the core, but not the sole component of smart buildings.

IoT collects and analyzes important information in buildings, which is analogous to eyes, ears, nose, and brain to human beings. Thus, IoT is identified as the crucial component that leads the future development directions of smart buildings. However, IoT will not be the only element to enable smart buildings. The layer that has the most potential to improve is the application layer in an IoT architecture, and the domain-specific data analytic techniques will occupy a critical role in the future. IoT will be enabled by algorithms that utilize fundamentals of physics, chemistry, and biology to deliver the necessary information for human consumption.

3. User experience is essential to be considered.

There are many cases where the architects and developers of an advanced IoT system over-emphasize the technical parts of the system while ignoring the actual needs from users within the building. Relevant questionnaire and survey is an effective approach to understand the feedback of building occupants, and thus progress towards the development of features from human-building interaction perspective which will improve user experience and form a smart and user-friendly built environment.

With the previous attempts to apply IoT in buildings and the envisioned trends of smart buildings, the following questions (Table 5) should be considered and answered by system users and designers prior to any prototype of integration being built and knowledge being transformed to the industry.

5. Challenges and recommendations for future research

Despite the benefits and advancement brought by IoT to the building industry, some challenges and problems remain to be resolved for researchers from different domains. This section discusses some of the issues and suggests future research areas for the successful implementation of IoT in this industry.

5.1. Security and privacy issues

With the exponential growth of number of connected devices, the security risks of IoT systems have grown accordingly. The vulnerabilities of IoT systems lie in different parts including web interfaces, network services, backend systems, software, and even physical hardware. Unlike traditional network, IoT covers many heterogeneous entities, services and networks, which makes it hard to directly apply existing security architecture or standards. Therefore, these connected smart devices with sensitive data necessitates security measures on each layer inside the IoT system [83] to resist attacks to different layers.

From users' perspective, since many applications includes personal data of users, an insecure system not only creates people's concerns and, therefore, may lower their willingness to adopting the technology, but also causes serious problems in exceptional cases. For example, the use of cameras in office buildings that are intended for safety monitoring, will record the activities of office workers at the same time, which may lead to uncomfortable of people; the use of GPS for localization purpose reveals the private whereabouts such as where the person has been or which route is the way to his/her destination, which is extremely private data. In addition, some personal data could have indirect impact on the privacy of users. Energy meters collect appliance use for optimizing future energy use. However, the energy use information could infer when the users were at home and what they did during certain time intervals, and if the information is disclosed to unauthorized personnel, it may possibly cause series of problems such as theft. Li et al. [76] pointed out the potential inappropriate use and consequence of patient health information in their IoT application case, even with the patient's appointed healthcare worker.

With respect to the security and privacy issues, potential solutions have been proposed by researchers. Computer-aided design can be used to design IoT devices at the hardware-level [22]; grouping embedded devices into virtual networks for fragmentation management is able to keep information to certain stakeholders [16]; encryption-based privacy preservation can ensure that data is not eavesdropped by adversaries [20]. Nevertheless, challenges remain unresolved for these solutions. Overall, a system that only allows one party to access the necessary data or control of the devices to their exclusive jurisdiction is the future development trend. This requires research on all sorts of directions including, but not limited to, cryptography algorithms, communication protection and hardware design, etc.

5.2. Data acquisition, processing, and storage issues

As the sensors and other devices lay the foundation of IoT application, enormous amounts of data with various types will be generated, and this information differ among diverse types of buildings. To some extent, data is the essence of realizing smart buildings. Therefore, instead of only establishing a warehouse of data, a complete system must handle many other concerns including valid data extraction, storage, and analysis, etc.

To elaborate, one of the most difficult and unique challenges IoT system faces is in the data collection process. Unlike other problems that usually use single source of data, such as 1) text analysis on news and media which collects data from Internet, 2) voice recognition which collects data from experimental human conversation or AI robot, and 3) business analysis which mainly collects data from company report, IoT system collects data from various sources due to its nature on the perception layer. As discussed in Section 2, for application in buildings, for example, IoT system collects data from indoor/outdoor environment, occupant behaviors, building appliances and isolation structure. To ensure meaningful data is collected, the system needs to have the capability to capture various types of data simultaneously. The process requires steps of 1) data transition, which enables robust data transfer from raw sensors to repository; 2) data cleaning, which removes corrupted and null data; and 3) data consistency checking,

Table 5
Questions to consider for system designers and users before system development and application.

Tech/Non-tech	Categories	Questions
Technical	System	1. What is the major function to be implemented in the building? What is the purpose of such implementation and how does it improve the overall efficiency of building operation? 2. What are the hardware and software requirements for each layer of the system? 3. Is the system available for multiple functionalities implementation? What is the mutual or optimal solution? 4. How should the hardware or software be maintained and reused across different projects or phases?
	Data	1. What types of data are required and collected? How do they aggregate together for use? What is the frequency of such data collection? 2. How is data being organized and stored in a way that it is shared in some format, while not accessed by unauthorized person? How are these stored and retained, and destructed after analysis?
	User terminal	1. How to make sure a non-intrusive system to the end users? 2. How much expertise is needed for application of the system for each user group? 3. What are the user requirements for terminal interface design?
Non-technical	Management and operations	1. Who should be responsible for the management of the system? 2. What kind of training is needed for relevant staff?
	Financial and economic	1. What is the economic impact and actual value/benefit of the system? Is it feasible to use? 2. Who should be paying for the services based on IoT?
	Applicability	1. What is the strategy and policy to expand the use of the system? 2. Is the use of the system in conflict with current regulations on user privacy?

which ensures data is not duplicated or contradictory with each other. To achieve the requirements, the data collection pipeline for IoT system should be well designed and tested to satisfy different application purposes.

Data formatting is the next challenge after the collection step, as data from diverse sources tend to exist in different formats. For example, to explore the relationship between building occupants and appliances usage, one may collect data from humans that contains image and voice, and data from appliances that contains textual contents. It is a complicated task to format these data in a consistent way so that they could be directly used for the problem. The system must be able to efficiently and effectively re-formatting the data in a timely manner, thus the output of the formatted data is ready-to-feed for possible solutions, such as machine learning algorithms.

Data availability and storage is another concern for future application of IoT. Since IoT system collects massive amounts of data, it is important to optimize the design of the storage architecture to guarantee that data is well-protected from hazardous events such as hacking and unauthorized use, easy to recover from backup, and always available for fetch. Currently, big data platform has been developed to support the requirements using distributed storage and processing architecture. However, the connection of the technology to smart buildings needs to be boosted in the future.

Lastly, data usage issue must be addressed. Specifically, an IoT system must identify the application objective for different stakeholders to leverage necessary data to certain groups. Generally, IoT system deals with multiple tasks rather than just one single scenario, with all related objects connected together. Therefore, a schema for data allocation is needed to reduce excessive information at the user end. Such function requires the combination effort of experts who develop the system and who have domain-specific knowledge, for bridging the gap between technical and application terminals.

5.3. Feasibility, adaptability, and practicality issues

Currently, the potential application of IoT in smart buildings is being discussed more in academia while at the earliest stage of adoption in the industry (Table 3). To promote the application of IoT platform on the industry, developers of the future generation of products, systems, and approaches need to not only focus on improving the robustness and feasibility of the system, but also comply with natural rules that could spread the use to a wider scope.

First, there is a gap between industry and academia. A number of research projects only proposed the ideas or framework of their IoT system and did not actually verify their solutions. Some of these research used simulated data or scenarios to test the performance of their system [72,77,84], which ignore many practical issues such as the range of application areas, or the data collection rate and accuracy. This, in turn, brings unreliable and unconvincing justification of the system for practical use. Furthermore, some projects are designed and tested based on assumptions from lab environment with controlled variables, which may not be applicable in real world situation. Only a few studies examined their systems on in-use buildings [85]. Since most of the research focused on the design and development of IoT system, it is understandable that efforts lean more on the technical side. However, future research should try to test the system in a more complex and dynamic environment to prove their realistic value and adaptability to the actual scenes. Hence, more interactions between industry and academia are needed. As seen from the use cases, some advanced IT companies such as IBM, Intel, etc., already have a sophisticated series of products on smart buildings. Academia should learn from industry to capture the application needs in market and industry should utilize the academic achievements to update their system to promote the IoT application on the building industry together.

Second, communications in the industry is also important. Specifically, the protocols and standards of different building systems should be integrated with minimum barriers. Building Automation Systems (BAS) are developed for controlling and management of equipment, HVAC, lighting, shading, security [86]. In recent years, the buildings are designed to be compatible in interacting with a wide range of mechanical devices and control systems to improve and accommodate building level services. Many of these systems involve machine-to-machine communication (M2M), but due to the generic data type and proprietary communication protocols, the flow of information is restricted to certain paths. Conversely, a truly smart building will require connectivity between all the various components of the building. So far in the industry, products from major vendors still do not “talk” to each other, probably due to competitive relations. This impeded the significance of applying IoT in the industry to be a smart system. Fortunately, voluntary collaboration during the recent decades between historic rivals has led to the adoption of open standards such as BACnet, Modbus, and LonWorks. This has and will enable manufacturers and contractors to have meaningful share of contribution to the development of integral service delivery of buildings, leading to higher comfort and efficiency, and lower operation cost [87]. However, the pace should be increased and thus the official standards can be formulated finally for this pending problem.

Another point to be considered is the Return of Investment (ROI) for these IoT systems. It is questionable of whether the public is willing to or capable of adopting IoT as a daily tool [88], which is directly associated with the cost of IoT systems. The expense of IoT systems includes the cost of hardware, software, and managing manpower. Adequate compromise should be considered in terms of device accuracy/quality and the price. Moreover, the benefits delivered by IoT to the building industry, such as time and energy savings, are able to offset the cost of certain devices or systems. The end users usually pay closer attention to the present services while, sometimes, failing to notice the long-term influences of the IoT system, thus they will probably be reluctant to use the system because of the extra cost. This leads to another feasibility issue for the future use of IoT: educating users about the system. Survey-based research may be conducted to understand and analyze the opinions and attitudes of building managers/planners, as well as potential occupants of the application target, to gain information about how to optimize the IoT system in order to better service people.

5.4. Collaboration between IoT developer community and building industry

IoT is a tool to facilitate and improve functionalities of buildings. Although researchers in electrical engineering and computer science areas devoted their efforts on the assembly and calibration of hardware, designing supporting software, and regulating wireless communication protocols, etc., IoT cannot realize its maximum value if it is not adequately applied to the building industry. For this reason, the collaboration between the technical team and civil engineering or building technology researchers need to increase to further advance the application of IoT in the industry. As stated earlier, researchers in building areas have better and deeper understanding of the potential demands and requirement of IoT application, as well as the challenges of adopting IoT in the corresponding areas. Therefore, effective collaboration can enable the IoT developers to revise and optimize the system pointedly whereas, building researchers should study how to augment the use of IoT, so that progress could be made in parallel.

In most of the current IoT research and industry application, lack of collaboration has hindered the full usage of IoT in the building industry. For example, the study in [51] is focusing on the algorithm and system design for positioning accuracy purpose, without any consideration on what application this system could be used; the system of [56] for building energy reduction used a rather simple algorithm for the control of building appliances, while there is more potential for higher energy savings. Moreover, most of the IoT systems, especially some commercial systems, did not take full advantages of the data collected. These systems at the application layer tend to merely implement a data visualization module, without further analysis of the data or useful results to push the application intelligence to the next level. In this regard, effective data mining process must be provided by domain-specific researchers to gain more insights and knowledge from the raw information to avoid the waste of data.

For IoT in smart buildings, for example, visualizing environmental or energy use data for end users is a basic function that is already existing in most systems. However, users may want to know more about their energy use pattern, or the HVAC system could automatically adjust the schedules according to the occupancy status if the information becomes available. Research is still being conducted to explore the relationship among certain environmental parameters, occupant comfortable levels and energy consumption conditions. Information about what functions are missing on which aspect of buildings must be clearly specified to the IoT developers, and data analysis results from domain researchers should be added to provide concealed conclusion or optimized suggestions for potential users.

In summary, the IoT technology is sophisticated enough to take effect towards smart buildings. However, how to make the most use of the technology to achieve the goals of smart buildings needs to be deeply explored. The expertise from both technical and application sides are equally important and only an integrated collaboration can reap the overall benefits of IoT to the building industry.

5.5. Explore more IoT opportunities in the building construction phase

IoT should not be limited to the operation phase of buildings. On the contrary, the application of IoT in the construction phase also aids the intelligentization process. Niu et al. [89] proposed the concept of smart construction objects and employed smart sensor node to construction resources (e.g. machinery, tools, device, materials, components, and even temporary or permanent structures) to enable better decision-making. The sensing, processing and communication abilities endowed with the embedded devices (GPS, GSM) on component surface could help synchronize as-built information with a Building Information Model (BIM) in a real-time manner and alleviate the human work load for searching logistical information for the particular component. In [90], Ding et al. built a real-time safety early warning system based on IoT to promote underground construction safety management efficiency. The design of their system was based on the specific conditions of the real-world project at a cross passage construction site, and the RFID-based system was proved to be effective for detecting safety risks. Dave et al. [91] discussed the use of IoT for enhanced lean construction management, particularly on production control on sites. The communication framework with IoT technologies and standards makes it convenient to automate communication functions across the supply chain and construction phase of project.

In general, integrating components among a project's entire life cycle should be studied to increase interoperability of IoT system and give birth to industry-specific standards. This integration is also beneficial to life cycle assessment, which is a technique used in assessing environmental impacts associated with all the stages of a product's life from its creation to its end. Furthermore, researchers and practitioners in the building industry should broaden the use of IoT to investigate more potential application opportunities, so that particular design on devices, standards, and approaches to data analysis and results presentation for the area will be initiated.

6. Conclusion

The rise of advanced technologies and its integration with various aspects of our lives have opened up new horizons for improving service performance of buildings, communities, and cities. Focusing on one important part of the vistas, this paper investigated the current research contributions and future potentials of IoT towards the envisioned goals of smart buildings. The typical enabling technologies of IoT were introduced in the sequence of a three-layered generic IoT architecture, namely 1) perception layer, 2) network layer, and 3) application layer. The state-of-the-art underline technologies used in each layer, the standards/protocols to develop each layer and the connections to building industry on each layer were explained. Subsequently, the current applications of IoT towards the development goals of smart buildings were discussed, which include both academia and industry use cases in the past decades. Principal criteria of smart buildings were abstracted to map these applications. Although this is not a complete list of applications, it can serve as a good starting point for future research in the relevant areas. It is concluded that current technologies – hardware, software and computing algorithms, have already become a significant part of the smart buildings development. However, continuous research effort is required on IoT applications to successfully implement the prospects of advanced smart buildings in the future. Accordingly, standard technical requirements of IoT and its integration needs to the building industry were identified. It is worth mentioning that, substantial amount of problems and challenges still remain to be studied, as summarized in this paper. These challenges will be valuable and ideal research problems for the researchers and practitioners who are interested in applying IoT concept and system in the building research areas, and further advance the progress in both technical and application sides of IoT.

Since the prime idea of IoT is to connect any individual, system and the entirety environment together from any location and at any time, the application of IoT will become ubiquitous, and possibly the main stream in the future development of smart buildings, or even to a larger scope, e.g. communities and cities. With the in-depth review of state-of-the-art technologies and applications for IoT in smart buildings, this paper expects to provide a novel and holistic vision to the academic community and practitioners who would like to delve the power of IoT in the building industry for more exciting innovations.

Declarations of interest

None.

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