Journal of Civil Engineering and Architecture 15 (2021) 475-487
doi: 10.17265/1934-7359/2021.09.004

IoT in Building Process: A Literature Review

Matteo Giovanardi, Matteo Trane and Riccardo Pollo
Department of Architecture and Design, Polytechnic of Turin, Turin 10125, Italy

Abstract: The pervasive diffusion of digital technologies opened up to new concepts in managing and monitoring the processes occurring in our society. Information and Communication Technologies (ICTs) become enabling tools to rethink our way of living, consuming and producing goods and services. Among these, the Internet of Things (IoT) represents the disruptive technology that may redefine the stages of the building process to meet renewed environmental challenges. This new technological paradigm imports in the Architecture, Engineering and Construction (AEC) sector new and not-tectonic instances. In this context, the paper maps the experiences related to the use of IoT for managing the building process. Through a systematic literature review, the article highlights the potential benefits generable by a widespread integration of IoT in the AEC sector. In particular, the article has three purposes: defining the IoT infrastructure for its proper application in the AEC sector; identifying IoT main application domains; investigating the integration modalities.

Key words: IoT, building process, literature review, smart building (SB), smart construction object (SCO).

1. Introduction

The development and spread of Information and Communication Technology (ICT) in the built environment has profoundly changed how we live and interact, combining the virtual dimension to the physical one. Since 1995, the world population with internet access has increased from 1% to 58%, reaching 87-89% in the most industrialized contexts [1]. Atzori et al. [2] highlighted how the current internet paradigm, based on host-to-host communication, has become a factor limiting the use of the internet. Experiences in this field, related to the theories of ubiquitous computing and based on the concepts of “everywhere”, “anywhere”, “anymedia”, “anything” and “anytime” [2, 3], confirm the will to overcome the “one person-one computer” concept. This approach constitutes the theoretical background on which the Fourth Digital Revolution in progress is based [4]. In this context, the neologism “Internet of Things” (IoT) refers to the extension of the internet to the physical world, creating a new hybrid physical-virtual dimension, where it is possible to share information from the real world.

The paper investigates the role of IoT in the Architecture, Engineering & Construction (AEC) sector through a scoping literature review. Defining the state of the art on the IoT in smart building (SB) perspective, the paper specifically aims to:

- Goal1 (G1): define the IoT architecture;
- Goal2 (G2): identify the IoT application domains;
- Goal3 (G3): investigate the spheres where the integration between the IoT and the SB occurs.

To this end, we structured the paper as follows. Section 2 introduces the socio-economic context; Section 3 focuses on the methodology used for the literature review, highlighting the procedure that led to selecting 50 articles; Section 4 shows the survey results; Section 5 discusses the results obtained, and finally, we reported the conclusions and future developments.

2. Theoretical Background

2.1 Smart Urban Infrastructure

The digitalization process through widespread integration is now turning into a growing supply of intelligent buildings and components in the real estate market. While this phenomenon can be framed as a

Corresponding author: Matteo Giovanardi, Architect, Ph.D. student, research fields: IoT and façade design.

dynamic service in response to the changing needs of the end-user, on the other hand, it represents an essential layer in the architecture of the Smart City (SC). Urban systems are gradually turning into real open-air computers, capable of producing and reprocessing a large amount of data to improve the interactions and ways of living in the city.

However, the SC must be populated with elements capable of communicating with each other and sharing information with the city's control and management. As in an interrelated and connected system, the SC requires a widespread network of buildings as basic elements of the system itself. In this regard, promoting the SB's concept, as a result of the integration between "modern science and technology" [5], follows SC's evolution and spread. SBs exploit the intelligence brought by the IoT and data processing technologies to offer new and dynamic ways of interaction, adapting their characteristics according to the users' changing needs. Using sensors and actuators for environmental parameters monitoring, SBs ensure greater control in resource consumption and an increase in the quality of services and indoor comfort [6]. In this perspective, Niu et al. [3] introduced the topic of Smart Construction Objects (SCOs) at a smaller scale. These experiences radically alter the nature of building components, introduce new management schemes and renovate the business relationships among stakeholders. A clear example is the Façade Leasing project linked to the concept of Product Service System (PSS) [7] that introduces business models. The current socio-economic and cultural context gives digital enabling technologies a central role in developing and managing urban processes.

2.2 Internet of Things

IoT identifies the paradigm of information technology as one of the most impacting and disruptive innovations in the field of communications [2]. In particular, the IoT indicates "a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols" [8]. The term immediately highlights the potential of enabling technologies in the control of dynamic processes. However, the definitions given by the scientific literature do not uniquely explain the meaning of "Things", which is a quite generic concept. Therefore, according to the different actors' objectives, it can be defined in different ways [9]. Atzori et al. [2] highlighted the coexistence of three different meanings of things in the IoT field: Internet Oriented, relating to the network; Things Oriented, referring more to the world of real objects; the Semantic Oriented, focusing on the modalities of connections of the two fields. Jia et al. [5] added a fourth one: that of the human component (Human Centered) to read the phenomenon from the user's perspective, favouring the interaction methods and the virtual interface.

As it emerged from the literature review (see Section 4.1), the three-layer architecture is the most used by the scholars. Jia et al. [5] and Daissaoui et al. [10] assume the following nomenclature: *Perception*, *Network* and *Application* layers.

The *Perception Layer* is the physical environment level, equipped with sensors to detect and collect information. This layer's task is to detect physical parameters or identify other intelligent objects in the real environment to share this information on the upper layers. The *Network Layer* is responsible for processing and transmitting the raw data collected. The term "network" identifies the technology used for transmitting the electrical signal, responsible for connecting intelligent things, network devices, and servers [5]. We divide communication and network technologies into wired and wireless technologies (such as Wi-Fi, Bluetooth, ZigBee infrared). In this regard we can note that over the years technological evolution has tried to solve the problems related to data transmission and pushed innovation by development of several communication technologies. The *Application Layer* is the highest level. Its goal is the front-end interface with the end-user, helping us in decision-making. According to Trappey et al. [11], it is divided into two main components: the application field and the computational part. The first is responsible for providing services, embracing the entire system's final goal, identifying the application field, the methods, and protocols to be used [12]. The second incorporates those enabling technologies capable of processing data, transforming into information, and making them available to the end-user.

3. Methodology

As highlighted in the previous paragraph, the topic's breadth requires a clear delimitation of the research domain. The paper uses SB's concept as the result of integrating IoT in AEC sector focusing on the most significant experiences in using the IoT at the building scale. We carried out the research following a scoping literature review methodology on two databases (Scopus and Science Direct) and one search engine (Google Scholar), to include also part of the "grey" literature by companies and market experience. We used the string "IoT" OR "Internet of Things" AND "Smart Building*" for titles, keywords, and abstract, limiting the period in 2010-2020 (December). Not computing the papers present more times and the non-Open Access ones, the research initially identified 638 articles. We refined the selection by analysing the titles and then the type of journal in which the were published, to make the results consistent with the objective of the review. Indeed, the interdisciplinary nature of the topic, extensively covered in communications engineering—but only marginally in architectural and AEC disciplines—required a selection of magazines based on their disciplinary macro-sector and impact factor. We consequently reduced the papers to 266. We then reduced the selection to 121 papers after analyzing the abstracts. We finally selected 36 products, to map the phenomenon through an adequate number of papers.

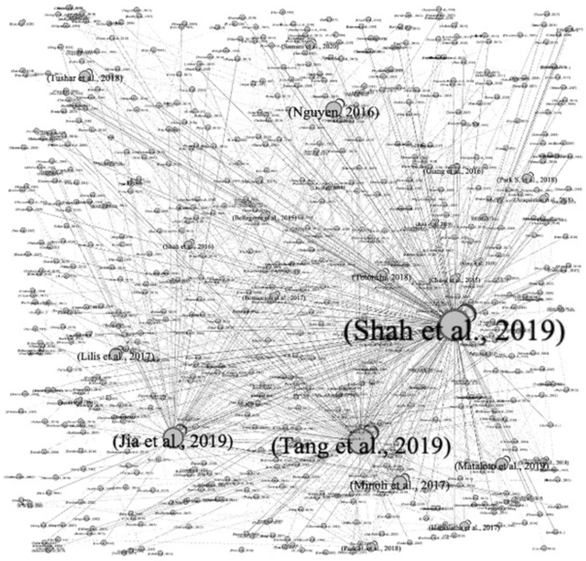

Fig. 1 Analysis of article reference using Gephi software.

We then expanded back the research domain using Gephi neural network software to refine the research (Fig. 1). By analyzing the bibliographies of the papers, it was possible to identify the most cited articles and integrate them in our selection, when relevant. This process allowed including those texts not explicitly containing the search strings keywords, but still necessary to trace the state of the art. The selection process led to the definition of the 50 most relevant articles in the period considered.

4. Results

As confirmed by Shah et al. [13], the analysis of the available literature highlighted the highly interdisciplinary nature of the topic. Here we propose a classification of the products analyzed according to the three research objectives. The proposed framework is not to be intended as an ultimate scheme, but as a classification helping to set the state in light of the aforementioned specific purposes.

4.1 IoT and SB: Layer Architecture (G1)

The reviewed papers can be classified according to the way they refer to IoT architecture. The IoT architecture is usually defined by layers, from three to seven (3, 4, 5, or 7 layers), including elements and functions [14] (Table 1), although conceptual and semantic differences are also present within the same cluster of papers. According to the literature survey, we identified the three-layer architecture as the most used one. Although, as reported, there is no univocal definition of the IoT layer architecture and not all the reviewed products adopt a clear nomenclature, all of them can be traced back to the three main levels aforementioned. Indeed, even if divided, the layers used in the reviewed literature, which also assume peculiar nomenclatures according to the specific research purposes, can all be finally traced back to the 3-layer architecture system used in this paper. For the purpose, we adopt the nomenclature reported by Jia et al. [5] and Daissaoui et al. [10]: Perception, Network and Application.

4.1.1 Perception Layer

A wide range of smart metering solutions and sensors are available on the market, often characterized by closed and vertical protocols developed directly by the manufacturing companies. The variety of devices to detect or measure physical properties and to record, indicate or respond to them is huge and out of the scope of our survey. Therefore, one of the most challenging aspects of the Perception Layer devices regards the interoperability and communication between them for better communication [29]. Wireless Sensor Network (WSN) represents the most suitable solution to allow the monitoring of several environmental parameters by integrating data as position, temperature, humidity, pressure, lighting, and acoustic given by the sensors. Moreover, wireless technology allows for widespread use of these devices, even in environments not originally designed to house such an infrastructure. RFID (Radio Frequency Identification) technology represents by now the most adopted solution in logistics and the production chain monitoring. Active, passive, or semi-passive, they need a simple reader and can reach ten years of life [30]. Finally, video cameras, motion sensors, and environmental sensors are mainly used for safety.

Table 1 Layer architecture analysis.

References	Layer architecture
3 layer architecture	
[15]	Data acquisition, processing, presentation
[16]	Physical infrastructure, control, application
[17]	Information, application, user interface
[18]	Field, data, processing
[19]	Sensor, communication, application
[20]	Sensing, processing, reproducing
[13]	Smart grid, fog, cloud
[21]	Process, communication, data
[22]	Data-source integration, services, application
[5, 10, 14]	Perception, network, application
4 layer architecture	
[23]	Information, connection, service, virtual
[24]	Perception, network, data, application
[25]	Data collection, transmission, service, interface
[26]	Device, gateway, cloud, App and application
5 layer architecture	
[27]	Physical, virtualization, aggregation, servitization, application
[2]	Object, object abstraction, service management, service composition, application
7 layer architecture	
[28]	Things, data, fog, aggregation, centralization, storage, application

Finally, mobile and wearable devices represent a primary source of data in the automation of a complex system: although they are not part of the building, they interact with it.

4.1.2 Network Layer

Data transmission in the AEC sector mainly occurs via Wi-Fi, Bluetooth, or Zig-Bee protocols. These technologies are used in data transmission, for example, between meters and service providers, between building energy management sensors and indoor environmental monitoring sensors, or between building users and smart appliances [29]. Wireless communications are preferred as they do not require an invasive physical infrastructure, although a more unstable transmission may characterize it. Wi-Fi is a communication technology that uses radio waves for local networking between devices based on the IEEE 802.11 standards. The most used frequency is the 2.4 GHz UHF and 5.8 GHz SHF ISM radio bands [5]. On the other hand, the Bluetooth system can connect mobile devices over short distances, also using radio waves. Finally, ZigBee is a technology designed for short-term communication and low power consumption, exploited in connecting many WSN systems. In this context, Li-Fi experiences as future alternatives in data transmission are engaging [28].

4.1.3 Application Layer

The most investigated area in this layer concerns the tools with which the end-user interfaces for managing the building system. BIM (Building Information Modeling) represents the most investigated tool in literature, being able to integrate in a standardized information network data from sensors placed in the environment. In this regard, Cheng et al. [17] suggested BIM for FM (Facility Management) activities, combining it with specific Artificial Intelligence applications to predict future building elements and subsystems state. To integrate sensor data into a BIM environment with more complex conditions, Alves et al. [15] proposed an alternative specific language (BIMSL) to facilitate query development [31]. At the urban scale, Geographic Information System (GIS) can represent an interesting tool for urban planning purposes, combining the information about energy and matter flows to space-temporal coordinates. GIS was also used as input data in energy simulation [22] and in managing emergency activities [32].

4.2 IoT and SB: Application Domains (G2)

The papers analyzed were classified into seven main application areas, as shown in Table 2

4.2.1 Design

The IoT is aimed at developing shared models capable of receiving and exchanging information among different design phase players. Until now, the IoT’s intrinsic characteristics have implied that its use lends itself more to process control than to be as a support tool for the project’s design phase. However, generating, collecting, analyzing, and sharing information opens new scenarios, facilitating exchanges between the many stakeholders involved in the construction process through interoperable platforms, such as BIM. Boje et al. [33] highlighted the incompatibility between IoT and BIM due to the formats and standards of data inherited from BIM, which limit their use and extensibility. Alves et al. [15] highlighted how many experiences attempted to extend BIM to closed application domains by developing applications for specific areas, such as energy management, building automation, fire protection, health, safety, and augmented reality. In this context, the introduction and evolution of the so-called Digital Twin concept may allow an intersection between digital and physical dimensions, as it is specifically programmed to receive different inputs and formats. The ability to reprocess the data collected through a virtual simulation model allows, on the one hand, to increase the reliability of forecasting algorithms [22], and on the other, to introduce industrial strategies such as Lean Construction Management Systems in order to use data in decision-making and design processes [55].

Table 2 Application domain.

Domain	References
Design	[2, 15, 22, 33, 34]
Construction	[35, 36]
Quality et al.	[3, 30]
FM et al.	[10, 16-18, 20, 37-39]
Energy	[19, 28, 29, 40-48]
Comfort	[23, 49-54, 56, 57]
End of life	[55]

4.2.2 Construction Site Management

It represents an area of great interest for the introduction of IoT solutions that can optimize the construction phases. Logistics, cost and time control, process traceability, and operator safety represent the most critical challenges in this context [30]. The management of site logistics and supply chain is a focus with the project's economic, time, and quality objectives. Most of the activities related to the construction site management, such as the materials procurement, the notification of low stocks, shipment, or storage can be automated through the IoT [55]. In this context, the most relevant experiences concern the use of RFID tags. Lee et al. [35] presented the Information Lifecycle Management framework, defining RFID main application to control the building process, from the production phases to the construction site management. In promoting the use of prefabricated building components incorporating digital devices, Li et al. [36] underlined their potential economic benefits for the installation phases. Niu et al. [3] designed prefabricated façade panels with integrated tags connected via Bluetooth, able to be recognized directly by the crane for the correct positioning of each façade panel.

4.2.3 Quality Process and Supply Chain

The IoT can monitor a supply chain and open new scenarios in managing building materials. Technologies for supply chain control, already used in other industrial sectors such as in the food chain [2], allow for greater control over the quality of the products used, too. Moreover, the regulatory evolution favored greater attention concerning the supply chain of building components, imposing the tracking of building elements and materials aimed at their recycling once they reached the end life.

4.2.4 FM, Security, Safety, and Maintenance

IoT represents a powerful tool for FM activities in the perspective of reducing operational costs in building's life. By analyzing 120 scientific papers on the topic of digital technologies for FM, Wong et al. [39] highlighted how the scope of application is wide and varied. In particular, they report on a number of experiences using the interface of BIM and GIS to reprocess data collected via RFID sensors. Improved technological accuracy of single tools needs to be coupled with the development of as-built models for existing structures to ensure greater interoperability between BIM/GIS databases. A building must ensure the safety and security to the people it hosts. The safety level is closely linked to the maintenance effectiveness, both regarding the systems and the single architectural components, and it represents a significant cost in the building's life [37]. Various experiences conceived the building as a machine in which each of its parts' functioning can be monitored to prevent various failures and malfunctions. Kueng and Bruner [38] proposed RFID sensors connected to strain gauges incorporated into the building's structural parts to monitor the building's static behavior in real-time, such as in bridges. Cheng et al. [17] studied a system to send to the manager an alarm signal if anomalies occur, thanks to temperature, humidity, and pressure, and airflow sensors and through the BIM interface. A further significant example in terms of user safety concerns the application of IoT technologies for evacuation in the event of a fire. Park and Rhee [20] designed a system to notify the safest escape route in real-time in case of fire to increase safety in multi-story buildings. A similar approach is proposed by Liu and Zhu [32], highlighting how artificial intelligence can help make more appropriate decisions in a limited time, to identify preferential escape routes.

4.2.5 Energy Management

It represents the area in which the IoT has had the greatest success to date. Smart Metering and Environment Monitoring have increased knowledge on how buildings perform [23]. The need to monitor the provision of energy flow in buildings to optimize performances and costs boosts the rapid development of various experiences, partially received by the market of technologies and devices [43]. The possibility of increasing domestic or work environments' responsiveness according to how people use them represents a central challenge in the contemporary architectural design debate too. In this sense, Araquistain et al. [40] highlighted how remodelling the HVAC (heating, ventilation, and air conditioning) systems based on a greater knowledge of the hourly profiles of use could generate significant savings. A recurring theme in this area represents the need to connect the Building Energy Management System (BEMS) already developed with a network of sensors widespread in all environments [19, 29, 42, 44, 46]. The flexibility of such networks aims to overcome the barriers by the data interoperability among products now on the market.

4.2.6 Comfort and User Interface

An effective energy management of the building is clearly linked to users' comfort and behavior. If, on the one hand, the IoT becomes a tool to increase the comfort and healthiness of the SB, it also assumes a fundamental role in informing the user and guiding him to the correct use of the building devices. The IoT has indeed reformulated the ways of interaction Human-Human, Human-System and System-System [56, 57]. The dynamics brought by these technologies encourages Demand Response (DR) approaches [28], capable of guiding the end user's behavior. Nevertheless, the most often used interfaces in the analyzed papers were developed for specific applications. Park and Rhee [20] highlighted how the IoT allows identifying the most suitable simulation model for guaranteeing indoor comfort. In this context, various scholars [49, 50] presented how the IoT can play a crucial role in controlling the environmental quality and healthiness. The integration of sensors in building components, for instance, can provide a detailed mapping on indoor and outdoor pollutants distribution and air quality.

4.2.7 End of Life

The application of IoT technologies in Construction and Demolition (C&D) waste management for the buildings and elements end of life is still little investigated. Although different papers [41, 55] mentioned the applicability of these technologies in the building's whole life, the experiences testifying possible advantages in this field are still scarce. In analogy with the installation and management of the construction site processes, we can assume that even the decommissioning phases of a building can be monitored through IoT devices, widespread on the site and integrated into the components themselves. In addition to this potential application, there are traceability and monitoring of the demolition and disposal phases. Indeed, the regulatory evolution, requiring growing attention to C&D waste, promotes the introduction of circular approaches to ensure the valorization of the waste.

4.3 IoT and SB: Integration (G3)

4.3.1 Systems

The ability to remotely monitor the correct functioning of HVAC plants involves significant benefits in terms of energy savings, costs, and indoor comfort. This led to a rapid technological evolution in this field. Voltage, frequency, and electrical load sensors of the HVAC system [17] are consolidated in the field of system design. In this field, Casini [43] highlighted the benefits of using IoT in the auto-programming and self-optimisation based on learning of users' habit of HVAC systems.

4.3.2 Building Components

Physical integration into building components is a topic of recent interest. SCOs, such as prefabricated elements, floors, stairs, beams, and pillars, can potentially integrate useful information for the construction, use, and management of a building [35, [36]. Structural monitoring remains one of the most investigated fields, aimed at increasing knowledge of buildings' real behavior in the use phase and affected by anthropogenic or environmental nature stresses. RFID sensors connected to strain gauges can provide real-time information to identify the mechanical behavior of a floor or a pillar, monitoring any construction defects or damage (crack detection) [37, 38, 58]. Among the building components, the façade system could be the most suitable element for integrating sensors. Furthermore, the idea of transforming the envelope into a dynamic component capable of adapting to endogenous or exogenous inputs has accelerated this integration. Indeed, the envelope is generally defined as an interface between environments under different conditions. Therefore, its role in defining building energy demand and indoor comfort is crucial [40]. In this context, the off-site construction process allows the monitoring of the different phases. As part of the RenoZEB project, aimed at developing smart facade modules for energy retrofit, Arnesano et al. [41] highlighted the advantages of using sensors to share information in building operation and management. In the experience reported by Niu et al. [3], information regarding essential parameters for traceability (dimensions, weight, materials, manufacturers) and component assembly (special fitting position, floor-ceiling height) are integrated into the prefabricated concrete facade panels for a high-rise building. Xue et al. [59] outlined the state of the art on the relationship between IoT and BIM, reporting an example in which RFID tags, placed inside a prefabricated facade panel and combined with BIM, improve production and installation activities. Giovanardi et al. [50] propose an indoor and outdoor air quality monitoring system through plug & play components embedded in the windows' frames.

4.3.3 Furniture

Furniture in the dwellings can represent a relevant source of information for the SH management. Product innovation has accelerated the transition to a connected and smart building. Lights, ovens, refrigerators, washing machines, and home automation are just a few examples of how the IoT has already taken root in our homes [60]. Programming the working of such equipment according to our habits redefines the way users interact with the home.

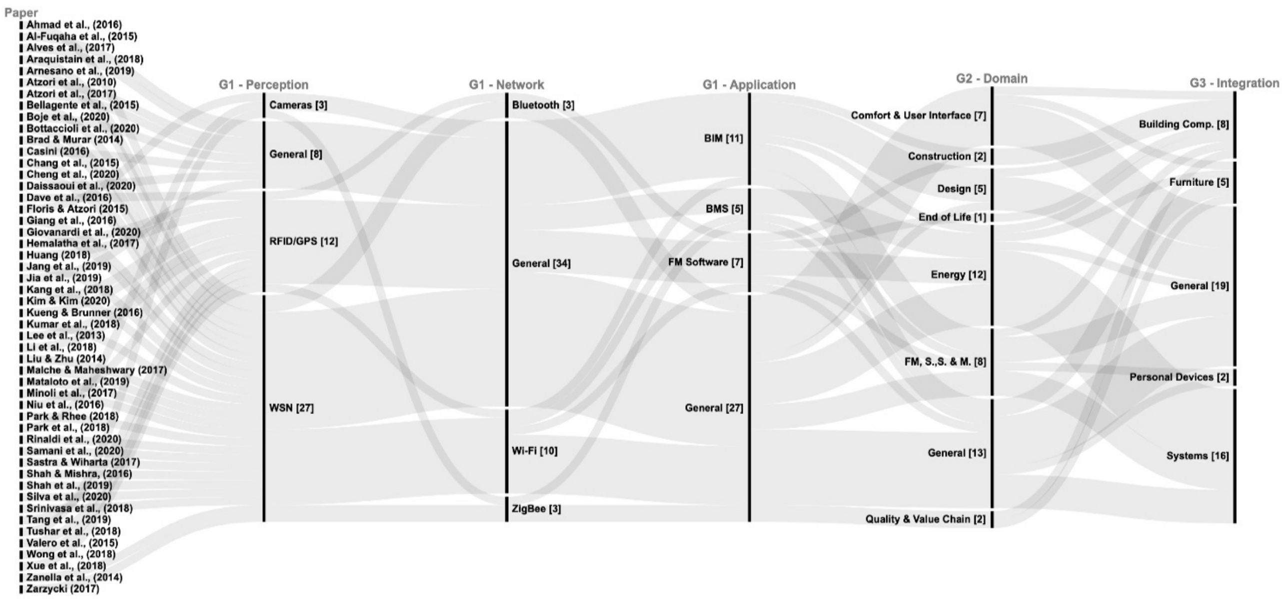

Fig. 2 Relationship between the articles reviewed, the IoT structure employed (G1), the application domain (G2) and the integration modalities (G3).

The responsiveness of the digital components represents a focal point in the future development of new products for the home. In hospitals, offices, public buildings, furniture and instruments can be traced within the spaces to facilitate locating the devices and allowing the inventory of the available items.

4.3.4 Personal Devices

Finally, the proposed classification reveals a series of experiences based on the use of data produced by wearable devices mainly to be used outside the building itself. The SB network connection with sensors and mobile devices represents a data source often used for users' safety and ensures them the best comfort conditions [23, 62]. The most significant experiences in this context occur in the healthcare and telemedicine sectors, where the same sensors help monitor patients' state of health and their rehabilitations [53].

5. Discussion

The literature review set out to answer the three research questions. As it emerged, the IoT architecture (G1) implies a variety of solutions still heterogeneous and rapidly growing. From Fig. 2, it was possible to identify the WSN as the most widespread technology in the Perception Layer for SB. Solutions for logistic and spatial tracking provided by RFID and GPS solutions are equally present. Experiences related to the use of cameras, although they represent an evolving field, are less common. In the choice of communication protocols it emerged that there is no predominant solution, although in almost all the case studies the use of wireless solutions is evident. However, experiences that attempt to exploit the potential of Wi-Fi and Bluetooth in transferring data are common; hybrid solutions are widespread. In particular, in most cases the WSN and RFID/GPS technologies are linked to the development of hybrid communication protocols. In the Application layer, the use of ad hoc created software and web pages for reading data is the most commonly used solution in literature ("General"). Several significant cases try to integrate data through software such as BMS, BIM or FM software, according to the main specific goal of the system investigated.

Among the IoT application domains (G2), Energy Management and FM are currently the most, in literature, as the monitoring of few parameters leads to a profitable development of systems. Indeed, the advances made in sensor innovation, which have led to the development of low-cost and energy-efficient (WSN) technologies, have drastically increased the use of such devices inside buildings. With the development of new smart meters for the profiling and recognition of the electric load, the environmental and energy demand sector represents the ones with greater IoT-SB integration. As for the Design application domain, to date the relationship between IoT and BIM is a widely debated issue and presents some barriers related to interoperability and the character of the data produced. As for the Quality process and Supply Chain fields, although today the methods of labeling and environmental certification of building materials are mainly based on voluntary certificates, in the next future the role of the IoT could be central, allowing the prompt availability of information and putting in direct communication all the stakeholders involved. As reported, the development of ad hoc application, which may constitute a barrier with respect to a more consolidated integration IoT-SB, covers many application fields. Broadly speaking, the End of Life, although it represents a central topic with respect to the Circular Economy and Waste Management issues, seems to be the weakest domain of integration IoT-SB. The use of ad hoc created software is widespread in Comfort and User Interface domain, which represents a domain in continuous development, where several experiences were developed. In the Safety and Security field, up to now monitoring experiences have been implemented mainly on the plant systems or to detect anomalies in big infrastructures, as a bridge.

Finally, to date the IoT-SB integration (G3) mainly occurs thanks to solutions (e.g. environmental sensors) that can not be defined as fully integrated into specific elements of SB, considering that sensors are generally applied on the specific components after the assembling. Therefore, the possible development of SCOs represents a promising field of research and development, in order to put the information produced in relation from the very beginning of the building process.

6. Conclusions

The review highlighted a wide panorama of experiences and devices whose technical limits in the wide scenario of possible applications are still under investigation. The introduction of these technologies, born to optimize and better manage an industrial process, still finds a certain difficulty in the built environment appliances. This is particularly visible, for example, in the End of Life management, where the use of IoT still finds barriers, given the presence of various stakeholders and national or local regulatory framework. In these terms, the design, production and installation of SCOs, where the digital component is embedded, could lead to optimization in all the identified application domains, and definitely push the innovation in the market. In this perspective, the use of SCOs represents an essential element in promoting alternative approaches and business models based on the concept of "product as a service".

Broadly speaking, the speed of technological development requires a rapid rethink of the building process as a whole. Digitization in the AEC sector today represents a standard to strive for, a new dimension in which the tasks of all the players involved—designers included—may be redefined and put in direct communication, thanks to the IoT and from the very first stage of a building process. The potential value associated with data opens new scenarios in managing the building process by involving new players, reshaping their role and promoting financial and contractual forms based on the performances provided by a service. However, the huge increase of data availability and parameters to be monitored still requires a shared regulation on their management. Indeed, although information is a primary factor for optimizing processes and resource consumption, the activities we carry out in a building, which mainly determine its behaviour and environmental profile, may undermine users' privacy. The use of such data still structured on closed systems and usually managed by private companies and public utilities, must still be properly regulated. The digital tool in this case should make itself highly permeable to the use of different stakeholders and in the same time guarantee the privacy to users. To this, the setting of a clear and shared concept framework about what we mean by IoT is central. In this field, the academic debate is still open; such a fragmented nomenclature, communication protocols and standard proliferation may not help the wide diffusion of the IoT in the AEC.

The AEC sector is lagging in sharing the benefits deriving from the technological revolution, because of the complexity and variety of building processes and stakeholders involved. The IoT represents a tool with great potential—up to now partly unexpressed—to renew production, use and consumption patterns of goods and services, in other words, to finally rebalance the relationship between man and environment with a view to climate mitigation.

References

[1] ITU. 2020. "Measuring Digital Development." Facts and Figures, ITU Publication. https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2020.pdf.

[2] Atzori, L., Iera, A., and Morabito, G. 2010. "The Internet of Things: A Survey." *Computer Networks* 54 (15): 2787-805.

[3] Niu, Y., Lu, W., Chen, K., Huang, G. Q., and Anumba, C. 2016. "Smart Construction Objects." *Journal of Computing in Civil Engineering* 30 (4): 1-10.

[4] Roblek, V., Thorpe, O., Bach, M. P., Jerman, A., and Meško, M. 2020. "The Fourth Industrial Revolution and the Sustainability Practices: A Comparative Automated

Content Analysis Approach of Theory and Practice." *Sustainability* 12 (20): 1-28.

[5] Jia, M., Komeily, A., Wang, Y., and Srinivasan, R. S. 2019. "Adopting Internet of Things for the Development of Smart Buildings: A Review of Enabling Technologies and Applications." *Automation in Construction* 101: 111-26.

[6] Huang, W. 2018. "Construction of Information Integration System for RFID-Based Urban Intelligent Building." Presented at MATEC Web of Conferences.

[7] Azcarate-Aguerre, J. F., Klein, T., Den Heijer, A., Vrijhoef, R., Ploeger, H., and Prins, M. 2018. "Façade Leasing: Drivers and Barriers to the Delivery of Integrated Façades-as-a-Service." *Real Estate Research Quarterly* 17 (3): 11-22.

[8] INFSO. 2008. "Internet of Things in 2020. Roadmap for the Future, European Technology Platform on Smart Systems Integration." https://docbox.etsi.org/erm/Open/CERP%2020080609-10/Internet-of-Things_in_2020_EC-EPoSS_Workshop_Report_2008_v1-1.pdf.

[9] Granell, C., Commission, E., Kotsev, A., Commission, E., and Ostermann, F. 2020. "Internet of Things." In *Manual of Digital Earth*, edited by Guo, H., Goodchild, M. F., and Annoni, A.

[10] Daissaoui, A., Boulmakoul, A., Karim, L., and Lbath, A. 2020. "IoT and Big Data Analytics for Smart Buildings: A Survey." *Procedia Computer Science* 170: 161-8.

[11] Trappey, A. J. C., Trappey, C. V., Hareesh Govindarajan, U., Chuang, A. C., and Sun, J. J. 2017. "A Review of Essential Standards and Patent Landscapes for the Internet of Things: A Key Enabler for Industry 4.0." *Advanced Engineering Informatics* 33: 208-29.

[12] Yassein, M. B., Shatnawi, M. Q., and Al-Zoubi, D. 2016. "Application Layer Protocols for the Internet of Things: A Survey." In *Proceedings-2016 International Conference on Engineering and MIS*, 1-4.

[13] Shah, J., and Mishra, B. 2016. "Customized IoT Enabled Wireless Sensing and Monitoring Platform for Smart Buildings." *Procedia Technology* 23: 256-63.

[14] Al-Fuqaha, A., Mohammadi, M., Aledhari, M., and Ayyash, M. 2015. "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications." *Chinese Journal of Computers* 17 (4): 2347-76.

[15] Alves, M., Carreira, P., and Costa, A. A. 2017. "BIMSL: A Generic Approach to the Integration of Building Information Models with Real-Time Sensor Data." *Automation in Construction* 84: 304-14.

[16] Liu, J., Li, Y., Chen, M., Dong, W., and Jin, D. 2015. Software-Defined Internet of Things for Smart Urban Sensing." *IEEE Communications Magazine* 53 (9): 55-63.

[17] Cheng, J. C. P., Chen, W., Chen, K., and Wang, Q. 2020. "Data-Driven Predictive Maintenance Planning Framework for MEP Components Based on BIM and IoT Using Machine Learning Algorithms." *Automation in Construction* 112: 103087.

[18] Rinaldi, S., Bellagente, P., Ciribini, A. L. C., Tagliabue, C. L., Poli, T., Mainini, G. A., Speroni, A., Blanco Codena, J. D., and Spagnolo, S. L. 2020. "A Cognitive-Driven Building Renovation for Improving Energy Efficiency: The Experience of the ELISIR Project." *Electronics* 9 (4): 666.

[19] Mataloto, B., Ferreira, J. C., and Cruz, N. 2019. "Lobems—IoT for Building and Energy Management Systems." *Electronics* 8 (7): 763.

[20] Park, H., and Rhee, S. B. 2018. "IoT-Based Smart Building Environment Service for Occupants' Thermal Comfort." *Journal of Sensors*.

[21] Giang, N. K., Lea, R., Blackstock, M., and Leung, V. C. M. 2016. "On Building Smart City IoT Applications: A Coordination-Based Perspective." In *Proceedings of the 2nd International Workshop on SmartCities 2016*.

[22] Bottaccioli, L., Aliberti, A., Ugliotti, F., Patti, E., Osello, A., Macii, E., and Acquaviva, A. 2020. "Building Energy Modelling and Monitoring by Integration of IoT Devices and Building Information Models." In *Proceedings of International Computer Software and Applications Conference*, 914-22.

[23] Park, S., Park, S. H., Park, L. W., Park, S., Lee, S., Lee, T., Lee, S. H., Jang, H., Min Kim S., Chang, H., and Park, S. 2018. "Design and Implementation of a Smart IoT Based Building and Town Disaster Management System in Smart City Infrastructure." *Applied Sciences* 8 (11): 1-28.

[24] Kang, K., Lin, J., and Zhang, J. 2018. "BIM- and IoT-Based Monitoring Framework for Building Performance Management." *Journal of Structural Integrity and Maintenance* 3 (4): 254-61.

[25] Abdel-Basset, M., Manogaran, G., and Mohamed, M. 2018. "Internet of Things (IoT) and Its Impact on Supply Chain: A Framework for Building Smart, Secure and Efficient Systems." *Future Generation Computer Systems* 86: 614-28.

[26] Malche, T., and Maheshwary, P. 2017. "Internet of Things (IoT) for Building Smart Home System." In *Proceedings of the International Conference on IoT in Social, Mobile, Analytics and Cloud, I-SMAC 2017*, 65-70.

[27] Floris, A., and Atzori, L. 2015. "Quality of Experience in the Multimedia Internet of Things: Definition and Practical Use-Cases." In *Proceeding of IEEE International Conference on Communication Workshop*, 1747-52.

[28] Minoli, D., Sohraby, K., and Occhiogrosso, B. 2017. "IoT Considerations, Requirements, and Architectures for Smart Buildings-Energy Optimization and Next-Generation Building Management Systems." *IEEE Internet of Things Journal* 4 (1): 269-83.

[29] Ahmad, M. W., Mourshed, M., Mundow, D., Sisinni, M., and Rezgui, Y. 2016. "Building Energy Metering and Environmental Monitoring. A State-of-the-Art Review and Directions for Future Research." *Energy and Buildings* 120: 85-102.

[30] Valero, E., Adán, A., and Cerrada, C. 2015. "Evolution of RFID Applications in Construction: A Literature Review." *Sensors* 15 (7): 15988-6008.

[31] Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., and Gao, X. 2019. "A Review of Building Information Modeling (BIM) and the Internet of Things (IoT) Devices Integration: Present Status and Future Trends." *Automation in Construction* 101: 127-39.

[32] Liu, S. J., and Zhu, G. Q. 2014. "The Application of GIS and IOT Technology on Building Fire Evacuation." *Procedia Engineering* 71: 577-82.

[33] Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. 2020. "Towards a Semantic Construction Digital Twin: Directions for Future Research." *Automation in Construction* 114: 103179.

[34] Kim, S., and Kim, S. A. 2020. "Framework for Designing Sustainable Structures through Steel Beam Reuse." *Sustainability* 12 (22): 1-20.

[35] Lee, J. H., Song, J. H., Oh, K. S., and Gu, N. 2013. "Information Lifecycle Management with RFID for Material Control on Construction Sites." *Advanced Engineering Informatics* 27 (1): 108-19.

[36] Li, C. Z., Xue, F., Li, X., Hong, J., and Shen, G. Q. 2018. "An Internet of Things-Enabled BIM Platform for On-Site Assembly Services in Prefabricated Construction." *Automation in Construction* 89: 146-61.

[37] Hemalatha, C., Rajkumar, M. V., and Gayathri, M. 2017. "IoT Based Building Monitoring System Using GSM Technique." *IOSR Journal of Electronics and Communication Engineering* 12 (2): 68-75.

[38] Kueng, R., and Brunner, B. 2016. "Monitoring of Building Constructions with Passive RFID Technology." In *Proceedings of the Wireless Congress 2016: Systems & Applications*, 1-6.

[39] Wong, J. K. W., Ge, J., and He, S. X. 2018. "Digitisation in Facilities Management: A Literature Review and Future Research Directions." *Automation in Construction* 92: 312-26.

[40] Araquistain, I., Saralegui, U., Anton, M. A., Castelruiz, A., and Olaizola, J. M. 2018. "IoT and Data Analytics: Annual Saving Potential for Building Envelopes and Occupancy Based Office Building Management." Presented at VIII International Congress on Architectural Envelopes.

[41] Arnesano, M., Bueno, B., Pracucci, A., Magnagni, S., Casadei, O., and Revel, G. M. 2019. "Sensors and Control Solutions for Smart-IoT Façade Modules." Presented at 2019 IEEE International Symposium on Measurements and Networking.

[42] Bellagente, P., Ferrari, P., Flammini, A., and Rinaldi, S. 2015. "Adopting IoT Framework for Energy Management of Smart Building: A Real Test-Case." In *Proceedings of 2015 IEEE 1st International Forum on Research and Technologies for Society and Industry*, 138-43.

[43] Casini, M. 2016. "Internet of Things for Energy Efficiency of Buildings." *Intelligent Environments* 21: 456-65.

[44] Jang, H., Kang, B., Cho, K., Jang, K. H., and Park, S. 2019. "Design and Implementation of IoT-Based HVAC and Lighting System for Energy Saving." Presented at MATEC Web of Conferences.

[45] Kang, K., Lin, J., and Zhang, J. 2018. "BIM- and IoT-Based Monitoring Framework for Building Performance Management." *Journal of Structural Integrity and Maintenance* 3 (4): 254-61.

[46] Samani, E., Khaledian, P., Aligholian, A., Papalexakis, E., Cun, S., Nazari, M. H., and Mohsenian-Rad, H. 2020. "Anomaly Detection in IoT-Based PIR Occupancy Sensors to Improve Building Energy Efficiency." In *Proceedings of IEEE Power & Energy Society Innovative Smart Grid Technologies Conference*, 1-5.

[47] Silva, B. N., Khan, M., and Han, K. 2020. "Integration of Big Data Analytics Embedded Smart City Architecture with RESTful Web of Things for Efficient Service Provision and Energy Management." *Future Generation Computer Systems* 107: 975-87.

[48] Tushar, W., Wijerathne, N., Li, W. T., Yuen, C., Poor, H. V., Saha, T. K., and Wood, K. L. 2018. "IoT for Green Building Management." *IEEE Signal Processing Magazine* 35 (5): 100-10.

[49] Kumar, A., Singh, A., Kumar, A., Singh, M. K., Mahanta, P., and Mukhopadhyay, S. C. 2018. "Sensing Technologies for Monitoring Intelligent Buildings: A Review." *IEEE Sensors Journal* 18 (12): 4847-60.

[50] Giovanardi, M., Giusto, E., and Pollo, R. 2020. "Infrastrutture digitali nei componenti di involucro per la gestione degli edifici." In *Conference Proceedings of International Conference Design in the Digital Age, Technology, Nature, Culture*, 243-48.

[51] Sastra, N. P., and Wiharta, D. M. 2017. "Environmental Monitoring as an IoT Application in Building Smart Campus of Universitas Udayana." In *Proceedings of*

2016 International Conference on Smart Green Technology in Electrical and Information Systems: Advancing Smart and Green Technology to Build Smart Society, 85-8.

[52] Shah, A. S., Nasir, H., Fayaz, M., Lajis, A., and Shah, A. 2019. "A Review on Energy Consumption Optimization Techniques in IoT Based Smart Building Environments." *Information* 10 (3): 108.

[53] Srinivasa, K. G., Sowmya, B. J., Shikhar, A., Utkarsha, R., and Singh, A. 2018. "Data Analytics Assisted Internet of Things Towards Building Intelligent Healthcare Monitoring Systems: IoT for Healthcare." *Journal of Organizational and End User Computing* 30 (4): 83-103.

[54] Zanella, A., Bui, N., Castellani, A., Vangelista, L., and Zorzi, M. 2014. "Internet of Things for Smart Cities." *IEEE Internet of Things Journal* 1 (1): 22-32.

[55] Dave, B., Kubler, S., Främling, K., and Koskela, L. 2015. "Opportunities for Enhanced Lean Construction Management Using Internet of Things Standards." *Automation in Construction* 61: 86-97.

[56] Dave, B., Buda, A., Nurminen, A., and Framiling, K. 2018. "A Framework for Integrating BIM and IoT through Open Standards." *Automation in Construction* 95: 35-45.

[57] Chang, C. T., Chang, C. Y., Shih, K. P., Martinez, R. D. B., Chen, P. T., and Chen, Y. D. 2015. "An IoT Multi-interface Gateway for Building a Smart Space." *Open Journal of Social Sciences* 3 (7): 56-60.

[58] Zarzycki, A. 2017. "Embedded Building Components." *eCAADe* 35 (2): 337-44.

[59] Xue, F., Chen, K., Lu, W., Niu, Y., and Huang, G. Q. 2018. "Linking Radio-Frequency Identification to Building Information Modeling: Status Quo, Development Trajectory and Guidelines for Practitioners." *Automation in Construction* 93: 241-51.

[60] Yun, J. H. J., Jeong, E. S., and Yang, J. H. 2015. "Open Innovation of Knowledge Cities." *Journal of Open Innovation: Technology, Market, and Complexity* 1 (2): 1-20.

[61] Brad, B., and Murar, M. 2014. "Smart Buildings Using IoT Technologies." *Construction of Unique Buildings and Structures* 5 (20): 15-27.