POLITECNICO DI MILANO

Master in

Building Information Modelling

European Master in
Building Information Modelling

BIM and BMS for the management of the building: the Manini Connect case for Digital Twin services

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Co-funded by the Erasmus+ Programme of the European Union

a.a. 2019/2020

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ACKNOWLEDGEMENTS

First, I would like to express my gratitude to my thesis supervisor, Ing. Alessandro Zichi for giving me the opportunity to explore the research questions and formulate the methodology. I would also like to thank my company supervisor, MRICS Stefano Bellini, whose invaluable expertise guided me throughout the work.
I also extend a special thank you to both the Manini Prefabbricati and Umbra Control companies who provided me with the case study and for their constant and invaluable feedback throughout the project.

Finally, thanks go to my master's friends, not colleagues, who have shared and given me the strength to face these uncertainties time.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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SOMMARIO

Le nuove dirompenti innovazioni tecnologiche e la loro democratizzazione, come IoT, intelligenza artificiale e machine learning, consentono la modernizzazione per il settore del Facility Management. I proprietari di edifici vanno oltre la tradizionale attenzione per la razionalizzazione delle operazioni, creando ambienti in grado di amplificare il benessere dei propri utenti.

Le soluzioni Building Management System (BMS), parte dell'universo del Facility Management, hanno il ruolo di ridurre i consumi energetici e promuovere il benessere interno. Tuttavia, i vari dispositivi e protocolli BMS generano problemi di interoperabilità che nell'attuale digitalizzazione del settore, devono trovare una corrispondenza con la metodologia e le tecnologie del Building Information Modelling. Pertanto, considerando le problematiche di interoperabilità e la digitalizzazione del settore AEC/FM, questa ricerca si pone l'obbiettivo di indagare la fase delle operazioni di un edificio, analizzando le specifiche soluzioni di Facility Management e le opportunità derivanti dalle nuove tecnologie, che stanno evolvendo gli edifici e la loro gestione.

Attraverso l'utilizzo di sensori interconnessi e tecniche di analisi dei dati, verrà stabilita una relazione tra il mondo fisico e quello digitale, e quindi la definizione di un Digital Twin in grado di reagire allo stesso modo. In particolare, l'obbiettivo specifico di questa ricerca sarà il caso studio di una applicazione sviluppata per il Building Management System di edifici prefabbricati, chiamata Manini Connect. Attraverso il metodo analitico verrà esplorata l'architettura del sistema Manini Connect, i protocolli e le soluzioni tecnologiche adottate. La ricerca mira ad esplorare la sua evoluzione attraverso i framework proposti, consentendo la correlazione tra la rappresentazione digitale dell'edificio e la visione dei dati in tempo reale.

Parole chiave: BIM, BMS, Digital Twin, Facility Management, IoT

ABSTRACT

The disruptive technologies and their democratisation such as IoT, artificial intelligence and machine learning, allow modernisation for the Facility Management sector. Building owners go beyond the traditional focus on streamlining operations, creating environments that can amplify users' wellbeing.

The Building Management System (BMS) solutions, part of the Facility Management universe, have the role of reducing energy consumption and promoting inner wellbeing. However, the various BMS devices and protocols generate interoperability issues, which in the current digitalisation of the sector needs to find correspondence to the technologies and methodology of Building Information Modelling. Therefore, considering the interoperability issues and the digitalisation of the AEC/FM sector, this research has the aims to investigate the operational building phase by analysing the specific Facility Management solutions and the opportunities deriving from the new technologies, which are evolving the buildings and their management. Through the use of interconnected sensors and data analysis techniques, a relationship shall be established between the physical and the digital world, resulting in a Digital Twin capable of identical reaction. In particular, this research will form a case study looking at the use of a Building Management System application developed for prefabricated buildings, called Manini Connect. Through the analytical method, it shall be explored the Manini Connect system architecture, protocols and technologies solutions adopted. The research aims to explore its evolution by using a set of proposed frameworks, enabling the correlation between a digital building representation and real-time data insight.

Keywords: BIM, BMS, Digital Twin, Facility Management, IoT

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1. INTRODUCTION

Buildings have always evolved, representing humanity during its history and by its needs, playing a significant role in global energy consumption. From the total carbon emission percentage, buildings are responsible for 39%, in which 28% is produced during the operational phase, by heating and cooling energy or light consume and 11% from the construction process and the materials used during the whole building life cycle (UN Environment, 2017).

World Green Building Council aims to achieve the sustainability goal of 100% net-zero emissions building by 2050 to stop the climate emergency (WGBC, 2019b). In order to decarbonise the construction sector, it is necessary to focus to construct efficiently and optimise the buildings' energy consumption during their life cycle. It is decisive the use of new technologies, which enable the possibility to achieve this sustainability goal.

The general term "life cycle" is defined as the "consecutive and interlinked stages of a product system, from the raw material acquisition or generation from natural resources to final disposal" (ISO 14040, 2002). A building life cycle begins with the feasibility analysis and the project planning design phase. Once the design phase is complete, the construction phase and building commissioning begin. The life cycle continues with the operational and maintenance phases, which are usually prolonged many years until the demolition or renovation of the asset, as present in Figure 1.

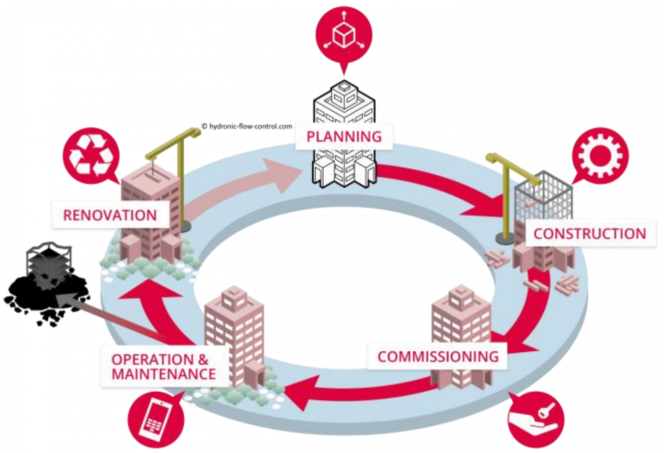

Figure 1 – Buildings' life cycle

Source: http://www.carbonleadershipforum.org

In the broader building life cycle, maintenance and deconstruction represent 85% of the total life cycle cost, while the design and construction costs account for only 15% of the total (ISO 15686-5, 2008).

In the early 1980s, to contain costs during a building life cycle, the United States created the discipline of Facility Management. It aimed to support building owners and real estate throughout operational and maintenance phases. According to Vyskocil, mentioned by Potkany, Vetrakova and Babiakova (2015), the IFMA (International Facility Management Association) defines the Facility Management as "a method whose task in organisations is to harmonise employees mutually, work activities and the work environment that includes principles of business administration, architecture and humanities and technical sciences." Facility Management improves the processes within an organisation by reducing long-term operating and management costs in conjunction with a reduction of the fixed-costs and carbon emission.

The essential part in adopting digital technologies in Facility Management & Real Estate was the energy costs. In the 1970s, the world faced an energy crisis due to the increase of the energy price and building' owners, and Facility Managers began to focus on solutions to improve facility efficiency. They realised an opportunity to apply newly available computer-based digital controls for efficient management of the mechanical and electrical equipment. It was the beginning of a new field, defined as Building Automation System (BAS) or Building Management System (BMS), which revealed the possibilities associated with the use of technological devices. These devices enabled enhanced building energy efficiency and reduced operational cost. In the past, all the devices were controlled and managed locally, thus working in a stand-alone mode. If there was a type of networking, it was strictly proprietary, linked to the manufacturer's specifications. Therefore, building services were created, such as the lighting system, HVAC, access control, security and others, but separately. The various data were, therefore, not used to make a cross-reference of all the devices' information. Moreover, the multiple subsystems were managed on-site or remotely, but not at the cloud level. Now, cloud computing and the increased availability of networks and devices ease the way to make big data analysis.

The AEC/FM industry, compared to the other ones, is still trying to adapt itself and implement new technologies and methods. A McKinsey report highlights the strong correlation between productivity and level of digitalisation: the construction sector's annual productivity has grown an average 1 per cent a year over the past two decades, compared with 2.8 per cent for the total world economy and 3.6 per cent for manufacturing (Barbosa *et al.*, 2010).

Professionals from the AEC/FM sector using Building Information Modelling (BIM) have been working on digitising the construction industry. The National Institutes of Building Sciences (NIBS) defines Building Information Modelling as the "digital representation of physical and functional characteristics of an object". However, BIM is not a simple three-dimensional representation, but an all-encompassing process of the building in which the models and its generated data are found and used in collaboration by the various project disciplines.

BIM is essential to create the real backbone of a smart building. It allows the construction or retrofit not only of the actual building but also the design of its digital twin, to facilitate the creation of multi-system solutions capable of generating an intelligent environment. Sensors, actuators and all other devices provide valuable information, most of which remains unused. Before, sensors were simply used to measure temperature, humidity or other environmental parameters; now, thanks to the Internet of Things (IoT) devices, data could be further examined by analytical solutions. The intelligent algorithms evaluate trends and recognise patterns in user behaviour or consumption, thus enabling informed decisions, predictive strategies and continuous optimisation.

Considering the interoperability issues and data integrity regarding BIM and BMS, the research aims to investigate the operational building phase by analysing the specific Facility Management technologies. For the development of this research study, it was considered a case study of a Building Management System platform, which belongs to the Manini company. Through the analytical method, the Manini Connect system architecture, protocols and technologies solutions will be explored.

The thesis' structure is characterised into seven chapters, organised as follows:

The Introduction presents a general overview of the Facility Management roles inside the entire building life cycle and along the BIM process and its related technologies. Furthermore, it is also presented by the Building Management Systems topic and the current technologies innovations trends.

Facility Management corresponds to the second chapter. It explains the Facility Management discipline, its characteristics and fields of interest. It explains the current FM software and the role inside the BIM processes, describing the current interoperability issues and possible solutions.
Building Management System corresponds to the third chapter. It describes BMS, its system architecture, and software components. It also highlights the interoperability issues between BMS and BIM processes, and it is presented an overview of the principal communication protocols which are part of the BMS architecture.
Smart Building and Digital Twin correspond to the fourth chapter. This chapter presents the concept of Digital Twin and its importance in future smart building ecosystems. It shall be described as the opportunity behind the big data analytics.
Manini Connect Service corresponds to the fifth chapter. It shall be investigated to introduce the company's case study, to describe the state of the art of the platform, its system architecture, technologies and current behaviours. It also shall explore the existing digital twin application solutions.
Analysis corresponds to the sixth chapter. This chapter presents the research conducted to develop the Manini Connect To-Be platform, describing the new components and functionalities. It shall be explained its evolution by a proposed framework which will enable a correlation between the digital building representation and the real-time data insight.
Conclusions correspond to the last chapter. It makes some consideration of the research work and about the broader topic. It presents future recommendations for test and experimentation of the company's platform, which will continue to be conducted in collaboration with the companies involved in the project.

2. FACILITY MANAGEMENT

This chapter introduces the Facility Management concepts extracted from a literature review. It shall define its characteristics inside the broader building lifecycle and its evolution and behaviours along with the BIM processes.

The holistic nature of the Facility Management is defined by the multiple disciplines which it spans from real estate management, human resources, health and safety associated together with the traditional concepts of service maintenance.

A literature review recognises different definitions of Facility Management due to its magnitude disciplines, as shown subsequently. Kelly *et al.* (2005) define FM as an integrated profession that ensures services are tailored to suit people and places, though mainly as a reactive and technical approach.

The European Committee for Standardisation (CEN) defined FM as "the integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities" (*EuroFM*, 2020).

Facility management of a company is overseen by a facility manager, who deals with the supervision of buildings and all the instrumental services at the provision of it. It is responsible indiscriminately for offices, shops or factories, and managing the multiple utilities ranging from maintenance and security to hospitality or cleaning services.

Besides, Facility Management also includes a series of management activities that require engineering, architectural, organizational and relational skills.

According to Soromova (2012) cited by Potkany, Vetrakova and Babiakova (2015a), Facility Management is "characterized by the interconnection of the three following areas: work management, space management and capital management".

Figure 2 brings an overview of how the facility management discipline can be understood, and the FM characteristics are displayed in Table 1.

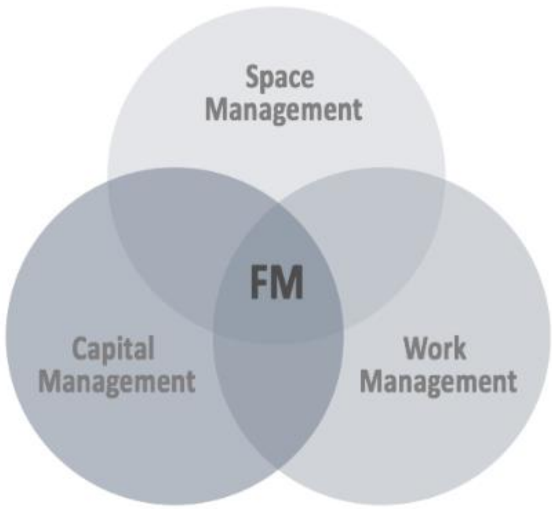

Figure 2 – Three aspects of FM

Source adapted from: https://www.axispointe.com/axisfm/fm_diff_one.php

Table 1 – The FM characteristics

FM characteristics	Description
Work management	It represents the strategic aspect, and it concerns every decision relating to the management and procurement policy of the services like the distribution of resources to be used to support the business objective.
Space Management	It is the analytical aspect, and it aims to understand the needs of customers by monitoring the results of management and efficiency. It also identifies new techniques and technologies which can support the company's business.
Capital Management	It concerns the management and coordination of all the services intended as a whole. It includes the definition of systems and procedures with the implementation and re-engineering of the supply processes.

In general, facility management improves the processes within an organization by reducing long-term operating and management costs together with a reduction of the fixed costs and a reduction of carbon emission.

The cornerstone of the Facility Management activity is the Computer-Aided Facility Management (CAFM) systems. They are computerised systems, started to be used during the early 1990s, implemented to facilitate access, monitoring and reporting of all activities functional to the provided services. Before then, all data were generally recorded in paper drawing and still nowadays, it is common to receive for as-built documentation, heavily paper documentation, fragmented and disorganised.

CAFM software allows connections between the parties involved, maintaining online control of the status of activities and in some cases of management costs. The results of the activities managed and recorded flow into a single database, available for any subsequent analysis.

The organisations using CAFM systems were able to utilise the space and resources better, reducing extra costs and enhance satisfaction. The systems generate more accurate reports and allow applying preventive maintenance.

In parallels with CAFM systems, during the years it has been developed different software solutions to cover the various aspects of FM. CMMS (Computerised Maintenance Management System) for example, concentrates more to the maintenance operations of the facility. The software allows keeping track of work costs and orders, labour records on the equipment and in general, a complete maintenance workflow. The goal is to ensure the smooth and safe operation of buildings, and it can be part of a CAFM system.

The Facility Management sector with CAFM systems and other solutions embraces, from the beginning, the opportunity given by the digitalisation of paper. Computerisation alleviates the asset information captures and retrieval. Perhaps the knowledge captured and the data analytics is still limited within computer-aided facilities management (CAFM) systems, despite its capability (Atkin and Brooks, 2005)

One of the problems of CAFM systems lies precisely in the input information that is often made available only at the end of the process, therefore in the construction or commissioning phases of the work. It generally arrives at facility management companies in an uneven way and from different stakeholders. The real revolution in the Facility Management sector has arrived, with the advent of Building Information Modelling, which has made it possible to overcome the limits of traditional CAFM systems.

2.1. BIM and Facility Management

Building Information Modelling allows architects, engineers, and contractor to collaborate on coordinate models and to optimise their actions, giving everyone a better insight into their work and how it fits into the overall project. Inserting the necessary and verified the information within the BIM model and working collaboratively, it means preparing a model which is subject to fewer future updates, thus reducing the variations in progress.

In this sense, Facility Management can obtain significant advantages from BIM technologies. The creation of a BIM model of a building allows you to organize knowledge, creating a database to manage all project information. It collects the graphical drawings and the component schedules in an intuitive and structured way. Each schedule allows you to view all the fields related to the component, geometric data, attributes, and related shared parameters, enabling quick access to information. The 3D graphic interface facilitates the understanding of the building and the spatial location of the elements.

The BIM scope is to produce all the information in a sequential waterfall model where the data integrity is maintained along the stages, avoiding mistakes or data loss. Figure 3 presents the data value during the lifetime of a building, comparing the traditional paper-based process and a collaborative BIM-based delivery process. In a conventional facility management database process, a large amount of information is lost in the passage from the construction activity to the facility management beginning. These information needs to be created again to support the operational phase.

Instead, applying a collaborative BIM process, the amount of information increases linearly until the building handover, before starting the operational phase. The data integrity is maintained, and it only changes its behaviour, from being created during the design and construction phases to be consumed during operational activities.

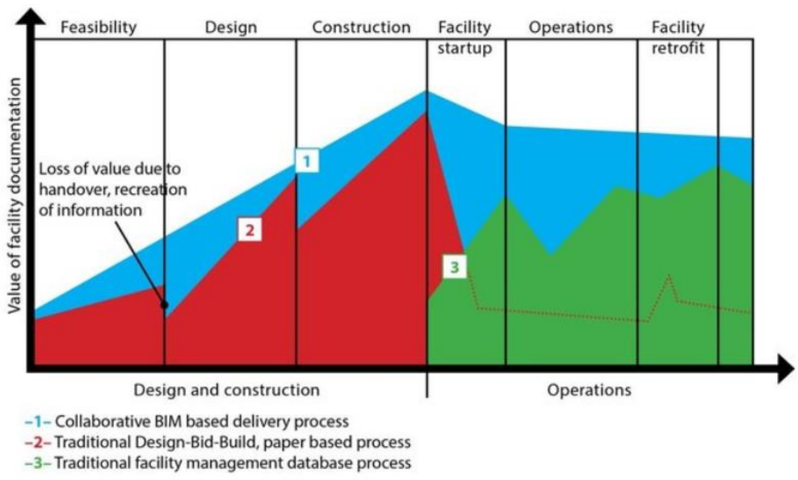

Figure 3 – Data integrity

Source: Eastman et al. (2008)

The ISO 19650 (2018), regarding organization and digitisation of information about buildings and civil engineering works, indicates the process and requirements for producing and share building information. It informs about the BIM methodology applied to the entire building life cycle, including strategic planning, initial design, engineering, development, documentation and construction, day-to-day operation, maintenance, refurbishment, repair, and end-of-life. It also considers the FM roles in the broader building life cycle.

The Project Information Model (PIM), a document presented by the ISO mentioned above, defined during the design and construction phases, enriches itself with as-built drawings and data useful to the Facility Manager, becoming an Asset Information Model (AIM). The AIM supports the facility management by providing the data and information required for the operations and maintenance (O&M), health and safety protocols, together with the computer system requirements that are going to be used as a platform for the management. The AIM information can be transferred to a CAFM system or similar platform, ideally bidirectional, capable of implementing the requirements of the maintenance manual and using them as input for planning the interventions.

Nevertheless, despite the connections between BIM and FM, there are some obstacles for the integration of the two subjects, i.e. there are interoperability issues between them. The next subsection shall address this question.

2.1.1. Interoperability between BIM and FM

The Facility Management implementation inside the BIM processes is slow and the main reasons, despite the possible cost advantages is due to a change of cultural habits to consider FM as part of the primary process combined with the interoperability issues between the two subjects.

Facility Management's role is fundamental during the operational phase but engaging it already from the initial stages of building life cycle can be an opportunity to increase savings of finance-related also to investment costs. The facility manager as a consultant, during the acquisition phase of a building, it can prescribe the space disposition and material solution required from the future operational costs in order to rocket the efficiency.

Interoperability is a critical concept in BIM; in fact, the transversality of the BIM approach necessarily requires maximum accessibility of information and processes among all those involved.

BIM is structured in different layers of information, defined as dimensions, which they represent a specific typology. Various research recognises different dimensions to the BIM information layers, and the 7th is dedicated to Facility Management and operational data (Charef, Alaka and Emmitt, 2018). Despite the integration and development in one of these layers of information, BIM and FM systems present many interoperability issues.

In general, interoperability is the possibility of exchanging data between different software and application platforms intended for the various functions involved in the activities (Noura, Atiquzzaman and Gaedke, 2019). Traditionally, specialised software developed for the management and processing of data within specific sectors, such as the AEC/FM, are lacking the ability to integrate each other.

Aligned with that, "Information interoperability or data mapping is critical for seamless information sharing between BIM and FM because the approaches to information representation in BIM and FM systems are different" (Chen, Chen and Cheng, 2018). The inadequate interoperability causes a loss of efficiency, which in the U.S. facilities, is quantified by 10.6-billion-dollar loss during the operation and maintenance (Lavy and Jawadekar, no date).

The Facility Management resources usually are represented in a relational database, while the Building Information Modelling is geometric and semantic information which can be defined by IFC schema. Industry Foundation Classes (IFC) and Construction Operation Building information exchange (COBie) are open standards that have been developed to tackle the interoperability issue.

BuildingSMART organization defines IFC as a: "standardised, digital description of the built asset industry. It is an open, international standard (ISO 16739-1, 2018) which promotes vendor-neutral and functional capabilities across a wide range of hardware devices, software platforms, and interfaces for many different use cases."

The IFC (Industry Foundation Classes) standard is widespread among professionals who use BIM technology as a data model to facilitate interoperability in the AEC sector.

One of the advantages of BIM is realised by the sharing of information between organizations, designers, and databases. The aim is to create a tool that does not depend on the proprietary formats of the software producers, to avoid a monopoly of BIM technology, which has at its base the concept of freedom of data transmission.

For this reason, the IFC standard acts as a supporter for the free communication of information between several different authoring software, which took part in the development of the standard to make their products compatible. The primary purpose of the IFC is to provide a set of definitions for all types of elements encountered in the AEC sector with a structure based on text-based information.

COBie, on the other hand, is an information exchange standard with the purpose to identify and exchange information regarding managed facility assets. It gives a linear process to implement data from the beginning through all the building life cycle. Like any communication format, a sender and a recipient are required; in the specific case of COBie, the figures involved are two phases of the building process. The construction phase, understood as the entire construction process of the building, from planning to delivery of the works. And, the Operational phase, i.e. the management and maintenance of the building organization.

COBie aims to enhance the means through which information is conveyed today, proposing a standardized digital information structure that can accommodate the contents typically included in product data sheets, user and maintenance manuals, warranty documents, etc.

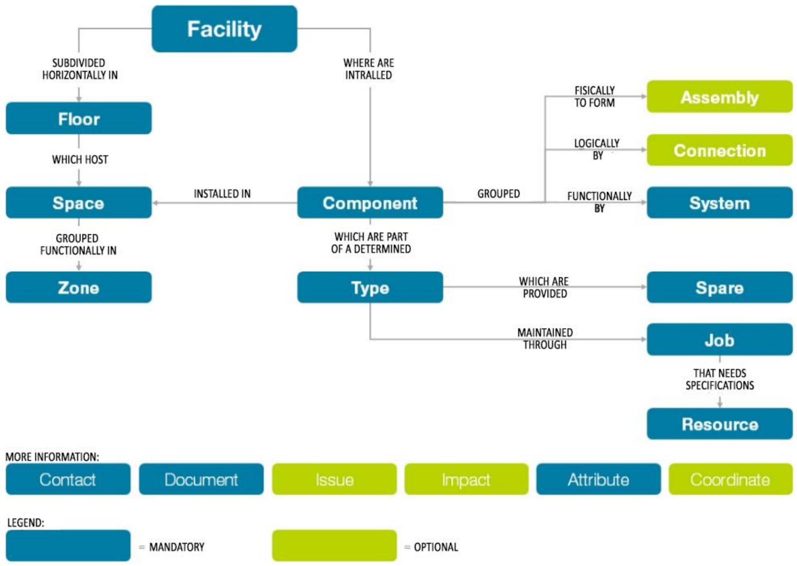

Figure 4 – Structure of COBie.

Source: adapted from Brumana *et al.*, (2020)

Figure 4 introduces the structure of the format and its different mandatory and optional elements (Brumana *et al.*, 2020).

The format structure follows a semantic schema where the single building is managed spatially through the mandatory concept of *Zones* and functionally through *Systems*. The *Zones* consist of different *Spaces*, each of them allocated to a specific *Floor*, coinciding with a level of the building. *Systems*, instead, are associations of *Components* which aim to provide a service. A *Type* describes each Component; this means that a hundred doors installed in a building will give rise to a hundred different components and maybe eight different types.

COBie also allows you to define other types of relationships that may exist between the installed products. *Assembly* allows you to determine which products are physically composed to form a more complex product; *Connection* will enable you to connect two products that are affected by a logical relationship. The products are then associated with information related to their maintenance: *Job*, descriptions of the maintenance operations to be undertaken; *Resources*, tools, and resources to carry out maintenance interventions and *Spare*.

It should be emphasised that each of the blocks represented in the diagram coincides with one of the COBie XML format worksheets. The COBie format data is a STEP physical format (Standard for the Exchange of Product model data), and it is only an information content. It can be viewed as a spreadsheet file in Excel, for example.

The format is compatible with all the classification systems; in fact, the owners may require Omniclass or Uniclass 2015, concerning the country where it is located. The use of classification systems creates a new layer of information that helps to navigate into them. It helps to bring familiarity and consistency between projects and owners. The use of COBie is mandatory by the U.K. government for all projects throughout the design and construction cycle.

The value of COBie lies to give a standardised structure to an information exchange process. If the process is organized, the information will be held; and if the information is classified, the user can find the information, process, and then use it.

Although COBie only deals with a part of the big issue related to building maintenance, the process of defining processes on an IFC basis is a fundamental ingredient in achieving the much-desired interoperability in the construction sector.

3. BUILDING MANAGEMENT SYSTEM

In this chapter, the concept of Building Management System as part of the building technological evolution during the last decades shall be explored.
A Building Management System is defined as a computer-based system installed within the buildings to manage and monitor equipment such as air-conditioning, heating, ventilation, lighting, power systems, among others (Sayed and Gabbar, 2018). Electrical and mechanical components in a facility are connected in a BMS system, which enables them to interact, and different subsystems which initially were independently operating are now connected with the aim to automate, taking control of the various facility operations.
Buildings are moving away from being a passive asset and becoming active contributors to business success. Looking at the number of intelligent systems that make up a building and the level of integration between them, the management system architecture can be characterised by greater or lesser complexity. A study conducted by the real estate company CBRE has discovered that already 80% of offices are controlled by Building Management Systems (CBRE Global Workplace Solutions, 2019), and it is becoming a necessity to handle the new energy efficiency requirements.
There are many acronyms in the world of building management, representing the different software solution available in today's market. BMS is also known as Energy Management Control Systems (EMCS), Building Automation Systems (BAS), Building Energy Management Systems (BEMS), Facility Management Systems (FMS) and Building Automation and Control System (BACS).
The following subsection will make a panoramic of the buildings’ evolution and requirements during the last decades.

3.1. Buildings’ evolution requirements

Human beings are sensitive to their physical environmental factors such as temperature, humidity, light, sound. The modern built structures are increasing in complexity, using new advanced technology associated with systems integrations able to maintain comfortable internal environmental conditions.
In the late 19th century, buildings began a rapid advancement in mechanical and electrical systems. They were explicitly designed to accomplish the tenants’ comfort. This approach has always been the norm, and it was limited to consider mainly the human comfort, with only a little regard to energy efficiency and none to the environmental impacts.
As introduced earlier, energy prices started to increase from the 1970s onwards. This led to the increased attention given to the efficiency of a building’s mechanical and electrical systems. The increasing awareness about environmental pollution and global warming has brought attention to the critical role that BMS systems and facility manager can play through operate the buildings efficiently.
The first *intelligent* buildings, before the 1980s, were constituted of manual switching controls or time clocks, that proved the on/off signals to enable pumps, fans, etc.
Until the 1980s, the automation of building systems was achieved at the level of individual equipment and single specific function such as ventilation. The integration and convergence of information systems started after. It is from the 1990s that building-integrated system combined Building Automation Systems (BAS) with Integrated Communication Systems (ICS) technologies and it was possible, for

example, to access remotely to the control system by using a telephone network (Popescu and Prada, 2013).

Later on, with the diffusion of internet technology, the systems were connected into an internet cable network. The main issue until that moment was that the technologies were expensive, and the diffusion was limited to only high-end specs building.

The BMS systems were evolved from a limited control of HVAC or electrical equipment to the central nervous system of modern buildings, with the possibilities of virtually control everything within the facility.

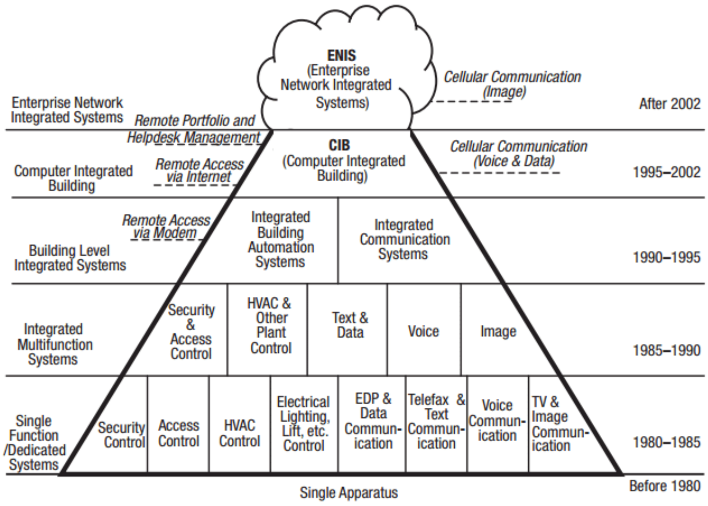

Figure 5 – Intelligent Building pyramid communication technologies

Source: Shengwei Wang (2010) mentioned by Popescu and Prada (2013)

It is from 2010 the growth of automated buildings and the birth of the building management system as we know today. The building started to get the ability to *sense* what was happening in the rooms and to understand the space by collecting information or alerting when some changes were happening.

In 2020, it is now possible to define a *smart* building, which is driven by the ability to connect more effectively different systems, technologies and by ensuring data transparency.

It is easy to understand what is happening everywhere in the building through sensors and use this information to make a suitable building managing. The system is not only reacting on specific triggers, but it starts to mix the various data, coming from different devices and disciplines, identifying new patterns inside it. The evolution in the future is the development of a *self-adaptive* building or *cognitive* building which makes pro-active decisions or mitigating actions, without any human control. It could limit the risks autonomously during the operational phase and provide personalised and seamless services to a specific user.

3.2. Applications and functions of BMS

In this subsection, the various BMS application and functions shall be listed. Buildings and construction sectors represent 36% of the total energy consumption; They consume 25% of all the global water, and they represent 39% of global energy-related CO_2 emissions (IEA and UNEP, 2019). The built environment sector has a fundamental impact on carbon emissions. It appears critical the necessity to reduce the energy consumptions and to move toward a sustainable industry, answering at the same time to the continues growth of population and building demands. Figure 6 shows the global consumption of energy and gas emission. The different shaded blue areas represent the building and constructions apport to the statics and are evident the impact which has the sector compared to transportation and other industry.

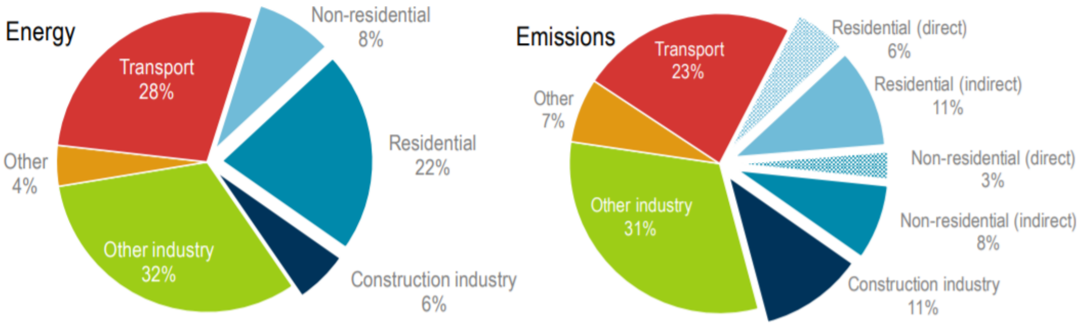

Figure 6 – Global share of buildings and construction final energy and emissions, 2018
Source: Global Status Report for Buildings and Construction (2019)

In 2050 the world's population will arrive at almost 10 billion, and the number of total buildings will double it (Emi Suzuki, 2019). Many countries are making efforts to promote sustainable buildings and reduce national emissions. In fact, by 2030, all new facilities, infrastructure, and renovations will have at least 40% less embodied carbon with significant upfront carbon reduction. By 2050, new buildings, infrastructure and renovations will have net-zero embodied carbon, and all the facilities, including the existing, must be net-zero operational carbon (WGBC, 2019a). This is the first main reason to adopt a building management system because it will help to reduce the energy consumed and achieve the sustainability targets. Nevertheless, a BMS is essential to promote the behaviours of each persona related within the building. A building can be considered having principally three different personas types: the building's owner, the facility operator and the tenants/visitors.

The building's owner often cares about not only one individual building, but it is concentrated on a bigger scale, with multiple buildings ownership. It is focused on the asset’s safety and the reputation of its buildings/brand, like a hotels’ chain, for example. It must reach a Return of Investment (ROI) from the building, and ultimately it could be interested in the sustainability aspects. Building management system applied to its properties’ asset can help to have a clear data insight regarding the way that the energy is consumed. It is possible to define the financial and sustainability goals straightforwardly, and it allows to create a seamless integration within the various assets. Imagine a hotel chain which knows already the client preferences from a previous stay and it can adapt the room with the same conditions in every hotel part of the chain. The building’s owner can assess the space utilisation or understand why the performances of one building are better than another.

The facility operator is the second persona type characterising the building. Its goals are to ensure low operational costs, information transparency, flexibility to different scenarios and accessible maintenance works. In the absence of a building management system, problems such as excessive deferred maintenance, costly maintenance expenses, and limited transparency could increase. Meanwhile, with a BMS technology, it is possible to have continuous monitor into assets and operations. It provides guaranteed performance that it will extend the useful asset life and ensure safe and secure operational works.

Nowadays, the tenants represent the key elements of an asset. A building's user spends around 90% of their life indoors (KLEPEIS *et al.*, 2001), and is looking for safety, comfort, easy access and significant experience within a building.

A modern BMS can interact with the user, inside and outside the building. It can learn from its routines by collecting data which it will define common patterns. The data analysis increases the results by acting for the user's behaviours and providing it with an excellent experience which it can improve its productivity.

It is possible to increase the human wellbeing by the creation of a healthy environment which it monitors and controls elements like lighting, air quality and noise. Various building standards, like WELL[1], defined by the U.S. Green Building Council, are being set to improve the wellbeing inside a building and BMS technology can help to reach those goals.

The BMS technologies are moving together with the wellbeing building concepts toward an Ambient Intelligence (AmI) vision. The user represents the focus of a pervasive environment, augmented with sensors and actuators, where an intelligent system monitors all the environmental conditions and takes proper actions to satisfy its requirements. In computing, Ambient Intelligence refers to electronic environments that are sensitive and responsive to the presence of people (Privat and Streitz, 2019). The Systems are characterised by low intrusiveness with the capability to adapt themselves and to anticipate the User's requirements. A Mark Weiser sentence can explain the concept of AmI: "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it" (Weiser, 1991).

In the specific context of a BMS and energy-saving, this visionary goal becomes even more complicated due to the presence of contrasting purposes: one is the satisfaction of the User's requirements the other is the depreciation of the consumed resources.

A study conducted by the Technische Universität München suggests that actively involving room users in the energy-saving process, can reduce energy consumption by up to 25% (Siemens, 2014). A building management system can integrate algorithm strategy to balance the energy consume and accomplish the Users' behaviour. If a user prefers to have temperature parameters different from a fixed saving energy range, the system of the room automation can make the User conscious about it. This is possible through the use of visual feedback, for example, by using a display inside the room which show an icon that it is changing colour concerning the energy used.

The AiM vision is part not only of the hospitality or residential sectors. Nowadays, companies are looking for solutions to provide a workplace experience which it can attract and retain the employees. The office concept, as we always knew, it has been evolving, moving toward flexible and smart working solutions. A BMS system can support the flexibility of spaces, especially in the co-working solutions by monitoring with occupancy sensors how people make use of them, and it helps to optimise the fruition.

BMS today is not only used to control complex buildings with extensive electrical, mechanical, HVAC (heating, ventilation and air-conditioning) and plumbing systems. Its scope is vast, and it covers various aspects within the building. Table 2 explores the different application of BMS in multiple fields.

[1] U.S. Green Building Council. Available at: https://www.usgbc.org/articles/what-well.

Table 2 – BMS functions

Field	Functions
Power	- Monitor the production of energy resources, like photovoltaic. - Enabling energy smart grid functions;
Energy efficiency	- Real-time monitor energy utilisation. - Energy peak of use and consumption patterns. - Room occupancy to adapt the energy consumption;
Lighting	- Shading systems blind in relation to sunlight. - Dimming and switching lights via presence, brightness, or scenarios;
Fire safety	- Fire and smoke sensors. - Automatic activation of fire suppressors;
Security	- Predictive analytics applied to elements failures ahead of time, based on usage patterns and history of incidents. - CCTV and AI video stream analysis. - Access control;
HVAC	- Settings room temperature. - Monitor humidity. - Monitor and control CO_2 and air quality levels;
3rd party integration	- seamless user's preferences and scenario across the building. - interaction with RFID or Bluetooth beacon devices. - Control media devices;

A Building Management System is usually structured with specific characteristics such as zoning, grouping, scheduling, scenarios and alert event.
The asset inside the building management system is divided into several zones, and for each one, it has its behaviour. Inside a single zone, different subsystems such as lights, ventilation or HCVA work together to provide specific conditions and scenarios for that space. The concept of a *zone* is not only used to let different systems work together, but it is necessary for locating the Users inside the building by the use of an application. Metadata in the management software integrates the idea of the zone. Usually, it can include the name of it, the uses, its location, its geometrical characteristics. It also explains which assets it contains and its relationship with other zones, as part of a subsystem.
Grouping is used to abstract a set of devices into a single one which they can be controlled together. For example, considering the lights in a meeting room, they can be grouped into a single command element. The natural and flexible way to achieve this, it is connecting the lights inside the software and not by a real cable connection. This ensures that the *grouping* concept can be modified during the time, adjusting the elements part of it.
Scheduling is used to facilitate daily routines; it is a set of time and date for specific tasks that can be automated by the Building Management System. A typical example is turning on the external lights when the sun goes down.
Another typical function in the BMS is a scenario because the assets of today are moving toward a flexible use of the spaces; it is required to adapt them to the various requirements. Different scenarios can set the different functions and characteristics of the spaces. For example, an open space can be used

for meetings or as a cinema room. The meeting room requires the lights on and the blinds open while a cinema space is an opposite. An exact scenario makes effective the use of a single area in different situations.
Specified events in the BMS can trigger particular automatic tasks or alarms. For example, it is frequent for fire security; when the fire sensor detects the smoke, it turns on the fire suppressor. Also, a user can be considered as a trigger event by entering a room. The system can be triggered by the phone app or by a Bluetooth beacon, related to the User and the room will start to set the room conditions adapting to its preferences.

3.3. BMS general architecture

The subsection will introduce the aspects which characterize the general architecture system of BMS. The different components in the BMS need to talk to each other to be valuable. Fundamental is the component choice related to the various protocols of communication choice. It needs to be guaranteed interoperability between the systems, to avoid, for example, data bottlenecks that could produce wrong strategic decisions.
A building management system is developed by the connection of software and hardware components. The software program usually is configured hierarchically, and it can use proprietary or open protocols. The hardware components are the devices, such as sensors which communicate via a network infrastructure and they report to a workstation or a brain of the architecture system.
The building automation of a building is divided into a pyramidal architecture, as showed in Figure 7, according to three different levels: the Management level, the Automation level and the Field level.

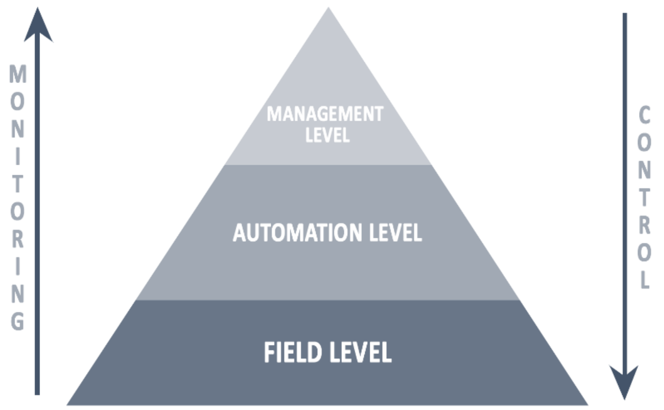

Figure 7 – BMS pyramid structure
Source: adapted from Fig. 1 Jáñez Morán *et al.* (2016)

The **Management level** (BMS) is the *brain* of the building where supervising and managing. It comprises the server and the panel control. In this level are set the alerts' parameters value, the different scenarios and the schedules for the facility operator. The data points coming from the automation level are analysed and verified accordingly with a specific setpoint. Setpoint is the threshold line which if passed, it requires action, for example, a target setpoint can be 30° for the room temperature, and when a data point reaches that value, measures from the managing system should be taken, like turning on the air conditioning. All the data coming from sensors are collected and stored in a database, hosted in the cloud or a local server for data logging. It is the process of collecting and storing data over time and analysing specific trends or recording the data-based events/actions of a system. Once there is a graph, there will be a trend, for example, could be the maximum and minimum energy usage during a month or week or a specific time. All the collected data and information are shown to the user through a graphical user interface (GUI). It is the interactive environment, where the user can monitor, change setpoint directly or generate reports.

The **Automation level** is composed of communication buses, that create the connection between the different systems, and they communicate to the management level. Their scope is to collect the data from inputs and then control the outputs. Through gateways and communication bridges, it is formed a logical network, binding the data points. Each control device can have one or more data points, but each data point belongs only to one control device. A datapoint can be a value, a unit or an attribute that refers to an input or output of the control device.

The **Field Level** consists of various control devices, such as actuators, sensor or controllers. They are different for each discipline, and they interact with the physical building.

The control devices, in the filed level, are connected physically by wiring scheme to the equipment. Usually, one control device is connected to various equipment, and all of them have properties necessary for the hardware connections and use. In an embedded system, sensors and actuators are essential elements. They populate the field level and act as the bridge between the real environment and the digital copy.

The main difference between sensors and actuators is a different purpose that they provide. The sensor monitors the changes in the environment. It is an electronic device that can measure the physical stimulus such as heat, light, sound, pressure, magnetism or a particular motion and it generates a considerate output, in the form of electrical signals.

The actuator, instead, controls the physical changes when it is required. It is a device that alters the physical quantity after it receives the control input. The electrical signal input generates a modification in the physical system by producing force, heat, motion, etc. There are many typologies of actuators like pneumatics, electromechanical and digital.

3.3.1. Software components

The architecture described in the previous subsection was related to the physical hardware connections of the system, and now it will be explained the characteristics of the BMS software architecture.

The BMS software is usually characterised by a three-tiers of logical computing, which are the Presentation layer, the Application layer and the Data layer, as shown in Figure 8 explored below.

The Data layer is the data access layer, and it takes care of persisting the information processed by the application. It knows how to read and save the information in a data source, which is not necessarily a relational database and is accessed by the upper level, which is the application layer, through the Application Programming Interface (API) calls.

The Application layer includes the set of rules that regulate the functioning of the application. It intercepts the requests coming from the Presentation layer, and it manages them appropriately.

The Presentation layer aims to manage the system's interaction with the outside world. The exchanges are in particular with the users. It includes masks for displaying and entering data, controls and mechanisms for intercepting and appropriately handling the events, according to the User’s actions. This

is possible through a User Interface (UI), usually graphical and accessible via a web-based application. The user interface commonly is a dashboard control, where are visualised all the siloed data sources.
A three-tier architecture is modular by design, and it gives a reliable control of permissions. The benefits include the scalability, and it speeds the development process because each later can be independently upgraded. It follows the typical software development by the division in front-end, which is the presentation tier and the back-end, which are the application and data layers.
The subdivision into layers is a winning solution also from an application security perspective. By dividing the application into several parts, it is possible to associate each of them with security standards and thus limiting the sensitivity of the system to vulnerabilities deriving from bugs within the application.

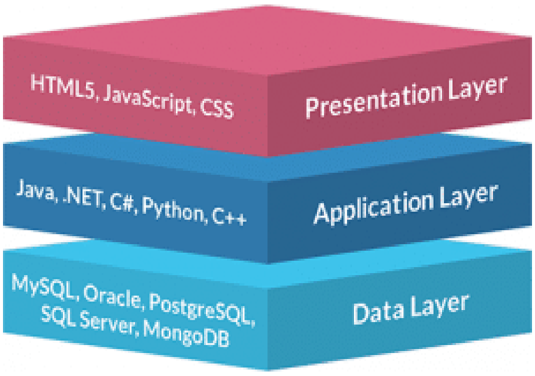

Figure 8 – Three-tier architecture

Source: www.jinfonet.com/resources/bi-defined/3-tier-architecture-complete-overview/

3.4. BMS interoperability

This subsection shall highlight the interoperability issues between the different BMS communication protocols and will present some of the main protocols utilised today in the following sub-sections.
The building management system sector is made up of a constellation of companies, devices and communication standards that make the use of these systems expensive even today that the technologies have become accessible. In the previous paragraphs were illustrated the different levels of architecture and the components of each one. The most significant challenge is to enable the interoperability between the various devices.
A simple choice is to select a producer company which can offer all the different devices categories. The notable brands' company in the sector try to catalyse the market on them by providing solutions that are simple to implement, thanks to proprietary communication standards. Vendors company, such as Siemens, can offer an integrated ecosystem. It is usually an expensive solution and with exclusivity standards, which implies the establishment of a dependence on a single manufacturer for the entire operational phase of the building.
The current market of the BMS devices is mainly compartmentalised in various silos, where each manufacturer is specialising in one specific function, targeting a particular sector, such as security, lighting and air controller devices. Usually, each silo has a specific communication protocol, that it can perform a particular function, and it is different from the other's; for example, the DALI communication protocol is mainly used for lighting.

It is expected the use of system integrator companies which are specialised in bringing together and enabling the interoperability between the different subsystems and protocols.
ISO/IEC 2382-1 (1993) defines interoperability as "the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units".
A Gateway can be used to integrate two different protocols, converting from one protocol to another, but it requires a lot of time wastage in conversion; hence it slows down the response.
Many building automation systems prefer to use open and interoperable protocols, but they are also not interchangeable. If one device using one protocol fail, we must substitute with the one that uses the same protocol. Open protocols are the result of a collaboration between corporations, user groups, professional societies and governments. They can be used for free or with a licence by anyone.
The advantages of open protocols are represented by the support which it makes able to stay current and to evolve, adding new feature and capabilities in the future.
For example, different platforms use the Building Automation and Control Networking Protocol (BACnet) for building automation. It allows for integrating third-party systems and components quickly and cost-effectively.
Communications' protocol can be classified as wired protocols or wireless protocols. Wireless protocols can be preferred in existing buildings because of their easy installation, but they cannot offer the same durability of wired protocols.
In the three levels of Building Automation are used different standard protocols concerning their function and use. The speed and size of the data necessary to be transmitted it is growing from the field level through the management level. Figure 9 shows the most used protocols across the various BMS levels with the required metadata size and transmission time.

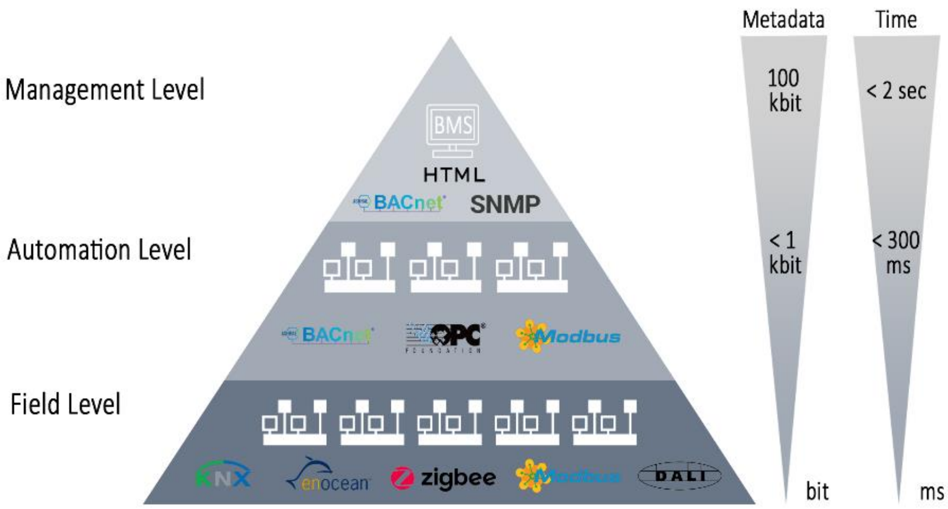

Figure 9 – BMS protocols standard
Source: adapted from the presentation Parrino A. Daniele (2020)

In the Field level, the information data that needs to be processed are minimal, in the order of bit size, but they require at the same time a high-speed transmission, in the scale of millisecond speed. In this level, there is the highest amount of devices and different vendor's product which creates many communication protocols available. Specifically, like various type of sensors, there are *LonMark*, *KNX*, *Modbus*, *DALI*, *EnOcean*.

The middle level, the Automation level, is the connection between the top and bottom level. The data are less than 1kbit and required a high-speed transmission in the order of 300ms. The standard communication protocols are *BACnet*, *OPC UA* and *Modbus*.
The top part, the Management level, the data are collected and processed as output to the User. The information is now more demanding, in the order of 100kbit and the latency response is <2sec. The preferred protocols are *SNMP, BACnet and HTML.*
The following subsections briefly describe the most common communication protocols and their technical characteristics.

3.4.1. KNX

KNX is a standard internationally accepted for building automation. It is a result of a combination of three different Standards: European Home Systems Protocol (EHS), BatiBUS and European Installation Bus (EIB). Its goal is to standardise the communication between building automation devices for future evolution. KNX technology provides a solution that carries all the control signal in a building, making it easy to implement by reducing the wiring complexities using a twisted pair bus. The KNX bus connects all the applications by the two-wire architecture route where there is a simultaneous connection between the electrical power supply and the devices in the network, enabling them to share information. The use of a bus connection increases efficiency, and it is easy to be physically implemented. Usually, a standard implementation solution uses a star topology (Globe, no date), where all the cables are direct to a central hub or switch, that broadcast the information. The solution has a high implementation cost, and it does not permit the easy addition of new devices. In fact, the importance of a decentralised bus system, like KNX, ensure that if one device stops working, the rest of the system continues to work. The KNX protocol is principally used in the automation and field level, and it can manage lighting, blinds, security systems, and many other building components.

3.4.2. DALI

DALI (Digital Addressable Lighting Interface) is a worldwide standard dedicated to lighting control in building automation systems. It is an industry standardised protocol which is part of the international standard IEC 62386, associated with specifications written by DiiA (Digital Illumination Interface Alliance, 2018), the Digital Illuminance Interface Alliance. The standard provides effective control over lighting by addressing each device separately, and it supports 256 levels of brightness. The communication is by high signal-to-noise ratio leads, and it remains bidirectional so that we can take feedback of the operating state of the lamp. Its flexibility can be known by the fact that you can easily change the bulb in case of lamp failure. A single DALI network can connect up to 64 devices, and multiple systems can be connected through gateways.

3.4.3. EnOcean

EnOcean technology is an energy-efficient wireless communication technology which is developed mainly for building automation. The EnOcean Alliance is the international association founded in 2008, involved to create and promote the specific open interoperability standard.
The protocol defines the use of energy harvesting devices which do not require any batteries or any other power source because the standard uses an ultra-low power consumption. It is possible to produce the

necessary energy for the communication only powering with a motion click, light or heat. For example, a light switch, without any cable connection or battery, uses the energy produces by the kinetic action to press the button switch.
The transmission is a small data packages that can travel in less than 1Ms, and it allows you to correctly receive the 99.9% of the signals with up to five-hundred broadcasters too close together. The Wireless transmission is thought the frequency band of 868MHz in EU and China, and it is currently the most used wireless building automation standard in the world. The wireless technology allows a flexible and easy solution for the implementation in an existing building.

3.4.4. BACnet

BACnet, Building Automation and Control Network, is exclusively focused on building automation. It is the most popular network protocol used by building automation system manufacturers worldwide. It is used for communication between different devices, and it is supported and updated by ASHRAE. The primary feature of BACnet is to provide interoperability among other vendors equipment freeing dependence on a singular vendor. Currently, it is used by more than 800 vendors across a wide range of products (Bushby, 1997).
BACnet was born in 1987, after a group of HVAC and building automation professionals, meant to produce a new open standard specifically intended for use in buildings as an alternative to the proprietary closed protocols that were offered by the large vendors within the industry at the time.
BACnet is focused on the needs of User's integrators and equipment vendors. It became one of the leading networking technologies used in building automation, and it found success in the market for some key aspects. The structure design is based on an object-oriented approach to standardise the representation of process and data within a device. It can provide more than one physical interface to accommodate small, medium and large-sized systems. Five interoperability areas are defined in BACnet which are: device and network management, scheduling, data sharing, trending, alarm and event management.
BACnet complies with the ISO 16484-5 global standard and is popularly used in the United States, Europe, and more than 30 other countries. It is commonly used to communicate between Management level III and Automation level II.

3.4.5. OPC UA

OPC UA, which means Open Platform Communication Unified Architecture, is an open standard communication protocol developed by the OPC Foundation, a vendor non- profit organisation.
Nowadays, OPC UA protocol is used for Industry 4.0 solutions because it is a communication platform developed to expose and consume information which any devices, machines or different systems. Furthermore, the intrinsic possibility in the protocol of managing secure transmission, it guarantees protection when the data from a machine travels in the world of the Internet (Burke, 2017).
The protocol has a multi-layers information model architecture, which is an object-oriented concept to describe any kind of data and expose this data and its metadata, becoming information, that provides not only the values but also the description of the values.
The OPC UA Information Model, as visualised in Figure 10, comprises the two base layers, indicated in blue, are the Meta Model and the Built-In Information Models. The OPC UA Meta Model is an

information-centric layered architecture to describe information, and there are basic rules for exposing this information and general object model to describe any kind of system. While the Built-In models describe data access information and it is built for alarms conditions, history data and events, programs and device description. On top of the Built-In, there is the Companion Information Models layer, indicated in Figure 10 by the green colour, which explains what described before the domain information and enable to standardise it. The level above, shown in orange, is the Vendor-Specific Extensions which will allow expanding the data defined which are outside the standards described with OPC UA.
The OPC UA servers can be devices ranging from tiny sensors to large machines and host from a few to thousands of data points. They can use mappings for high security or communicate without protection by only using the high-performance OPC UA binary encoding.
The protocol is used in the automation level to connect the various field devices, and it is usually adopted when the BACnet protocol is not compatible with the devices, the two protocols are complementary with each other.

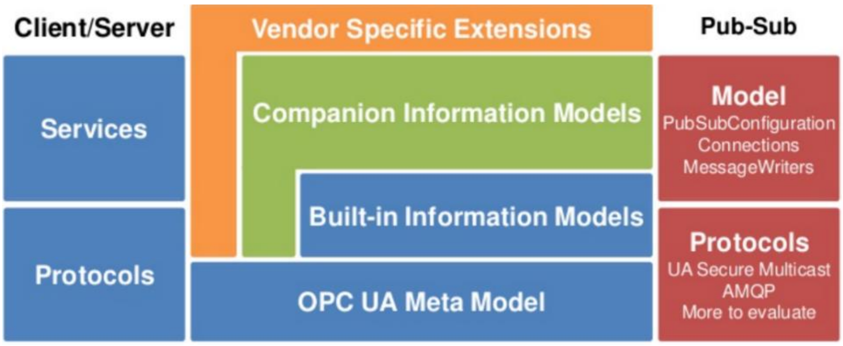

Figure 10 – OPC UA Information Model

Source: OPC Unified Architecture (2018)

3.4.6. Modbus

The Modbus communication protocol is used mainly in the Automation level, and it was created by Modicon, in 1979, to enable the communication of its Programmable Logic Controller (PLC). It is the oldest protocol, and by far, the most popular for automation (Knapp, 2011).
Modbus provides a common language for devices and equipment to communicate with each other, and it became a standard in serial communication thanks to its characteristics. It is open protocols and royalty-free, and it moves raw bits and words without apply many restrictions to the producer. It is a Master-Slave protocol, with a series of telegrams defined to read analogic and digital data, instead of sending orders.
Between the Modbus nodes, the communication is achieved with send request and read response messages with a peer-to-peer structure. The devices communicate using a master-slave technique, which only one device can initiate a query. Any peripheral device can be defined slave if it responds by supplying the requested data to the master, or by acting as indicated by it.
The Master's device can send a message to individual slaves or initiate a broadcast message to all. Slaves return a response to all message queries sent to them individually. Still, they do not respond to published messages, and they do not initiate messages on their own, but they only answer to message queries transmitted from the master.

The master's query structure consists of four components: the slave address (or broadcast address), a function code with a read/write command, the data information and a CRC *Error Check*. The *error checking* is a value the master or slave creates at the beginning of the transmission or response and then checked when the message is received to verify the contents are correct.
A slave's response, as shown in Figure 11, contains the confirming that it received the request, the data that needs to be returned and an *error checking* data. The slave's response includes the data requested, when there is no error, while, If an error occurs in the message query received by the slave, or the slave is unable to perform the action requested, the slave will return an exception message. The *error check* field allows the master to confirm that the contents of the message are valid.

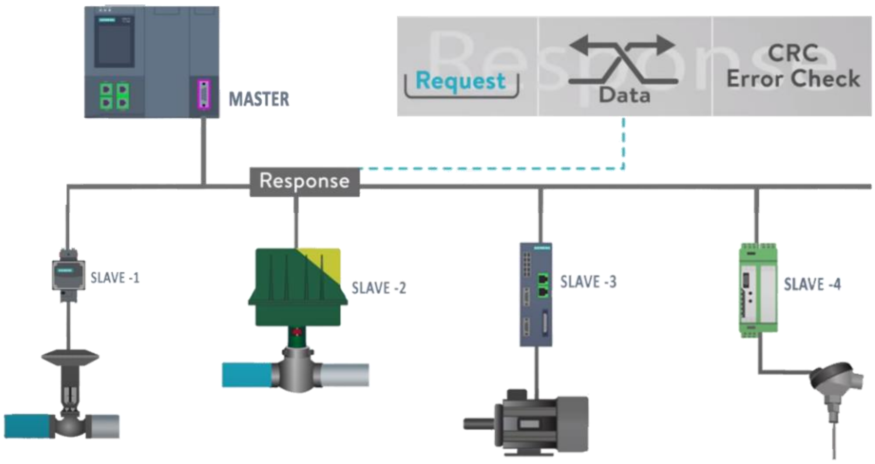

Figure 11 – Slave's response elements
Source available at: RealPars: https://realpars.com/

3.4.7. Zigbee

ZigBee is an open-source wireless technology standard that defines a set of communication protocols for short-range communications. It was developed at the end of '90s from the ZigBee Alliance, which now comprises more than two hundred companies that collaborate with the aim of creating reliable wireless devices, with low costs, low power and based on a globally open standard.
The standard is built for control sensor networks, and the name derives from the pattern of life and behaviour of domestic bees which live-in communities with a single queen, a few male drones and thousands of working bees. Their survival depends on the continuous and fruitful communication between all the members who dance in a "zig-zag" way sharing vital information.
The ZigBee devices, therefore, propose to imitate this model, with a continuous exchange of information by devices with characteristics of low power with low data rate in short-range wireless communications. The architecture systems are characterised by an input switch, like a light switch, that sends the wireless signal to a controller which after it directs the message to the right device like a light. The controller can be connected through a gateway to the Internet and collects data. The main advantage of ZigBee is low power consumption, in fact, a device can typically operate for several years on a single battery, and it can be connected with other devices in an extensive network up to 65000 devices.
The ZigBee standard, like Wi-Fi, is used to make devices communicate over short distances, but while the latter travels at speeds of up to 10Mb / s, ZigBee has significantly lower transmission speeds, with

equally limited consumption. The data transfer via ZigBee are Low data rate, between 20kbps – 250 kbps and the range of communication is limited indoor between 75 and 100m.
Table 3 below compares the different protocols previously described together with their characteristics.

Table 3 – Protocols' comparison

Protocol	Developed by	Information Transfer	Transmission Mode	Applications and BMS level	Security
KNX	Konnex association in 1990	Wire PLC Wireless (not standard)	Communication happens through Gateways	HVAC, lighting, security and energy management	Data encryption and authentication
DALI	DiiA members	Wire Wireless	Communication happens through Gateways	Wall switches, motion detectors and gateways to other protocols	No security measure implemented
EnOcean	EnOcean Alliance 2012	Point-to-Point Wireless Communication	Wireless	Occupancy sensors, key card switches, lighting and other room control	Data get encrypted using the AES algorithm with a 128-bit key
OPC UA	OPC Foundation 2006	Wire PLC Wireless	Machine to machine communication	Industry 4.0 solutions	Authentication, authorization, encryption and data integrity via signatures
BACnet	ASHRAE in 1987	Wire PLC ZigBee wireless	IP, Ethernet, ARCnet	HVAC, lighting, physical security and fire protection	TLS (Transport Layer Security)
Modbus	Modicon in 1979	Wire PLC	Master-slave communication	Automation level	Modbus/TCP Security with TLS (Transport Layer Security)
Zigbee	Zigbee Alliance 2005	Wire	Wireless mesh network	Field level for short-range communications	128-bit integrated encryption

3.5. Interoperability between BIM & BMS

The subsection will introduce the interoperability issues which occurs between BIM processes and Building Management Systems.
BMS relies on sensors devices to collect the status condition or to control actuators which they will conduct physical actions. Different subsystems in the BMS requires to communicate with each other, and the communication protocols play a vital role in the information exchange. In fact, standard communication protocols, such as Building Automation and Control Networks (BACnet), LonWorks, KNX, and MODBUS, dominate today the building management communication networks.
From the other side, Building Information Modelling assists the data exchange and information flow among architects, engineers, clients and contractors throughout various project stages by the use of the Industry Foundation Class (IFC) standard.
The integration of BMS and BIM has been explored for energy management solutions or building design optimisation. However, the exchange of BMS information is rarely happening during the various project stages using BIM tools, and the two realities are still considered as parallels worlds.
The design of a BAS system is still characterised by 2D technical drawings based on CAD, without metadata which could activate the communications between devices.
The first issue is that BMS relies on the facility management actor, and it usually participates to the BIM information exchange only in the final phases, before handover
Typically, a Building Management System is the last technological system which is designed and built in the construction phase, and it may suffer from error and corrections made during the setup and installation of other networks. Because BMS does not participate in the BIM information processes, it is typical falling into error or clash design, due to the various complexity of the building systems. Still, the BMS information and requirements could be integrated along the different stages:
During the design phase, it is possible to design and modify the BMS network architecture, inserting the object-related, using a BIM authoring software, without the needs to specifying the device's vendors. It is only helpful to know where it is going to be located and the devices' type to coordinate with the other systems.
In the construction phase, the BIM model, which will contain already information about the devices type and their interconnections, can facilitate the selection made by a Contractor or a Client of the single manufacturer's products. The BMS design, during this phase, has already been established and corrected from errors and possible clashes with other systems.
During the building handover, the BIM model, which contains the updated BMS model, after the as-built modification, could be used by the owners and the Facility Managers for the operation and maintenance jobs. In fact, the facility managers now have a complete building model representing the virtual copy of the existing which it contains all the information from the building's design to the operation and maintenance data, like schedules, instructions and assets inventories. The BIM model, in future, will be possible to be transferred in a Digital Twin platform which it will show real-time data sensors.
The challenge today is to provide a smooth passage during the last stage and facilitate the transfer from BIM authoring' software towards the BMS software solutions. Currently, the settings of BMS requires work to connect and activate the communications between the different devices. Even when all the devices information will be included in a BIM model, it is still needed a system integrator and a common standardization to enable the communications between them.

4. SMART BUILDING AND DIGITAL TWIN

This chapter shall introduce the concept of Digital Twin and the future mission to integrate an increasing amount of data which are produced by IoT devices.

Traditional BMS is becoming obsolete due to the rapid technological advancements and the limits of the platforms in expanding for new functionalities or its scalability. The implementation of IoT inside the Building Management Platform opens new possibilities, creating a holistic building vision and predictive and proactive maintenance, which it defines a *smart* building. In general terms, the word *smart* refers to the development, integration, and utilisation of intelligent systems based on Information and Communication Technologies (ICT) and, more specifically, the Cyber-Physical Systems (CPSs) (Gao *et al.*, 2018). CPSs are smart systems highly interconnected and integrated that include engineered interacting networks of physical and computational components (Gao *et al.*, 2018).

The National Institute of Building Sciences defines a building *smart* when is capable of providing "advanced functionality through an intelligent network of electronic devices designed to monitor and control the system mechanical, electrical, lighting and other systems" (Griffor *et al.*, 2017). The ultimate goals are to improve livability, increase safety and save energy and the main difference between building of the past and the construction of today/tomorrow is that *smart* buildings can interact, learn and adapt by connecting people, technology and its environments (Tang *et al.*, 2020).

A similar definition is provided by the European Commission which defines a smart building as "a set of communication technologies enabling different objects, sensors and functions within a building to communicate and interact with each other and also to be managed, controlled and automated in a remote way" (Ramahandry *et al.*, 2017).

The physical devices behaviour can be represented as a virtual sensor, but it is essential the interoperability between all, creating a network architecture, or network topology, where the scope is to guarantee the performance of communications among different sensors standards and devices.

Under the broad umbrella of Industry 4.0 and IoT, the digital transformation process is reshaping entire industries, and in the construction sector are arising the concepts of Digital Twins and Plan-Build-Operate-Integrate (PBO-I) (buildingSMART International, 2020).

The Digital Twin is a dynamic virtual representation of a physical asset, and it uses real-time data to virtually represent the functioning of a building as conceptually described in Figure 12.

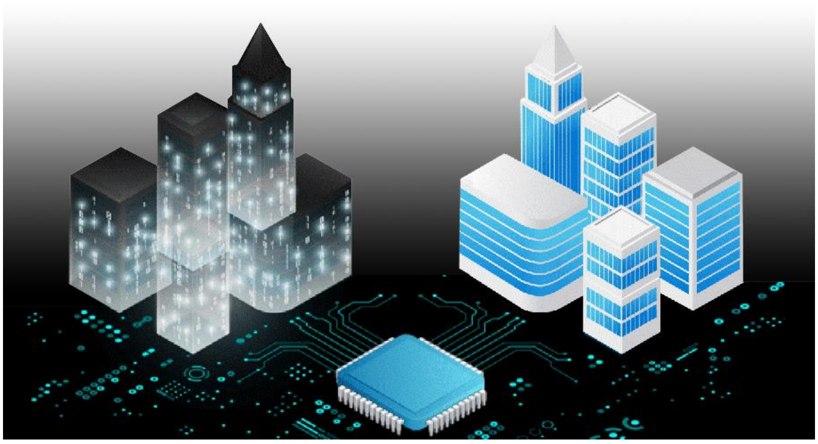

Figure 12 – Digital twin concept

Source adapted from: https://azure.microsoft.com/en-us/services/digital-twins/#features

A *smart* building can increase its analytical potentiality by the definition of a Digital Twin of it, starting from the BIM model. During a BIM process, the building information model, after the construction and as-built updates, could become the base for the development of a digital twin of the real building.
The solution will increase the asset performance, but it requires the use of different technologies such as AI, machine learning, IoT sensors network and cloud computing for a dynamic exchange between the physical and digital world and to deploy the simulations.
In fact, a digital twin can simulate a specific building scenario, and it could help builders, engineers and facility managers to understand and predict various issues. It is not a solution applicable only for brand new assets, but it can also be developed from an existing building. In this case, during the renovation phase, it will be possible to replicate the building architecture by the use of technology, such as laser scanning and photogrammetry, to create the digital copy. The physical sensor devices required for the real-time data; instead, they can be applied by the use of wireless communication technologies which they can be easily integrated into the pre-existing architecture.
The European Union is currently sponsoring a project in the Horizon2020 program called Sphere[1] which it aims to provide a Digital Twin Platform, based on BIM, in order to optimise the building life-cycle, reduce costs and improve energy efficiency in residential building. During the four years of the projects, it will be developed an ICT platform, in particular, a Platform as a Service (PaaS), which will connect the building assets to the digital world and achieve end-to-end integration and synchronisation with the building's data. The information dataset will use an extended graph database ontology based on ISO standards and protected by blockchain technologies.

4.1. An ecosystem of Digital Twins and CIM

This subsection shall introduce the concept of Digital Twins ecosystem and its opportunities to improve the cities life.
A city is an interconnected system, which is made and defined by infrastructure, operations and people, and it is funded by many interdependencies from Government, council, producer, asset owners and designers. There is a tremendous amount of data produced inside the city by the different sensors, not only public but private, and which they could be integrated to empower the city government and operations, defining a *smart* city. A Cisco report highlight that in 2020 there are over 50 billion devices connected to the Internet, but in 2015, they were half of it (Evans, 2011).
The work is currently focused on the integration of the BIM data together with the GIS data which is a Geographic Information System (GIS) framework designed for land management, in order to provide adequate tools for management and planning processes.
GIS information offers an urban, regional and national representation scale dimension, differently from the BIM data which is applied to a smaller dimensional scale for the representation of a specific building structure. The scope is to combine these two relative scales and share the information seamlessly between them, eliminating data redundancy.
The combination of these two different information technologies could define a city-scale 3D model, enriched by a database of information which they will become the backbone of a City Information Model (CIM) (Gil, Almeida and Duarte, 2011).

[1] Available at: https://sphere-project.eu/

In the future, the planning system could be working around a 3D updated model of the city, and it will allow architects and developers to test new building proposal before actually built it. It represents not only a value for the operator in the AEC, but also for the public administration and the citizens which they will understand what is happening in the neighbourhood and query planning applications, promoting transparency of public related information.

The challenge is not only to connect all the BIM data information layers with the GIS layers and scale but also to combine them with real-time data series provided by the IoT sensors and enable the creation of a Digital Twins ecosystem. It will integrate dynamic and static data, allowing valuable, accurate and up-to-date insights which are the basis for better-informed decisions and that will lead to improved outcomes and overall better quality of life (buildingSMART International, 2020).

Today, there are many issues for the integration of the data from different sources, different formats, and various scales, which requires common strategies and standardization. The BuildingSMART International organization operates in the government level, and it promotes by a Top-down approach, the development of open standards and workflows for the exchange of information and by ensuring a holistic view for data integrity and transparency. Figure 13 describes the interconnection between the building construction phases of a single building and its relationship within the macro ecosystem of the city.

Figure 13 – Ecosystem of smart buildings

Source: Enabling an Ecosystem of Digital Twins, buildingSMART, 2020

4.2. Big Data-driven in Facility Management

This subsection shall introduce the big data analytics concepts and its driven role in the Facility Management decisions, enabling predictive maintenance algorithm.

The FM operations are influenced by varies information management technologies which are vital sources of big data. Building Management System (BMS), Energy Management System (EMS) and Building Information Modelling (BIM) are the ideal supply of raw data to be used for data analytics.

Big data is defined as "datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyse" (Manyika *et al.*, 2011).

Because the traditional management systems are now evolving following the technology progress, it is expected exponential growth of big data.

Various sources for big data are provided by the sensor and mobile technologies that are becoming affordable, including, for example, Radio Frequency Identification (RFID), Field Data Capture Systems, photogrammetry and laser scans. The combination in datasets of all these structured and unstructured data from the disparate systems is driving opportunities to automate maintenance monitoring, minimise risks and maximise the equipment uptime.

There are different classification and identification of big data and Gandomi and Haider (2015), for example, classified the big data by four main characteristics as also indicated in Figure 14: volume, velocity, variety and veracity. The volume means the amount of data that needs to be stored, and the velocity is the speed required to generate and deliver data. The variety expresses the broad typology of sources, spanning from structured and unstructured data, while the veracity focuses on the quality of it.

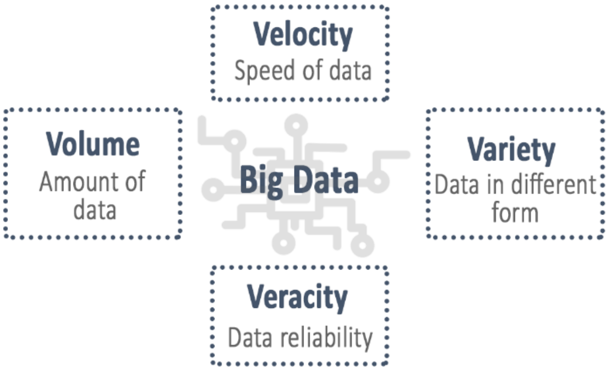

Figure 14 – Characteristics of big data

Source: adapted from Gandomi and Haider, 2015.

The data collected, firstly, need to be cleaned from the invalid data, by only selecting the relevant and after it needs to be normalised for being used in the following processing. Data normalisation is the process of data model organisation and information attributes to minimise redundancy and dependency. The data can be structured or not; Structured data are those that respect a predetermined set of rules or for which it is possible to define the type and the reciprocal relationships. It depends on a schema and can be represented by rows and columns datasets, which it is stored in a central repository, typically a relational database, from where they can be recovered separately or in a variety of combinations for processing and analysis.

In addition to structured data, there are also semi-structured data, which contain semantic tags without conforming to the typical structure associated with relational databases. They are data without a schema, not suitable for a relational database, which is represented by labels, graphs and tree structures.

Examples of semi-structured data are email, HTML, XML files, mainly used to transmit data between a server and a Web application.

According to Gartner, the unstructured data now represent 80% of the company's information assets, and their growth occurs at the rate of 65% per year (Taylor, 2018). Recent technologies have been developed to extract valuable information from unstructured data, like data mining, and to perform large-scale processing. For example, artificial intelligence (AI) can help by automatically add a structure to the data and by NLU processing assigning meaning to business documents, mail, magazine and social media posts. Algorithms can use pattern recognition to identify people, animals or other objects in images and videos and they are possible by increasingly sophisticated analysis techniques, based on advanced use of mathematics and the ability to define representative models of business scenarios.

There is a general FM industry's reluctance to use big data caused by various technical issues such as reliance on inefficient and time-consuming searching interfaces, a lack of a unified interface for the exchange of information and the inability of the average system to store and process large volumes of data.

Every day, tons of data are produced, and the growth is not going to slow down. Forbes predicts, as indicated in Figure 15 that IoT sensors market in 2021 will grow to about $520B, more than double the $235B of 2017. In fact, "the average rate per capita of data-driven interactions per day is expected to increase 20-times in the next ten years as our homes, workplaces, appliances, vehicles, wearables, and implants become data-enabled" (Reinsel, Gantz and Rydning, 2018).

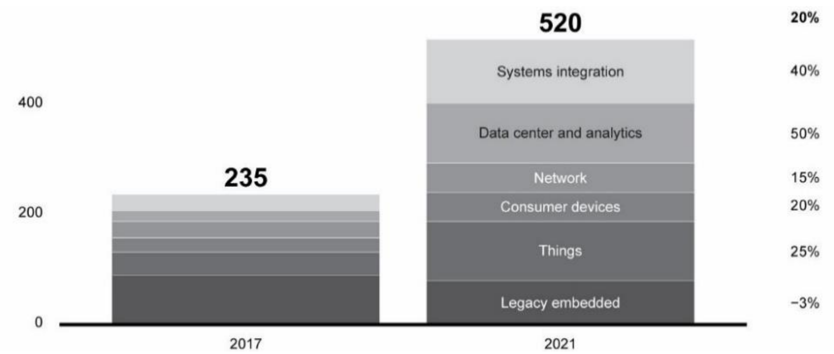

Figure 15 – IoT and analytics revenue

Source: Gartner; IDC; Harbor; Cisco; Ericsson; Machina Research; market participant interviews

Data-driven Facility Management opens new opportunity, empowering the facility managers roles to better decision making and use algorithms for predictive maintenance.

The FM industry can use data coming from maintenance operation and sensors to develop predictive maintenance strategies and digitising the faults feedback process.

The traditional way of operation is that a facilities manager will take “calls” for problems which required to be fixed and defining a process which it involves a three-way communication where the users communicate the problem to a facility manager, who then alert technicians to rectify the issue. There are potential problems caused by communication delay or miscommunication, and a solution of these feedback approach is the use of automation devices that can be used to detect abnormalities and adapt to a new environment based on surrounding situation. These systems will have the ability to collect and transfer data electronically without a human to human intervention. It can be achieved by digitising the feedback system to collect thermal comfort information or report any faults.

Currently, technicians' teams, during facility operations, apply preventive maintenance to solve any breakdown or failure, and it is carried out by technician staff which it involves a simple parameter reading operations or sensory inspections. The major drawback of this system is the personnel and time consumed doing the controls by having to inspect, for example, the entire mechanical and electrical systems of a hospital or an airport.

New technologies enable predictive maintenance, which is a methodology that uses condition monitoring technologies and techniques, to track the performance of the equipment, during regular operation. Its scope is to identify any anomalies and resolve them by collecting historical info associated with data patterns behaviour which could detect when a specific element might break down.

Traditionally, the job to analyse data and adapt systems to the changes in data patterns was made by the human. However, the ability for humans to make sense from data is possible only for a limited volume of it, after that, it is necessary to switch to automated systems, which can learn from data and adapt consequently. Machine learning brings the promise of deriving meaning from all of the data produced and using it to answer questions. It will first observe the data coming from IoT sensors to find patterns in it, after it will use these historical data patterns, to make predictions. More data is gathered, and more, the model can be improved over time and new predictive models deployed.
The main benefit of predictive maintenance is an increase in revenues by reducing the number of maintenance interventions and optimizing their execution, which will result in a significant decrease in operating times. It also increases the security and safer working conditions by it will indicate the potential problems before they will occur.

4.3. Big-Tech cloud interest in FM

The subsection shall introduce the increasing interest by the Big-cloud tech companies in the construction market and in particular in the Building Management Systems. The global facility management industry is estimated to worth around 1.12 trillion U.S. dollar, and the demand for facility services is growing globally (Fernandez, 2016). In fact, the American research firm Markets and Markets estimates an overall growth sector for Facility Management from $ 39.5 billion in 2020 to $ 65.5 billion in 2025 (MarketsandMarkets, 2020).
The operation industry has been behind the innovation curve, but cloud computing and IoT technologies can be a catalyst for innovation which they can speed up the sectors' digitalisation.
The BMS development was one of the first computerised systems, and still, nowadays, it is viewed as a static and immutable service along with the building operational phase. It is not rare to find old building automation system control in the basement room, running on dusty PCs, but as well today it is impossible to consider a technology which it will not require updates during the years.
It is inevitable the paradigms changes of the current BMS systems, which it needs to adapt to the technology evolutions and moving from a static system to a cloud solution. It is rising the demand for cloud-based Facility Management software, such as BMS platform associated with the use of IoT devices along with data analytics, Machine Learning (ML) and Artificial Intelligence (AI). Cloud computing represents the ideal ground base for a modern Building Management System because it is scalable, always updated, and it can adapt during the time to new technologies. It is also the perfect solution for multi-site facilities management, where it is required to collect and monitor data coming from various assets in different world locations. Google Cloud and Microsoft Azure, two of the biggest cloud providers, are starting to take the first steps into the building management sector, aware of the growth potential of the industry.

4.3.1. Google Digital Building Platform

Google is currently using a Building Management System into its company's buildings around the globe, and in future, it may also distribute it as part of its cloud platform. The strategy was to build a data platform which aggregates and augments IoT data coming from its buildings and using it for maintenance; the process was possible by combining telemetry data with building ontology and spatial mapping.

Google recognises that traditional Building Management Systems are a reliable solution because they have been around for a long time, but fundamentally they mainly work in separates fields where there are different silos, one for each category of use: A.V., Energy, Lighting, Security, BMS and Real estate. Each one usually has its UI, stack, personal storage, own communication protocol and sometimes its exclusive platform.
The Google Digital Building platform is structured by different levels, like a traditional BMS, where at the bottom, there are the devices, the network and their connectivity to talk, which can happen through a gateway or I.P. connectivity.
An added value of a cloud platform is that the devices can use any industry standards available, in fact, the *IoT core*, which is part of the Google Cloud, is a service developed to connect, manage, and digest data from various devices. The *IoT core* is combined with a Data Lake through a Pub/Sub-system, which is a publish-subscribe mechanism to aggregate dispersed device data into a single global system. Pub/Sub is a fully-managed real-time messaging service which allows you to send and receive messages between independent applications.
Inside the Data Lake is collected information from each of the devices with time-series data trends which are following the ontology and relationship of the device between each other. Every device has a building ontology, which is metadata describing the topological concepts of a building and the relationship between the sub-components of it.
The Data Lake used *Bigtable,* which is a NoSQL database that can handle vast column database for TB to PB datasets. It is necessary to be able to store high memory datasets because currently Google for one hundred building, it has held around 500GB of data from them.
Above the Data Lake, there are APIs available for a standardised way to access and manipulate the data, enabling the creation of third-party applications, like a facilities chatbot that rely on Machine Learning, in particular, on Natural-language Understanding (NLU). Figure 16 shows the Google digital building platform architecture and its different levels.

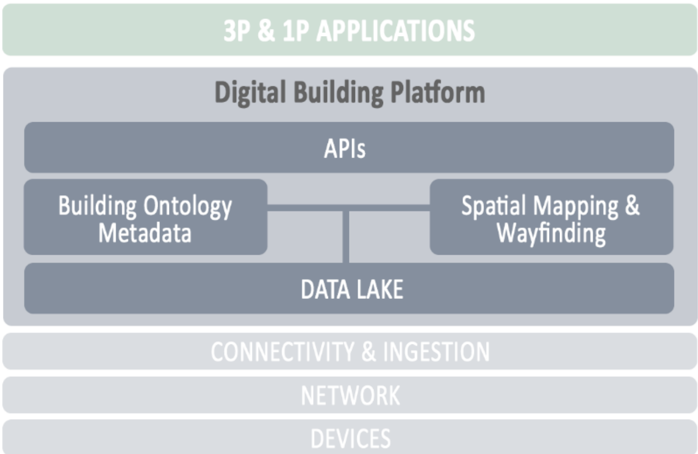

Figure 16 – Google Digital Building Platform architecture
Source: adapted from Cloud Next conference, 2019

4.3.2. Azure Digital Twin and Bentley iTwin

The subsection shall introduce the Azure Digital Twin platform under development from Microsoft and the collaboration with the software company Bentley to develop a service called *iTwin*.

In the last years, the Microsoft company has shifted its investment and significant profit in cloud computing services, through the Microsoft Azure platform. It offers different cloud computing services, and one it is an IoT platform, called Azure Digital Twins platform (PaaS), able to develop *smart* buildings for the building management.

The Azure Digital Twins Platform tries to simplify the process of creating IoT networking due to many devices' vendors and protocols. The platform can virtually represent the physical world by the use of the Digital Twins Definition Language (DTDL) which it will generate a knowledge graph that establishes the semantic relationships between the various entities such as devices, sensors, and people. It is an open-source specification language and programming, based on JSON-LD, which it describes a domain vocabulary with the entities and how they relate and connect. The twin object model is described in terms of properties, telemetry events, components and relationships.

The DTLD supports inheritance, and it can be used when a specific type needs to be specialised for a given use case. The different instances are connected by relationships between them, making up a topology graph, setting nodes and edge, as shown in Figure 17.

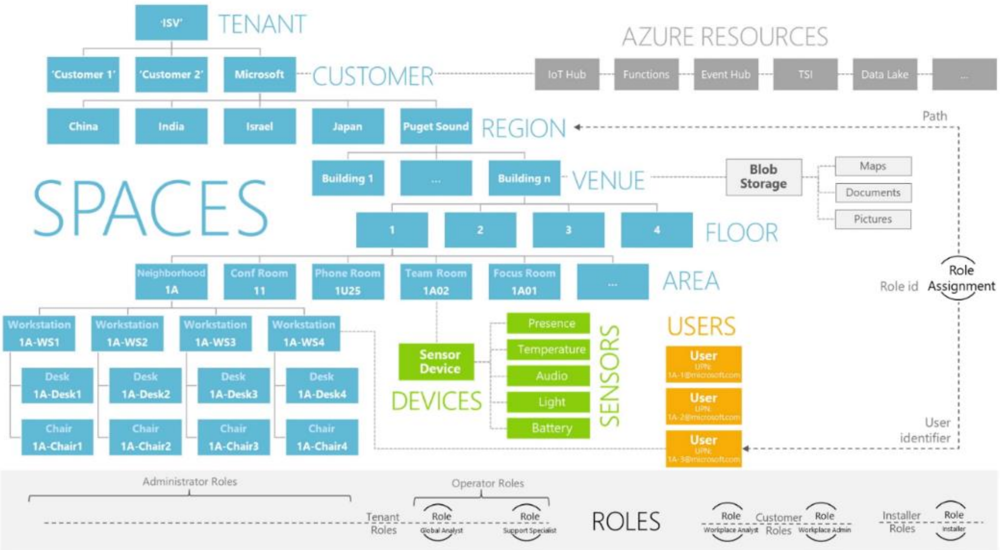

Figure 17 – Example spatial graph of a smart building

Source available at: https://docs.microsoft.com/en-us/previous-versions/azure/digital-twins/concepts-objectmodel-spatialgraph

The Digital Twin is populated with data from the IoT devices and other sources which are collected inside the Azure *IoT Hub*. It is a central message hub for bi-directional communication between IoT application and the devices connected. The transmission can happen in multiple ways such as bi-directional device-cloud, telemetry ingestion or request-reply methods, and it supports different communication protocols like HTTPS, AMQP and MQTT.

When data coming from different devices requires an initial manipulation, it will pass through Azure *IoT Edge*. Considering, for example, is requested a room occupancy number, which it can be obtained from a CCTV camera, but for privacy and bandwidth reason, it is not possible to share the stream in the cloud. The *IoT Edge* module can extract only the room occupancy information with an edge computing data analysis and without sharing the video stream for privacy reasons.

The platform service is still under development, but it is clear the interest from Microsoft in the digital twin sector for the building management. The scope is to provide an IoT data service platform that can be shaped and adapted to different software vendors and companies in the construction field by creating a common ground which it unifies the processes. It will be a construction software start-up or an AEC/FM company to integrate with the platform the BIM visualisation model and its knowledge about the specific sector.

In fact, the cloud platform Azure Digital Twin is used to support a Bentley service called *iTwin*, which is a digital twin solution. Bentley decided to collaborate with Microsoft Azure cloud to offer a combined product, where each company could cover an aspect of the platform and use its know-how; Bentley is leading regarding BIM technologies, while Microsoft Azure in cloud computing.

The platform captures geometry and metadata of the project and its environment, which drives daily decisions throughout the entire lifecycle of the project (Khelifi, 2020).

The application uses an interoperability standard called *iModel.js*, which can be considered as a GitHub for CAD data. The *iModel.js* is an open-source set of tools and libraries written in JavaScript.

The models from different stakeholders, in format *iModel.js*, are synchronised and merged during revisions in iModelHub, which is a single relational database. The iModelHub is the source of truth for the topology information and geometry information, and it generates a DTDL and a JSON file type through an export agent.

The DTDL will be used in the Azure Digital Twins platform to process real-time IoT data, while the JSON file will constitute the 3D BIM model in the visualisation. At the same time, from the Azure platform data are piped through digital twins into time series insight.

The front-end application will display all the converged data from Azure Digital Twin, time-series data, the 3D BIM model and a background map data. Figure 18 shows the integration framework between Azure Digital Twin and iTwin.

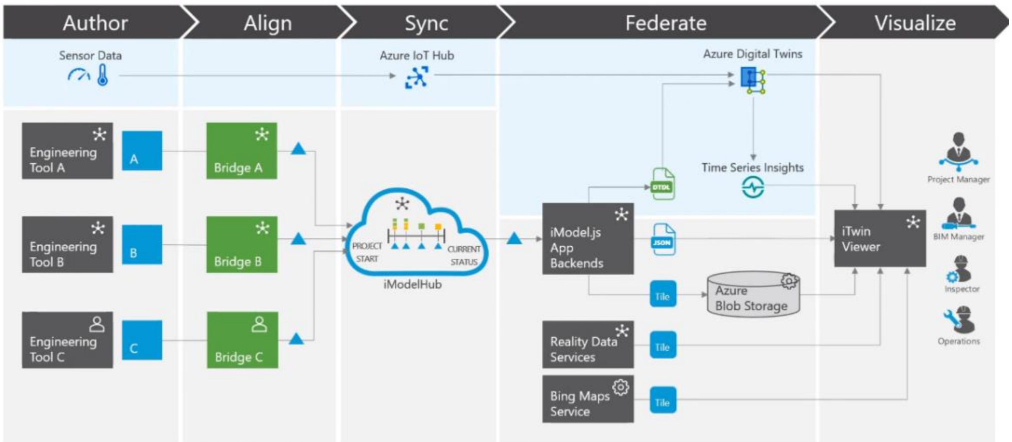

Figure 18 – Azure Digital Twin and iTwin integration

Source: Bentley Systems (2020)

5. MANINI CONNECT SERVICE

This chapter shall introduce the Manini Connect service, its functionalities and the architecture of the building management platform.

In Italy, the technical construction standard from 2018 has sensitised the population to greater protection of the new structures, and considerable attention has been given to the development of technological solutions capable of monitoring the structural stability (Ministero delle Infrastrutture e dei Trasporti, 2018).

The leading company of the prefabricated buildings sector, Manini Prefabbricati SpA, has developed a patented system platform: called Manini Connect, which can monitor the structural dynamic behaviours of a building and the internal/external thermo-hygrometric properties by a set of devices (sensors).

The Manini Connect initial idea derives from the necessity to solve a typical structural problem: a building in static conditions and during regular operation is affected by the tensions induced on its structural elements due to external actions such as rain, wind and snow. When these natural actions hit the building with to above-average or unusual levels, such as in an earthquake, sudden storms or strong winds and snow, the structural components suffer variations in the tensions of the elements. All of these are due to the vast amount of dynamic stresses recorded, and it can compromise the nominal life of the building by altering its structural characteristics more or less permanently. It used its know-how in prefabricated concrete structure to develop an algorithm able to interpret the structural behaviour of the building and its "health" status.

The Manini Connect aims to increase the level of safety, prevention and efficiency of buildings, through the use of ICT and IoT technologies, for industrial and public service, also having the advantage to be able to insert the device elements in a controlled way, during the production phase. The company can be an enabler not only of the design and production of the prefabricated elements but also could have an active role in the maintenance and monitoring of them after the handover.

The various sensors are inserted inside the pillars and also into an external box installed on the roof, which allows monitoring of the external and internal thermo-hygrometric characteristics of the building as well as the variations due to dynamic stresses.

The platform's development has involved the participation of the Umbra Control, which has been appointed as a system integrator to deliver the technology hardware solution and the software platform. The service includes the typical functions of a BMS system such as "early warnings" deriving from natural events or "alerts". All the alerts information are sent to the control centre, where they are verified and in case filtered to the user, who has constant access to the sampled data and its management system, where checking-up the sensors and activate or deactivate the monitoring system, thanks to a dedicated platform accessible from PCs and other devices.

Figure 19 – Manini Prefabbricati & Umbra Control logos

Source available to the companies website

The main feature for the company was to develop a technology to monitor the seismic behaviour of the building which not only requires the placement of sensors and collection of data, but also the development of an algorithm that is able to analyse the data received. The analysis of the data found produces a behavioural result of the movements, which occurred during the seismic event, and it highlights the possible residual displacement of the building's pillars information by interfacing together sensors such as accelerometers and inclinometers positioned within the building pillars.

The system involves the use of bi-directional piezoelectric seismic accelerometers positioned in boxes, respectively at the base and the top of the *intelligent* pillar and they allow the measurement of accelerations in both directions of the building. In particular, the accelerometer positioned in the acquisition box n° 1, at the base of the *intelligent* pillar, allows the recording of the actual acceleration to the foot undergone by the building and identifies, based on the calculation model, the expected displacement.

It is possible to measure the displacements of the two identified points, one at the base of the pillar and one at the head of it, defining the deformation curve. It is also integrated an inclinometer/gyroscope inside the acquisition box n°2, which helps to measure the rotation/displacement of the pillar head during a seismic event. The accelerations and displacements/rotations measured are compared with the design values imposed by the Italian regulations, and the data provided allows to send alerts, following seismic events of particular importance.

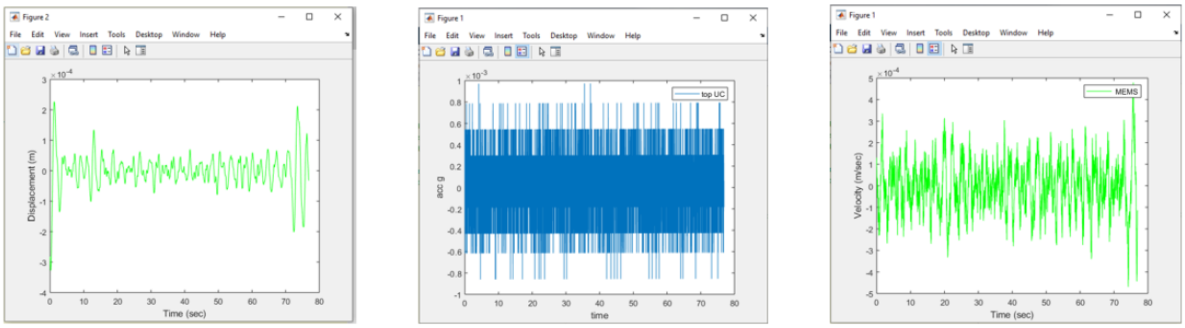

Figure 20 – Reading of sampled data from inclinometers and accelerometers

Souce: Passeri and Control (2018)

The system, along with the monitoring of the function of the structural behaviour, integrates various sensors to collect different types of data that together monitor the "health" status of the building.

For example, specific devices are installed anchored to the external acquisition box installed on the roof, and an anemometer is used to measure the wind speed and a rain gauge which, during a rain event, allows the volume of rainfall to be quantified. By exceeding the set threshold, the system activates the reading of a capacitive and level sensors in the descendant pipe inside the pillars, which they monitor the correct functioning of the downspouts and, indirectly, the rainwater disposal system.

If the quantity of water, expressed in mm/h, poured onto the roof does not correspond to that detected in the descendant, the system sends an alert to the control centre, and it is immediately managed by the Manini engineers who on the basis of the data compared with the photographic roof documentation, evaluate the possibility of communicating to the client the need to carry out an inspection on it. Similarly, the level sensor in the foundations, makes it possible to check the correct disposal of rain in the sewer network, which indicates the absence of reflux phenomena.

Along with the sensors necessary to monitor the structure behaviours and the correct water reflux, there are installed devices which allow monitoring the climatic conditions both inside the building and the environment outside it.
The temperature sensors, for example, positioned in the pillars' boxes, allow useful information to be extracted relating to the efficiency of the energy systems over a whole day with data recorded every fifteen minutes.
The humidity sensors are used to keep the characteristics of the materials and problems of industrial processing constant by reducing airborne dust and avoiding problems for the production process and operators. The daily data collected allows monitoring of the fractions of suspended particulates and thin dust present in the air. It is also possible to monitor the inner air quality by the level of CO_2, nitrogen oxides, and sulphur dioxide concentration and the measured values are compared within limits imposed by the regulations.
The Manini application can monitor and also visualise the energy production of installed photovoltaic panels or other energy production system; in the future, it could be integrated into a smart energy grid.
There is also the option for integrated closed-circuit television monitoring (CCTV), located on the external roof box which provides visual feedback during the alert event, and it is useful for general security.
The total amount of data produced by the different sensors is relevant, and they are managed by a single centralized software. The seismic data are processed in real-time to guarantee an immediate control, and because of this, data buffer is used to ensure completeness, alleviating the impact of the endless amount of data in the system.
The environmental data are instead sampled by definable intervals as they do not require continuous monitoring. The specific ranges are parameterized for every installation, and they differ from the various data types: temperature, humidity, anemometer, air quality, CO_2.

5.1. Manini Connect As-Is

The subsection shall inform the actual Manini Connect hardware sensors' architecture and its characteristics. The Manini Connect monitoring devices follows the typical architecture according to the hierarchical logic of the Building Management System.
The Field level comprises the different sensors necessary to produce data and can be divided into two main groups: the devices which characterise the *intelligent* pillar and the devices hosted in the external station above the roof.
The intelligent pillars have floated the sensors inside its concrete in specific boxes during the prefabrication phase, while the external station is installed on the building roof, during its construction. In the external shelter, the station houses the sensors necessary to monitor the meteorological factors and the hardware network connection to the server. These include the temperature and humidity sensors, a mass memory, a backup battery and a data transmission system. Above the external station a weather station is anchored with a rain gauge and pressure switch as well as capacitive sensors such as anemometer, barometer and sensors for monitoring air quality. In the roof's station, a CCTV is also installed to provide image feedback of the building.
Table 4 identifies the different typologies of sensors installed and their measurement functions.

Table 4 – Sensors and measurement

Source: adapted from Passeri and Control (2018)

Typology of sensor	**Measurement**
Accelerometer	Acceleration/Displacement
Inclinometer	Rotations/Movements
Temperature sensor	Temperature
Hygrometer	Relative Humidity
Anemometer	Wind speed
Rain gauge	Rainfall
Capacitive sensor/level sensor	Correct water disposal
Acoustic sensors	Noise
Air quality sensor	PM10 PM 2.5, CO_2, SO_2, NO_x

Figure 21 shows the *intelligent* pillar sketch with the location of the different sensors' devices across three acquisition boxes encapsulated in the concrete, and the roof station with its sensors' devices, the PLC and the CCTV.

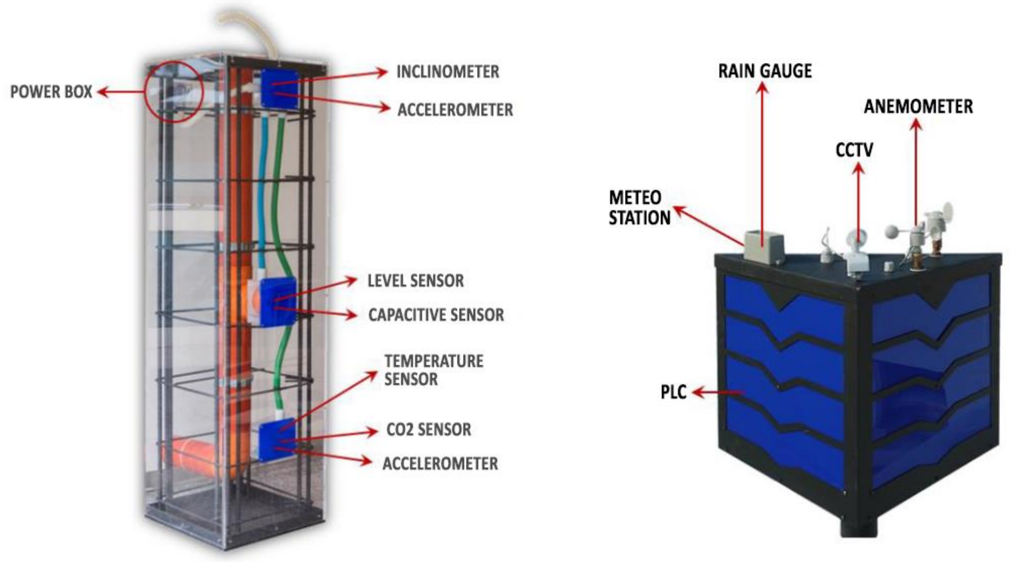

Figure 21 – Sensors in the *intelligent pillar* and above the roof

Source: S.p.A., M. P. (2018) 'Manuale software manini connect'

In the Manini Connect BMS architecture, the Automation level comprises a Programmable Logic Controller (PLC), which is a rugged digital computer adapted for devices' control. The used PLC is suitable for industrial production environments, and it can guarantee the safety and reliability of the sampled data during real-time monitoring. The PLC is connected by EtherCAT communication cables to the bus-terminals and has a client OPC UA integrated. The system architecture is designed by using a Master-Slave structure, which guarantees high reliability and redundancy of control and storage.
The Management level is based merely on a broker MQTT, handling the data from the field sensors, which carry out sampling on a regularly base. The majority of data management is happening already inside the PLC. The MQTT (Message Queuing Telemetry Transport) and security algorithms TLS 1.3 are used for the data communication from the single device to the centralized infrastructure and ensure capability for modular expandability or any future integration.
The platform allows different levels of privileges, in fact, the Manini control centre employees have access to the various buildings' data in order to monitor all the alerts and filter to the client which has access only to its asset. The system is structured by an early warning service which following extraordinary natural events send alerts to the control centre. Here the signals are post-processed and analysed by the technicians based on the structural modelling data performed. Upon exceeding the set thresholds, the engineering team of Manini Prefabbricati Spa evaluates the response of the structure and, if necessary, sends an alert directly to the Client.
Figure 22 shows the Manini Connect control centre, which is located in the company's headquarter. The control room is equipped by six 4K monitors which visualise 24h every day the Manini Connect platform. In the Control Centre, all the building information could be visualised, from the sensors' data to the early alerts coming from the complete buildings portfolio where Manini Connect has been installed.

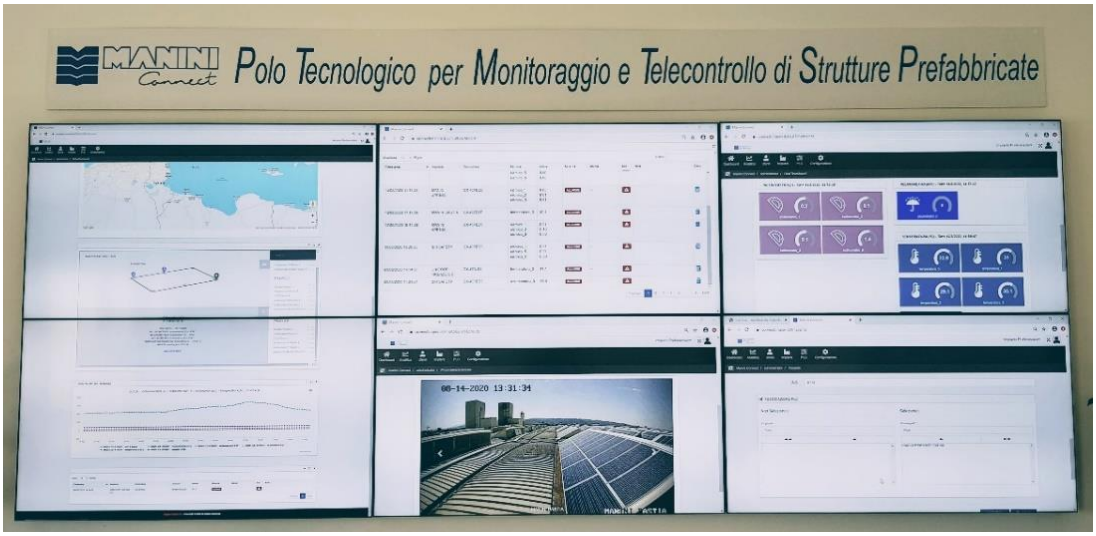

Figure 22 – Manini Connect control centre
Source: the author.

5.1.1. Web application characteristics

The subsection shall introduce the Manini Connect application frameworks and functionalities.
A web application architecture defines the interactions between applications, middleware systems and databases to ensure that multiple applications can work together (Stringfellow, 2017). It comprises two codes running side by side: the client-side code or front-end which is everything the user sees and interacts with, and the server-side code or back-end which enables the interface to work (Stewart, 2019). The Manini Connect back-end application is based on a multitier architecture, which the principles were explained in the previous chapter Software components, and it comprises a Business Logic Layer, a Data Receiver Layer and a Data Access Layer. The Business Logic Layer is an intermediary for the data exchange between the Data Access Layer and the Data Receiver Layer. The Data Access Layer has access to the SQL Server, a relational database, and to InfluxDB, which is a NoSQL and time series database. The Data Receiver Layer is translating the data received from the OPC UA Client and MQTT Client, verifying the reliability and sending for further display in the front-end UI. In fact, all the data information required for the front-end visualisation are called by RESTful API, an HTTP data transmission channel which uses an OAuth Token Bearer as a security token to protect the data transmission by authentication.
The platform front-end is based on ASP.NET and designed with the Bootstrap open-source HTML, CSS and JS framework. Inside the framework are used varies JavaScript libraries such as Highchart.js for the dataset graph production.
The UI is characterised by two levels of information privileges, one for the client and one for the Manini control centre, which differentiates the correspondent information visualised. The client-side UI enables the visualisation of data relating only to the assets owned by the Customer once its logged-in. The platform is accessible via web or by an application developed for different devices such as smartphone or tablet.
The access to the main screen shows an *Overview*, where it can observe the geographical location only for its monitored building assets. A click on the position indicator allows you to access the building's smart functions, as shown in Figure 23.

Figure 23 – Monitored buildings location map

Source: adapted from S.p.A., M. P. (2018) ‘Manuale software Manini Connect’

The "double arrow" indicator allows the user to access an interactive axonometry of the building, which is created by a UI template, based on the .svg format, and is adaptable to the different device’s screen dimensions.

The interactive axonometry has two levels: a top-level showing the weather station positioned on the roof and a bottom level where are indicated the location of the *intelligent* pillar, as illustrated in Figure 24. The interactive axonometry view reacts to click-button commands when a pillar or the Manini blue icon is selected, displaying specific sensors data group contained on the right hand side.
It is also possible to see the data analysis of the last reading sent by the software by clicking on one of the monitored sensors, listed on the right of the screen, or searching by name using the appropriate *search* bar.

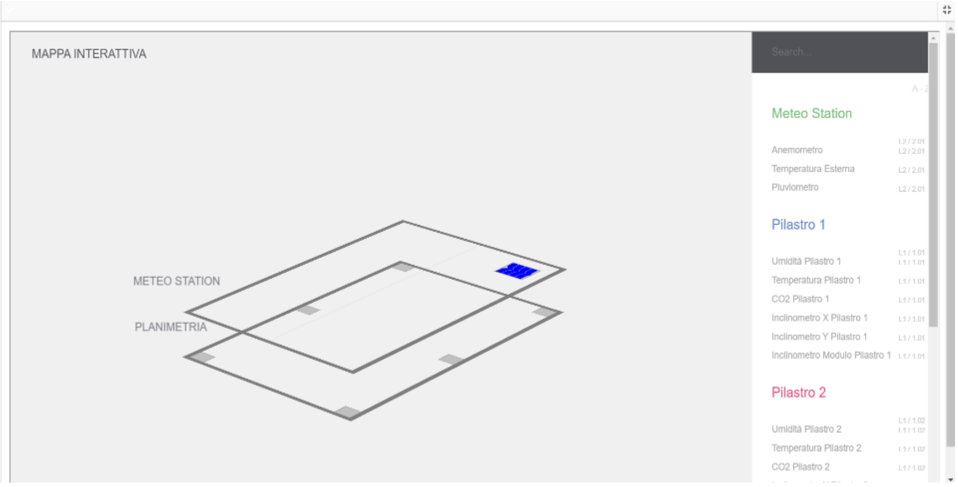

Figure 24 – Interactive axonometry visualisation

Source: S.p.A., M. P. (2018) 'Manuale software Manini Connect'

After selecting a specific sensor, an infographic visualisation will be produced representing the particular dataset related to the last 24 hours. In case of a critical event, a window will appear below the graph showing the historical alert events detected from that sensor.
Similarly, by clicking on the camera icon, it is possible to take a real-time photo of the roof enabling evidence of what is happening above the building to be seen. It is useful not only for security but also during critical events, such as water bombs or heavy snow. The captured images are then sent to the server database and can be visible in the *Photo Gallery* section in addition to the three essential daily acquisitions carried out automatically by the system. Figure 25 shows the graph and the picture feedback functions.

Figure 25 – Real time picture and graph visualisation

Source: adapted from S.p.A., M. P. (2018) 'Manuale software Manini Connect'

The UI is characterised by a ribbon bar at the top part which comprises different icons, one for each function category. The Client UI ribbon bar shows specifically only two main buttons for the client privileges, *Dashboard* and *Analytics* while the Manini administrator UI also has *Users*, *Facilities*, *PLC* and *Configurations* control buttons. At the click action on one icon in the ribbon bar, a window will be open with different functionalities.
Inside the *Dashboard* button, the *Real-Time* tab, for example, allows the Client to access the real-time data recorded by the devices, through the visualisation of the last value that has been sent from the device. It received samples every ten minutes, and the visualisation is enabled by the tool named iQueryKNOB. It is possible, inside the *Measurements* tab, to select the desiderate system from the *Filter* button and display the full dataset of measurements recorded. It is, therefore, possible to check the correct functioning of each device and evaluate any possible reading anomalies. Figure 26 shows the visualisation layout for the real-time data information where each devices typology has a specific colour and icon for easy recognition.

Figure 26 – Real-time devices measurement value

Source: adapted from S.p.A., M. P. (2018) 'Manuale software Manini Connect'

Moreover, it is possible to make precise recorded measurements' evaluations, as showed in Figure 27, specifying the particular sensor in reference to a selected time frame by accessing the *Analytics* button and the *Sensor Data Analysis* option. Instead, the monitoring of the structural response by making an assessment on the recorded measurements in selected time frames is displayed through the *Seismic Data Analysis* option. On the client-side, only the accelerometric signals that are related to events that have exceeded the alarm thresholds will be displayed to verify their correct functioning.

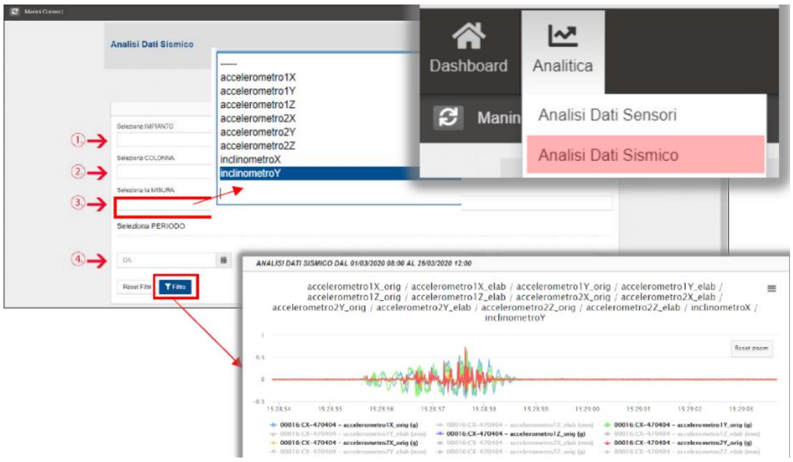

Figure 27 – Seismic Data Analysis

Source: adapted from S.p.A., M. P. (2018) 'Manuale software Manini Connect'

Figure 28 shows the As-Is system architecture of the Manini Connect application, its communication protocols and technologies as previously described.

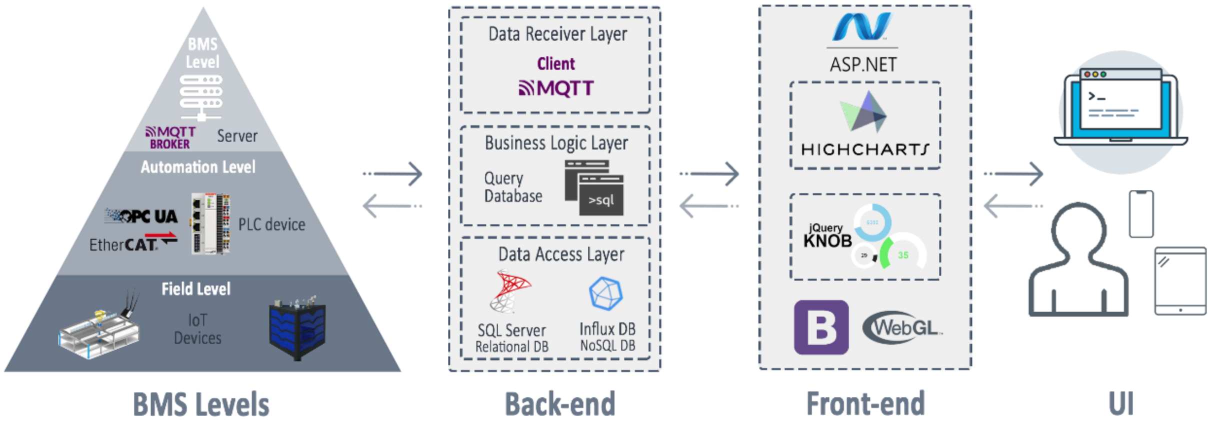

Figure 28 – Manini Connect system architecture

Source: from the author.

The Manini company utilises BIM authoring software's during the design and pre-fabrication phases, but the 3D model containing all the building technical information, after the construction phase it is forsaken. The axonometry viewer that represents a building (Figure 24) within the platform is only a standardised schematic plan, used for all the facilities, which is used to identify the intelligent *pillars'* references.

5.2. Web tools for BIM visualisation

The research proposal idea is to substitute the current simplified viewer, with a 3D building model viewer, which shall show the building design enriched by pin elements in the three-dimensional space, that will identify the devices location and the specific cross-references.

In order to understand a possible accomplishment for the application viewer upgrade, a research has been conducted with the support of Umbra Control, the system integrator involved in the platform development. The research aimed to identify a technological solution to integrate a BIM model viewer window inside the web application UI. Initially, the available market solutions were explored: there are subscription solutions which provide an out of the box BIM viewer to be, which can be implemented in the UI, for example Autodesk Forge.

Forge is the Autodesk's cloud development platform characterised by a set of web service APIs, that can be used to build applications able to automate processes or visualise data. One of the leading API is the Viewer, which is a WebGL-based JavaScript library, able to visualise 2D and 3D model rendering. The Viewer can be included in a unique web platform because it is built on the top of Three.js and the great advantage is that it uses the Autodesk know-how in conversion and visualisation from different file format, like its proprietary BIM format .rvt.

The potential of the Forge platform to develop a Digital Twin is expressed in a proprietary beta project named Project Dasher 360. It is a cloud web application which combines a detailed as-built BIM model with the BMS sensors, to provide to the building owners more significant insight into real-time building performance.

The application architecture is structured on the back-end by using some Autodesk Forge services API and is built as a Node.js application, while the front-end instead is based on the Forge Viewer together with time-series data. Project Dasher 360 adapted the Viewer by adding a new toolbar, a timeline series and more critically the sensor dots. The dots can display sensor data in the 3D model, and at the click-command of one of them, a hovered window is opened to display relevant data.
Figure 29 illustrates an example application of the Project Dasher 360 platform, which is characterised by a full-screen model viewer and some buttons bar, one on the left and the others at the bottom. All the dataset from the devices is visible in a window at the click-command to the pin element. At the bottom, it is visible a timeline to set the specific historical information request.

Figure 29 – Project Dasher 360 UI
Source: Autodesk Project Dasher, 2020

The use of Autodesk Forge requires the payment of a cloud credit subscription and the dependencies to the software house, which does not align with the Manini Connect's vision.
Considering the Autodesk platform eco-system dependencies, instead, it was decided to assess open source BIM viewer solutions which it could be used for the Manini Connect viewer.
Previously, interoperability issues were highlighted regarding the building information and the role of the .ifc format as the leading solution for the exchange of construction and facilities management project information. Consequently, it has been researched different embedding solutions for a web application which allow the visualisation of the IFC model, and as a result, it was found out two different toolkits: Xeokit and Xbim.
Xeokit, developed by Xeolabs, is an open-source toolkit for implement a high-detail 3D models viewer in-browser application. The IFC model to be visualised in Xeokit requires to be converted in two separates files: a .xkt file, which is Xeokit's native binary, containing the geometry and a JSON file containing the IFC structural metadata (Xeolabs, no date). After creating both files, they can be loaded into the viewer-created from the Xeokit SDK, following the GitHub repository instructions. The SDK to be utilised for commercial use requires the purchase of a license.
On the other hand, xBIM is an available alternative of open-source toolkit, which provides a solution to 3D viewing for web platforms. It has been developed by Northumbria University in the UK. It uses as input a wexBIM format, which is the xBIM custom binary data format, requiring a simple code for the conversion file.

Both the open-source solutions, xBIM and Xeokit, demonstrated a similar framework which is to convert the .ifc files in a format that can be rendered in the browser using reduced resources by the Web graphic library. Web Graphics Library (WebGL) is a JavaScript API for rendering high-performance interactive 3D and 2D graphics within any compatible web browser without the use of plug-ins (MDN web docs, 2019). It is developed by Kronos Group which is also promoting the Graphics Library Transmission Format (glTF) as the “Jpeg of 3D”. The format is open, without any cost and represent a simple way to share or visualise a 3D model.

The AEC/FM sector involved many actors who are not entitled to modifying the model, but only to visualise it in a correct and easy way. The Facility Manager, for example, is not a model author but it requires a complete and updated 3D model of the building in which it will be possible to integrate a layer of information based on the data sensors.

All the cloud systems such as Autodesk Forge, which provide a model viewer API for web application, they pre-process the uploaded model and convert it into a proprietary format, to deliver a smooth and efficient 3D model visualisation, for example the .svf format for the Autodesk platform.

The .glTF format provides an efficient, interoperable format for the loading of 3D content minimising runtime processing. It is as a 3D model format for web applications and it could represent the solution of the cloud companies’ behaviour to silo the data and use proprietary standards.

The .glTF format is already supported by many tech companies such as Google, Microsoft, Facebook and by JavaScript libraries such as Three.js and Babylon.js. It is used “by hundreds of content tools and services, streamlining 3D authoring workflows and enabling the interoperable use of realistic 3D models across the industry” (Patrick, Adam and Marco, 2020). Figure 30 shows the vast ecosystem support of the .glTF format and the web applications which already adopted and it has been considered as a proficient format for the model visualisation inside the Manini Connect application.

Figure 30 – The glTF ecosystem support

Source available at: https://constructingdata.wordpress.com/2018/09/08/gltf-and-construction-part-2-3d-for-everyone/ (Accessed: 25 July 2020).

5.2.1. The Vi-Sense project

The subsection shall present a research project made by five students during the International Media Informatics course at the HTW Hochschule für Technik und Wirtschaft in Berlin.

The project called Vi-Sense visualises the data from heating systems and water systems into a 3D model of the building. Vi-Sense gives technicians and facility manager an overview of all sensors in a building and about data anomalies which could indicate potential errors. The combination of the 3D representation with the visualisation of the measured values makes it possible to carry out detailed error analysis sources, such as the failure of heating or pump systems. In addition, the sensor states in the building model are supported by colour highlighting, which is a feature for detecting threshold exceeding value limit and ensures quick orientation (Metr, 2020a). The web application also includes a configurable timeline for a chronological tracking of the measured values.

The UI is characterised by a main navigable 3D window where the building model can be viewed with sensors pin elements, and on the left side a sidebar where the sensors and the anomalies are listed. At the bottom, the bar is reproduced with specific sensors data within a timeline.

The project architecture comprises the back-end where are executed two docker containers. The first one contains the RESTful API, which provides endpoints to the building models and the corresponding sensors. There is also an anomaly endpoint that returns calculation for sensor-specific overshoots or undershoots as well as high slopes of measured values. The second docker container is used to serve the front-end providing static files via https.

The web application front-end is visualised in Figure 31, and it uses a progress framework for adaptable user interfaces called Vue.js, whereby babylon.js was used for the visualisation and navigation within the 3D model. It is a JavaScript framework for displaying 3D models in a web browser via HTML5 and WebGL, and it supports the load of the .glTF format which it has been used for the building model visualised. In order to display the measured values of the sensors, a bottom bar timeline was implemented with the library D3.js (Metr, 2020b).

The Vi-Sense research project demonstrates the functionalities and the possible framework technologies for the integration of a 3D model viewer in a web application such as Manini Connect.

Figure 31 – Vi-Sense front-end layout and components

Source: Metr, 2020

6. ANALYSIS

This chapter includes an analysis of the Manini Connect platform with a focus on the digital twin UI principles. It also details a proposed framework for implementation of these principles within the front-end UI of the Manini Connect application.

As part of the analysis, relevant details of the Manini Connect platform and digital twin UI principles from previous chapter will be summarised, followed by the details of the proposed concept for the new Manini Connect UI and a possible implementation framework.

In previous chapters, the opportunities which derive from the new technologies with the concept of *smart* building and Digital Twin were investigated. During the research, the analysis of the Project Dasher 360 powered by the Autodesk Forge platform, gave an example of a possible design layout for the Manini Connect UI. It also identified the fundamental role of the 3D viewer associated with pins element.

Project Dasher 360 condensed all the IoT information within the 3D model space by overlaying an information layer, populated of pins element, above the model representation. The pins are simple screen icon's dots, located within the 3D model in correspondence of the sensor's devices location, and they create a direct reference with their real-world hardware device localisation.

The Vi-Sense research, which was described in The Vi-Sense project chapter, also recognises the sensors' device location in the 3D world by the use of pin elements. Both the solutions used a 3D model to create a clear and easy correlation between the sensors' devices location within the building, and their measured output data value. The Manini Connect platform shall follow the described examples by introducing a 3D viewer and finding a solution which can easily reference the sensors' devices into it.

Figure 32 shows the concept scheme of the proposed front-end UI, which combines aspects of the current Manini Connect platform with a new 3D viewer. Three sections characterise the new UI screen layout: a main 3D model viewer, a sidebar on the right with the real-time data values, and at the bottom a dataset chart viewer.

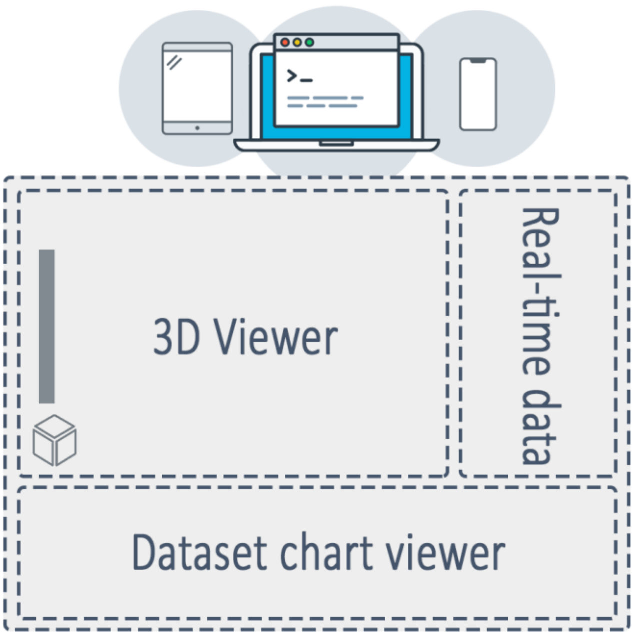

Figure 32 – Front-end UI layout

Source: from the author

6.1. 3D building model viewer

In this subsection, the implementation of a 3D viewer within the platform shall be explained. As indicated in Figure 32, the viewer represents the base-ground of the Manini application upgrade, and it could be implemented in the actual Manini Connect code, by the use of the Autodesk Forge API tools. However, as explored in the subsection Web tools for BIM visualisation, this would be associated with cost in the form of an Autodesk cloud platform subscription. For this reason, the Autodesk Forge API tools solution does not align with the Manini Connect commercial strategy at present due to the incremented services cost to their clients.

Referring to the previous chapter considerations, the xBIM toolkit is an open-source alternative; however, before to visualise the model in the viewer, it operates a file conversion from the IFC format, into a custom binary data format, which could create future interoperability problems. After considering these various options, the research focused on two open-source JavaScript libraries, Babylon.js and Three.js, which could be used to implement a model viewer.

The Vi-Sense application used the Babylon.js library to implement its model viewer, while the Three.js library is the base framework currently used inside the Autodesk Forge platform.

Both the JavaScript libraries recommend and support the use of the .glTF format for displaying 3D models on the web application because it can guarantee optimal visualisation performance. On the other hand, the BIM format for excellence, the IFC format, is not the preferred in web applications environments, due to its high calculation performance requirement. In fact, all the web viewers who support the .ifc format, during the upload action, make a conversion of it.

After these considerations, a .glTF model viewer was chosen for the Manini Connect platform, according to also with Umbra Control which will guarantee optimal visualisation and low calculation requirements. The .glTF model viewer also requires a file conversion as in the similar case of the xBIM toolkit, but it has the added benefit of a vast eco-system that will guarantee future support.

Different plug-ins and web services are available online to easily convert the .ifc file in a .glTF format, and a format file comparison has been conducted to verify which metadata are preserved during the conversion. The structure of the .glTF format is simpler than the .ifc format to guarantee optimal web performance. Because of this it cannot capture all the metadata structure and relationship contained in a complete .ifc file. The Manini Connect viewer requires only specific information such as the model geometries and the elements' ID to identify the sensors, which are all contained in the converted .glTF file. In case of necessity, the .glTF specification allows attaching metadata to the objects using *extras* property. Table 5 presents a comparison between the two JavaScript libraries.

Table 5 – Comparison between Babylon.js and Three.js

Characteristics	Babylon.js	Three.js
Founder	Catuhe D. and Rousset D., 2013	Cabello R., 2010
Description	JavaScript library which uses WebGL API	JavaScript library which uses WebGL API
Purpose	Mainly game development	General web animation
Online playground	Available	Not available
Getting started	Sets the scene, renderer, camera, mesh and material	Sets the scene, renderer, camera, mesh and material
Supported format	.glTF, .obj, .stl	.glTF, .obj, .dae, .fbx

The proposed platform shall test for the model viewer, using both Babylon.js, and Three.js JavaScript libraries to detect possible compatibility issues with the other front-end components.
In general, the viewer will have a toolbar with buttons command on the side, that enables to control the visualisation setting and to questioning the model. In the bottom corner of the windows viewer, there will be a navigation cube that identifies the axis orientation.
In order to implement the viewer, the JavaScript code of both libraries, Babylon.js and Three.js, will require the creation of the scene, a virtual 3D space where the building model will be placed. Together with this, the definition and setting of a camera and a render will be required. The render is fundamental to enable the camera to show the mentioned scene. There are different cameras available that can be used and modified by their attributes such as field of view, the aspect ratio and the distance from the clipping plane. The rendering of the model inside the scene is enabled by using the WebGL API, which makes use of the screen device acceleration hardware.
The render will happen after a caller in the code, which will create a loop, that allows rendering times per second. During initial tests has been tested the functioning of open-source viewers already set by the community in both JavaScript libraries.

6.1.1. Pins element characteristics

Considering the viewer implementation for the Manini Connect application investigated in the previous subsection, the solution to identify in the 3D space, the devices' group locations, within the intelligent pillars and above the roof, by pins element shall be explored.
The pin elements will create a direct correspondence between the virtual device locations with the actual building's position. They will be represented as a separate UI layer inside the viewer by using HTML, CSS and JavaScript as part of the front-end and they will require to be localised in the 3D space, fixed to their correspondents' elements.
The localization of the pin element can be enabled by associating the coordinate position of its correspondent's element or by associating, as a child element, directly to the specific object, like a pillar. This is possible by using the unique ID information contained in every item in the model and which is maintained inside the converted .glTF file.
In both cases, after the pin's coordinates in the 3D space have been identified, they need to be converted in 2D normalised coordinates, which represent on the UI, the 2D screen projection. These normalised coordinates lie between -1 and 1, where the 0 represents the centre of the screen.
After 2D coordinates are defined, the pin element can be drawn on a 2D canvas in HTML which will have the screen size of the viewer and finally loaded back into the 3D space. The pin element will be load back into the 3D scene by using a sprite plane[1], so it will always face the camera.
The pins element could lower the opacity when they are behind the building model, which is possible by comparing an average data vector from the pin element with the normal camera vector. When the normal is pointed away, it can produce an effect such as the fade of the component. Moreover, the pin element could simulate an alert event modifying its colour, when are passed predefined thresholds level. Furthermore, it shall be added an event listener to the click-event by the use of essential 3D interaction with raycasting in the case of Three.js or by the integrated built-in in Babylon.js; in fact, when the mouse

[1] A sprite plane is a plane which always faces towards the camera. Source available at: https://threejs.org/docs/#api/en/objects/Sprite (Accessed: 17 July 2020).

clicks the pin element, it will react visualising a floating window panel, drawn on the HTML canvas and at the same time will send an input command to the UI sidebar, requesting to visualise the devices which belong to the selected group.

Figure 33 shows the 3D viewer, which envision the building model and the pins element associated with the current IoT devices group such as the *intelligent* pillar or the roof station. The viewer will occupy the largest part of the UI screen, prioritising for the client the visual information compared the analytical. The right-side bar will show the devices real-time data by reusing the JavaScript component jQuery Knob[1], which is already part of the current platform code.

The sensors' group hosted in the singular *intelligent* pillars is selected by a click-event of its pin element in the viewer area, and consequently in the right sidebar part will be shown the selected devices' group and their real-time data measured. The bottom bar instead will visualise a chart showing the dataset history of a specifically chosen sensor by the user, and it will use the JavaScript library Highcharts.js, which was as well part of the current Manini platform. It shall be followed by a conservative approach, where the majority of the elements part of the actual Manini Connect platform are maintained, and only the frontal 3D model viewer will represent the significant change.

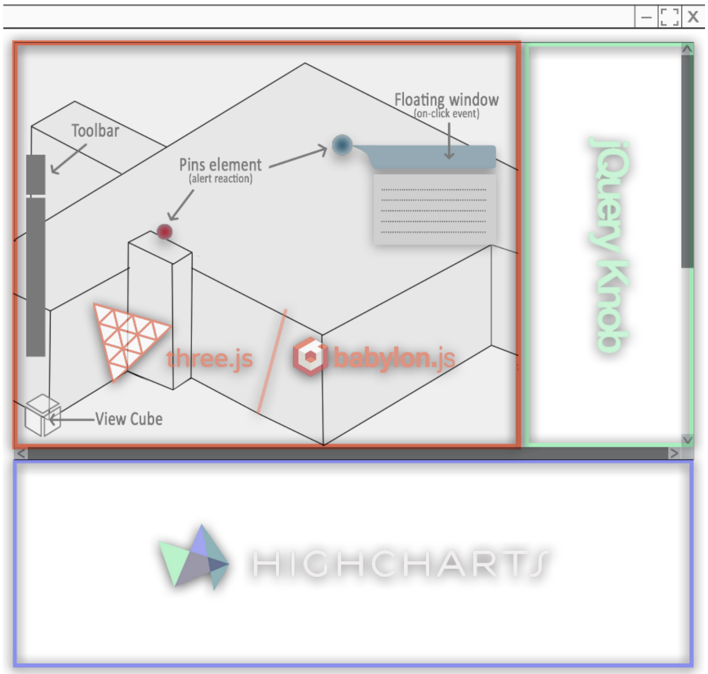

Figure 33 – Front-end layout and components

Source: from the author

The back-end architecture will require necessarily to be updated in order to enable the new functioning of the front-end UI logic and structure. In particular, new data structures will be created on the Business Logic layer and indeed of the Data Access layer to host the model viewer information. Only the Data Receiver layer will remain as the current one because the already set Clients will stay as they are now. The back-end BMS as well will not require modification for the currently proposed improvements.

[1] Available at: http://anthonyterrien.com/knob/ (Accessed: 7 June 2020).

In future, to support the growth of the platform infrastructure, derived from the higher building number being monitored, it will be necessary to shift from the current physical servers to a cloud platform.
Figure 34 shows the Manini Connect To-Be UI concept and its different components described before. The main window is characterised by the 3D viewer, where the model will appear in a simplified version, compared to the original BIM model, because its visualisation will be filtered, removing irrelevant information. The model geometry will be presented by a limited number of mesh colours palette related to the materials, and it will be adopted a light colour style, which facilitates a quick orientation and simplifies the localization of the overlayed pin elements.
The 3D model will be fully navigable in the space, and the possibility of including a clipping plane tool will be studied, to make it easier to access the visualisation of the internal devices' location. It could be implemented as a plan selector. Still, it this case it will be required a pre-set of the model before the file conversion from IFC or a plan decomposition in different files.
The pin element will react to the mouse click-event by showing the sensors' group identification name and a brief list of the devices. On the sidebar will be visualised the specific devices group selected in the viewer, like from an *intelligent* pillar and by intuitive icons and number values which will indicate the real-time updated information.
The bottom part will visualise a complete insight of a single device, or a group of them, after being selected in the sidebar. The visualisation is by a graph which will show a unique or various dataset combined across a timeline.

Figure 34 – To-Be application UI

Source: from the author, building picture adapted from Behance Student Show[1]

[1] Source available at: http://www.studentshow.com/gallery/90069803/Quick-Look-of-3D-MEP-BIM-Model-of-Biscuit-Factory-USA (Accessed: 25 August 2020).

7. CONCLUSIONS

Climate change is influencing our behaviours and responsibilities toward the planet, and it is demonstrated by the environmental impact caused by the buildings and the construction sector in general.

Through international agreements, countries have been set ambitious targets to reduce the carbon emission and limit resources’ consumption. Digitalisation and technological innovations have become essential instruments to achieve these sustainability goals, providing solutions to address new asset behaviours.

Every building, from the Burj Khalifa to a single house in the suburbs of England, requires maintenance and operations to preserve functionality and mitigate unnecessary costs. In this sense, the Facility Management subject rapidly started to become a fundamental factor along with the buildings’ operational phase due to its transversal role and a multiplicity of responsibilities, enabling cost-cutting and efficiency maintenance.

The adoption of the BIM methodology and technologies and its ability to model objects’ database in 3D, could revolutionise many of the maintenance processes, observed in the Facility Management field. In fact, digital technologies, which may transform documents, information, manual transactions into bits and automatic flows, are the most important among the efficiency factors for the professionals. It is interesting to examine what happened in other industrial sectors such as aeronautical engineering, to realise that the digital revolution is essential also for the future of the AEC/FM sector.

BIM can make the typical business processes of Facility Management more efficient, flexible, reactive and, in perspective, cheaper through the growing integration of technical and management activities. The use of digital technologies has always characterised the FM sector. In fact, BIM technology can be considered as a young innovation compared to the Building Management Systems (BMS), which were born to support the FM activities almost fifty years ago. The first BMS implementation was able to monitor the data produced by separate subsystems, with their own specific system infrastructure. But it is from the connectivity between them, that the BMS showed its potentiality, driven by the energy efficiency purposes, becoming *deus ex machina*. The building technological systems have been evolving, and the BMS system continues to be improved in order to control and manage all the different aspect with a new holistic approach. In fact, the scope of the BMS today is not only focused on an energy cost reduction but also provides a pervasive environment for the user.

Nowadays human wellbeing is becoming a priority for the Facility Management roles, and the democratisation of new technologies such as IoT devices are enabling the exploration of innovative user-centric experience within the building. The traditional BMS paradigms and structure architecture are being forced to follow new behaviours, requiring the use of cloud computing and new communication protocols, able to standardise and ease the setting of these new IoT devices.

A smart building will have the ability to connect the multitude of IoT devices together and ensure proficient data insights, driven by new needs of energy efficiency, smart working and user wellbeing.

The vast amount of data conveyed will require abilities of machine learning data digestion and AI, which could generate building scenario simulations or predict future machine failure. The NASA corporation due to the necessity to do operational maintenance works/services from millions of kilometres of distance was the first to experiment the creation of a Digital Twin to verify the correct functioning and predict maintenance work.

Building management systems have bought the technology into Facility Management sector, and today the IoT devices will make it smart.

The Manini Connect case study showed how the paradigm and principles of the Industry 4.0 could be applied not only to the industrial machinery but also expanded to the shell which contains them, a prefabricated building. Manini Prefabbricati, aware of the BMS principles and the potential technology of applying IoT sensors to the prefabricated building structure, proposed a service shaped for the new industries requirements. In fact, the company shifted from sixty years of traditions in design and manufacturer prefabrication, towards a services provider company able to use its patent technologies and experience know-how to perform a smart building monitoring.

The drive for innovation came from the IoT devices as a key factor in guaranteeing economic savings alongside the proactive intervention to anticipate potential events, likely structural damages. In this perspective, the application of machine learning algorithms manages to replicate the building structural' behaviour.

The development of the services platform highlighted the different interoperability issues faced and the lack of digital standardisation which pervade the AEC/FM sector. For that reason, it was required the support of a system integrator company, able to untangle the new BMS technologies.

The actual concept of the Manini Connect platform was developed by maintaining an open-source approach, bearing in mind the multiple technology opportunities now available such as BIM and AI algorithms, which could represent the natural evolution of the platform, equipped by modular expandability and future integration capabilities.

The research study has demonstrated a possible platform advancement by the integration of a 3D pervasive visualisation of the building, able to identify the devices' location within the facility easily.

It concludes that the lack of standardisation and interoperability has proofed the challenges to define a single trustable solution, because are continuously developed different solutions and settings and the technological evolutions is faster than the actual construction capabilities to absorb it.

The potential benefits of integrating BIM model visualisation within a BMS platform is only at primordial stages, the BIM shell enriched with sensor's datasets will enable the development of a support machine intelligence for the energy, safety, human wellbeing.

The Manini platform development will continue, exploring the new opportunities coming from data convergence and IoT connectivity capabilities and for future works, it is recommended to explore the convergence of data coming not only from the buildings' devices but also from the internal machinery, contained within the prefabricated buildings, which it will deploy a completely holistic approach interconnecting together humans, machinery and building behaviours.

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LIST OF ACRONYMS AND ABBREVIATIONS

AECO	Architecture, Engineering, Construction and Operations
AI	Artificial Intelligence
API	Application Programming Interface
BACnet	Building Automation and Control Networking Protocol
BIM	Building Information Modelling
CCTV	Closed Circuit Television Monitoring
CIM	City Information Model
CDE	Common Data Environment
CLI	Command Line Tools
CPS	Cyber-Physical System
DALI	Digital Addressable Lighting Interface
DTDL	Digital Twins Definition Language
GIS	Geographic Information System
ICT	Information and Communication Technologies
IFC	Industry Foundation Classes
IoT	Internet of Things
KPI	Key Performance Indicators
NLU	Natural-language Understanding
OPC UA	Open Platform Communication Unified Architecture
PaaS	Platform as a Service Solution
PBO-I	Plan-Build-Operate-Integrate
PLC	Programmable Logic Controller
RFID	Radio Frequency Identification
ROI	Return of Investment
STEP	Standard for the Exchange of Product model data
JSON	JavaScript Object Notation
NIST	The National Institute of Standards and Technology
XML	Extensible Markup Language
UI	User Interface
glTF	Graphics Library Transmission Format

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APPENDICES

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