www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

FROM BIM TO DIGITAL TWIN. IOT DATA INTEGRATION IN ASSET MANAGEMENT PLATFORM

SUBMITTED: May 2024
REVISED: November 2024
PUBLISHED: December 2024
GUEST EDITORS: Vito Getuli, Farzad Rahimian, Nashwan Dawood, Pietro Capone, Alessandro Bruttini
DOI: 10.36680/j.itcon.2024.049

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SUMMARY: *Real estate asset operations typically represent around 80% of investment and management costs, with space management and system monitoring being crucial for user well-being.The AECO industry is moving towards a data-driven model, combining various type of data from various sources. In addition, the inclusion of sensor systems in buildings is leading to a shift towards a distributed semantic approach, requiring a deeper understanding of reality and the ability to link different ontologies from various fields. So, the need to address challenges such as data interoperability, integration of different semantic domains, and improvement of information exchange processes has recognized semantic web technologies as a powerful tool for enhancing the value of BIM models by facilitating data integration and enabling the application of complex queries across multiple data sources.*

The proposed paper aims to analyze the state of art about IoT and semantic web technologies, and their possible integration in a BIM environment to aid decision-making in building maintenance. It will provide a first ongoing approach for the digitalization of the assets managed by the University of Florence's Building Area. The study shows the two different workflows set up to connect BIM models with sensor data.

The first one involved the use of DTH22 environmental sensors integrated through Node-Red to the open source platform Snap4City for data management; the second one involved the installation of LORAWAN sensors within a building and the use of a property platform, Niagara Tridium, for data manipulation and sampling to be convolved within a BMS platform. The work is part of a larger EU Next Generation research project titled, "BIM2DT. BIM-to-Digital Twin: information management to support decision-making in the building life cycle".

KEYWORDS: *BIM, digital twin, IoT, linked data, facility management.*

REFERENCE: *Carlo Biagini, Andrea Bongini, Luca Marzi (2024). From BIM to digital twin. IOT data integration in asset management platform. Journal of Information Technology in Construction (ITcon), Special issue: 'Managing the digital transformation of construction industry (CONVR 2023)', Vol. 29, pg. 1103-1127, DOI: 10.36680/j.itcon.2024.049*

1. INTRODUCTION

Governments, organizations, and others in the AECO sector have prioritized digitalizing the construction process for years (Daniotti et al., 2022). This sector, which has a historical lag in technology adoption compared to manufacturing, aims to harness the efficiency, competitiveness, and sustainability benefits that IT-driven process innovation can bring. Specifically, the introduction of regulations at the national and international level regarding the information management in construction processes, such as Building Information Modeling (BIM) tools and methods in public contracts, have required reorganizing data and information exchange during real estate asset delivery and operation (Mêda et al., 2021). Notably, 80% of a building's life cycle costs are in the operation phase (Volk et al., 2014), where data-driven strategies in managing complex assets are crucial for user well-being, safety, and health. Thus, implementing BIM in Facility Management significantly contributes to the goals of the European Green Deal and Sustainable Development Agenda 2030 (Ciribini et al., 2016; Mirarchi et al., 2018).

Presently, smart buildings must perform various functions using task-specific programs, often without context interaction. Information management in building operations typically involves separate tools like Computerized Maintenance Management System (CMMS), Computer-Aided Facility Management (CAFM), Building Automation System (BAS), and Integrated Workplace Management System (IWMS). However, an integrated system to manage data dispersed across different databases is lacking. As data-driven applications now need numerous components from diverse domains, such as ML training models, energy demand forecasting, and optimization problem-solving, a data integration process is crucial. This is because the data is heterogeneous and comes from different sources.

BIM can serve as a comprehensive information source for building and surrounding data (Qiuchen Lu et al., 2019), preventing the loss of data from design to operations phases, typically seen in spreadsheet-based 3D information. This information loss can be minimized by standardized practices and open data exchange formats (Patacas et al., 2015) like IDM (Information Delivery Manual), MVD (Model View Definition), IDS (Information Delivery Specification), ISO 19650 and ICDD (Information Container for Linked Document Delivery). These standards play a crucial role in this new approach by defining processes and checking information needs. Furthermore the widespread adoption of the Internet of Things (IoT) devices has enabled real-time data and information access about building operating conditions and surroundings, aiding facility managers in enhancing building performance management, lowering energy use, optimizing routine and non-routine maintenance, and boosting user satisfaction and well-being. In this context, the integration of structured data from Building Management Systems (BMS), time-series databases, weather services, and unstructured data such as BIM models, technical drawings, P&IDs (Process and Instrumentation Diagrams), spreadsheets, and maintenance manuals, enables the creation of a comprehensive digital representation of building's components and their relationships. This "Digital Twin" (Boje et al., 2020) facilitates the management of existing assets and enables a two-way exchange of information between the physical and digital worlds. However, the implementation of an integrated process for utilizing all these data types is not straightforward, and the development of customized applications or monolithic solutions is limited in terms of scalability, reusability, and modularity. This can lead to difficulties in integrating with other services due to the lack of a well-designed architecture and well-defined APIs, which are crucial for a smart building.

The need to address challenges such as data interoperability, integration of different semantic domains, and enhanced information exchange processes has fueled significant research interest in semantic web and linked data technologies within the construction sector. Although initially viewed as just one of several potential solutions for improving information exchange, the semantic web has since been recognized as a powerful tool for enhancing the value of BIM models by facilitating data integration and enabling the application of complex queries across multiple data sources. Additionally, the integration of sensor systems in building environments has led to a shift from a model-centric approach to a distributed semantic one, which requires a deeper understanding of reality and the ability to connect different ontologies produced by various disciplines while maintaining their unique perspectives (Rezgui et al., 2011).

The adoption of semantic web technologies such as Resource Description Framework (RDF), RDF Schema (RDFS), and Web Ontology Language (OWL) can facilitate the achievement of Building Information Modeling (BIM) maturity level 3, as defined by the Brew-Richards triangle, and enable high levels of interoperability. These technologies allow for the definition of ontologies/vocabularies (T-Box) and the semantic connection of data individuals (A-Box) based on RDF constructs. To further advance the integration of BIM and Linked Data, BuildingSMART has developed the ifcOWL standard, an ontology of the IFC schema based on OWL, which aims to mirror the original EXPRESS schema. However, due to its complexity and inflexibility, ifcOWL may not be suitable for real-world use cases that involve interfacing with topics not covered by the schema, such as existing buildings, GIS, facility management, or circular economy. In response, the World Wide Web Consortium (W3C) is promoting the adoption of simpler and more modular ontologies that can be adapted to specific use cases, as opposed to traditional monolithic ontologies.

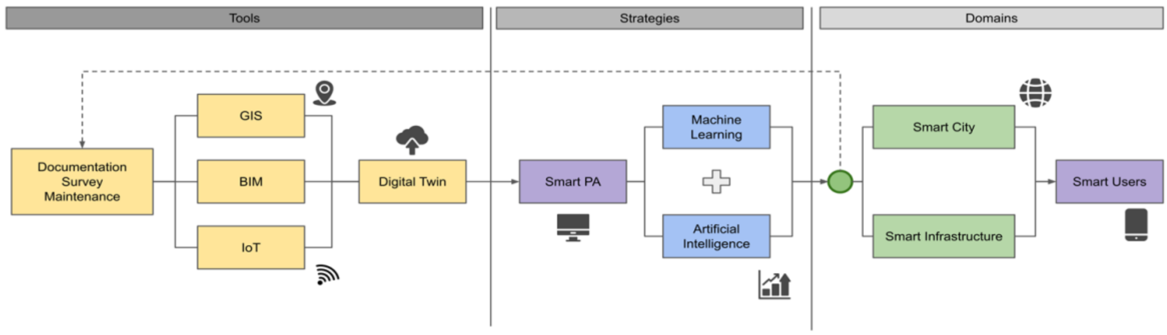

Figure 1: Conceptual outline of the BIM2DT research project.

This contribution represents a first outcome of a wider research activity within the PNR Project, "BIM2DT. BIM-to-Digital Twin: information management to support decision-making processes in the life cycle of buildings", which intends to define an operational framework for the collection and management of data aimed at the implementation of DTs of existing real estate assets, created on the basis of the integration between BIM platforms, existing databases and IoT technology oriented to subsequent developments of big data analytics and AI applications (Figure 1). The objective is to support the decisions of the various operators involved in the planning of scheduled and/or corrective maintenance actions in the operational phase of buildings, and to generate content, recommendations, and best practices by formulating predictive analyses on managed assets throught the use of semantic web technologies.

Chapter 2 will delve into the current state of the art regarding the semantic web, IoT devices, BIM methodology, and integration among these domains. It will critically analyze various approaches to defining an IT architecture that supports an IoT reference model, with a focus on protocols similar to those used in the current Internet infrastructure. In contrast, Chapter 3 will present an ongoing application of this technology in the real estate assets of the University of Florence's Building Area, which are being digitally implemented on a BIM platform.

2. TECHNOLOGIES FOR THE MANAGEMENT OF BUILT ASSETS

Buildings are complex systems that generate large amounts of diverse data related to the environment, comfort, security, and other factors. This data was traditionally collected and stored locally by Building Management Systems (BMS). However, data is now increasingly being moved to cloud environments with the integration of more Internet of Things (IoT) solutions. The Building Information Modeling (BIM) methodology has also led to major changes in the architecture, engineering, and construction (AEC) sector by shifting the paradigm for how model semantics and information are defined and managed beyond just geometry. Efforts now focus on the entire building lifecycle and how information can be shared and accessed. As a result, the industry is promoting more web-based and data-driven solutions, helping develop robust semantic structures and well-organized connection maps. The need to combine and link information from different sources has thus driven significant research interest in semantic web and linked data technologies. While this research began in the early 2000s, semantic web was initially seen as just one of several options for improving information exchange in construction. It was later realized how these technologies could enhance the value of BIM models by enabling integrated data access and complex queries across sources. Additionally, as sensor systems have been applied in building environments, research has looked at how to incorporate this new real-time information for building management.

One of the major ongoing issues is the lack of compatibility and reliance on proprietary systems that restrict us to platforms that sometimes can't scale or allow development across multiple systems. There is a need to use core project data within integrated systems and technologies that work together to avoid common problems from manually updating data or redundancy in favor of traceability and reliability. The information connected to BIM elements also usually can't be used outside modeling environments, and only a few applications have started integrating data from different sensor types. With growing demand for smart buildings, applications are needed that can handle different data transmitted in various formats, protocols, and languages. Achieving an integrated workflow across an asset's lifecycle phases requires data interoperability in the AEC industry to be extremely important. Moving from model-focused to distributed semantic approaches implies deeper understanding of reality rather than how to compress it within a single model. This inevitably leads to different ontologies depending on the discipline of those producing them, so the challenge is connecting them effectively while maintaining different viewpoints.

The starting point, however, must be an understanding of the infrastructure and the technologies available for the AECOO sector and how these can be used to improve and implement the semantic content of information models produced using BIM methodology. These chapter try to explain some of the basic knowledge behind these technologies and how they can be interconnected.

2.1. Semantic web and Linked Data

The term "semantic web" was coined in 2001 by Tim Berners-Lee (Berners-Lee, 2001) to describe an extension of the World Wide Web where data is given meaning through semantics to allow computers to understand it, using a technology stack similar to today's. The term 'Linked Data' (Berners-Lee, 2006), on the other hand, was later coined by Berners-Lee himself in response to his consideration that the data that were published online ostensibly following the idea of the semantic web in reality lacked links to external references, thus failing to realise the initial idea behind the semantic web, i.e. the interconnection between resources. Berners-Lee then proposed four rules for publishing and using Linked Data on the web, which were later expanded in 2010 with a five-star rating system for publishing Linked Open Data (Janowicz et al., 2014). In 2016, FAIR (findable, accessible, interoperable and reusable) principles were defined as technology-neutral and domain-independent guidelines for data management (Poveda-Villalón, 2020). Following these recommendations makes it possible to develop vocabularies and ontologies that are easily accessible, comprehensible and reusable by researchers who often face issues like poor documentation, URI and versioning problems, and other difficulties that make data hard to use (Garijo & Poveda-Villalón, 2020).

The vision of the Semantic Web is to present the web no longer as documents on HTML pages designed to be read by humans but rather as an environment in which information is given well-defined meaning, better enabling computers and people to work in cooperation. It provides a collection of machine-readable structured data and sets of inference rules that can be used to perform automated reasoning processes, deriving new information from existing information. Just as the World Wide Web relies on the HTTP and HTML protocols to present documents, the Semantic Web uses RDF and RDFS to present data. It consists of a layered architecture based on several components: UNICODE and URI, XML, RDF, RDFS, OWL, Logic, Proof and Trust (Figure 2).

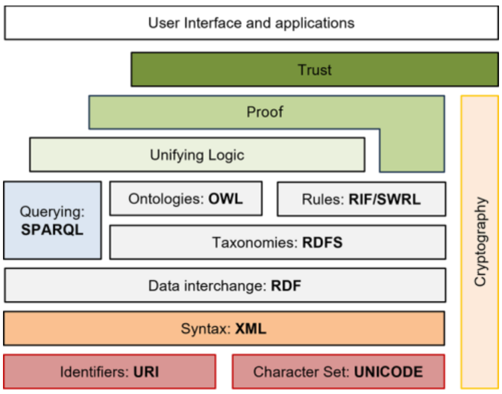

Figure 2: Semantic web Layout architecture.

The semantic web is based on the RDF language (Hayes & Patel-Schneider, 2014), which became a W3C recommendation in 1999 (Figure 3). RDF allows information, properties, and relations to be represented as a graph (direct labelled graph) where each node represents a real-world object with a unique identifier (URI or IRI). Graphs can be serialized in different formats like RDF/XML, N-Triples, Turtle, and N3; furthermore, the definition of a voocabulary or ontology is required to associate a shared meaning with such a graph. An ontology is formally defined as an »*explicit specification of a conceptualization*« (Gruber, 1993). It specifies concepts and relationships in a domain that is understood by people and applications in that domain. Borst (Borst, 1997) defined ontology as a »*formal specification of a shared conceptualization*«, meaning it is machine-readable and shared by multiple parties rather than individual. Studer et al. (Studer et al., 1998) later combined these definitions as »*a formal and explicit specification of a shared conceptualization*«. More specifically computational ontologies formally model the structure of a system, including relevant entities and relationships useful for a purpose (Guarino et al., 2009). The basic elements for the description of an ontology can be found in RDF Schema (Brickley & Guha, 2014), which allows the specification of classes, sub-classes, comments and datatypeswhile the OWL language (W3C OWL Working Group, 2012) further extends the expressiveness of such concepts by allowing the introduction of restrictions on cardinality, types of constraints and expressions of complex classes. These standards provide the foundation for applying rules and verifications needed for applications. Graphs defined using OWL concepts are called OWL ontologies.

In particular OWL (Ontology Web Language) is an ontology language for the Semantic Web with formally defined meaning. The first OWL specification by W3C was released in 2004, but it was replaced by OWL2 in 2012. OWL2 Description Logic is based on SROIQ (Horrocks et al., 2005), so the ontology structure must be compliant with some conditions to be traslated in SROIQ. Ontologies that respect these limits are defined as OWL2 DL. Within this definition we can identify three profiles: OWL2 EL, OWL2 QL e OWL2 RL. These profiles are subsets of OWL2 DL that give up expressiveness in exchange for greater computational performance. A language expressed in DL (Description Logic) consists of two components called A-Box and T-box. T-Box instructions are the »terminological component« that outlines a domain's classes and properties as a domain vocabulary. A-Box statements are the »assertive component«, expressing individuals related to the conceptual model or ontologies of T-Box. Together, they form the Knowledge Base, the foundation for deriving unexpressed notions in the ontology through reasoning methods. Following these principles OWL2 ontologies provide classes, properties, individuals, and data values which are stored as Semantic Web documents. OWL 2 ontologies can be used along with information written in RDF, and OWL 2 ontologies themselves are primarily exchanged as RDF documents. OWL has more structures to express meaning and semantics than XML, RDF and RDF-S, and so OWL goes beyond these languages in its ability to represent machine-readable content on the Web.

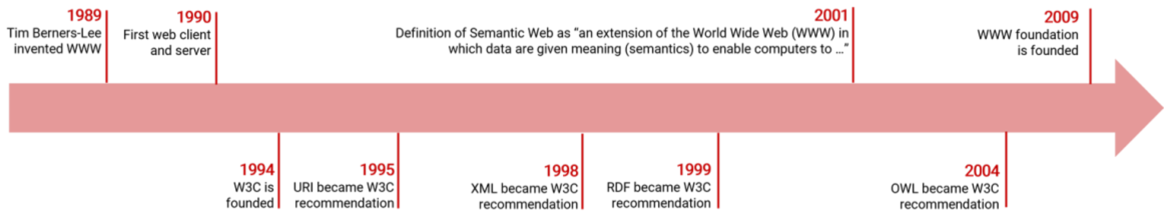

Figure 3: History line about W3C recommendation.

Another important concept is the issue of knowledge representation. Traditional techniques such as BIM methodology differ from semantic web technologies in two different approaches: CWA (Closed World Assumption) and OWA (Open World Assumption). According to the first CWA approach, any statement that is not known must be considered false. If applied to a BIM model or a traditional database we can say that if a piece of information is not specified it is most definitely not there. On the other hand, according to OWA, if a statement is not known then it cannot be considered either false or true, but must be considered unknown. It can only be defined in the future when more information is provided. Semantic web technologies are generally based on the latter concept as it is assumed that the web is like an incomplete information system, whose information is added over time, and therefore one cannot say that something is not true just because the information is not specified at that particular moment. Understanding the difference between these two types of information allows us to map information representations in CWA, coming from BIM models, to information representations in OWA. Thus, if adopted correctly, semantic web technologies are an addition to, and not a replacement for, existing technologies such as BIM.

2.2. Internet of Things Model

The term "Internet of Things" (IoT) was coined in 1999 by British engineer Kevin Ashton, co-founder of the Auto-ID Center at MIT (Ashton, 1999). In 2001, MIT's Auto-ID Center presented its vision for IoT, which the International Telecommunication Union (ITU) later built upon in its 2005 Internet Report. The ITU defined IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (ITU-T Y.4000/Y.2060, 2012). Meanwhile, the Internet Society described IoT technologies as "scenarios where network connectivity and computing capability extends to objects, sensors and everyday items not normally considered computers, allowing these devices to generate, exchange and consume data with minimal human intervention" (Rose et al., 2015). As there is still no single agreed upon definition, we can understand IoT involves new ways of digitally managing building resources using connected devices and their associated tools and methods of data analysis. When we speak of the Internet of Things, we are referring to any type of smart object that has the ability to connect to the Internet through either wired or wireless connections. This dual communication capability allows objects to communicate with both other machines and humans. To be considered a smart object, a device must have several key characteristics: the sensing component, i.e., the ability to gather information from the real world or to perform an action following an input, a unique identifier to identify the source from which the data is received, a connection to the Internet, for communication and notification of the information, and finally, one or more software platforms for the analysis and processing of the data collected.

In its simplest terms, the Internet of Things can be thought of as the intersection between Internet infrastructure, connected objects, and the data they generate and share. However, more complex definitions also account for the standards and processes that enable objects to connect to the network and exchange information according to industry protocols. These standards guarantee interoperability and support automated processes between devices. As a result of this new technology, we now must manage information flows not just between individuals but also between individual machines and devices. The IoT opens up many potential applications across various sectors such as smart homes, cities, healthcare, retail, and transportation. The main question is how to enable interaction between different systems and tools to provide simple, immediate service for end users both professionally and personally. Standards were created to address this issue by facilitating communication within specific application areas of IoT. For example, there may be a need for efficient communication with minimal packet loss but low enough latency for near real-time interaction. Alternatively, a less reliable protocol could be preferred that works with low-power, low-performance hardware. Each protocol offers certain functionality or functionality combinations making it more suitable than others in different situations. Key factors that influence the choice of protocol include location, power usage, physical barriers, and hardware expenses.

The classical communication protocols were not suitable for IoT devices due to their strict hardware and power requirements. This necessitated developing new technologies without complex computations for simple devices. A core goal of an IoT architecture is connecting the physical world to the digital one and over the years, many organizations and developers created new communication mechanisms, giving us a wide variety of protocols today. However, these protocols were not designed to interact as they are based on different concepts. Therefore, international bodies aimed to prevent fragmented commercial solutions by defining open standards and mapping the traditional IP network model to the new concept of an IoT network comprising heterogeneous interconnected devices. The reference model proposed by Cisco, IBM, and Intel divides the IoT architecture into seven levels (Figure 4). This reference model follows the subdivision already used for the Internet, namely the OSI (Open Systems Interconnection) model, which consists of seven layers grouped into three media layers (physical layer, link layer and network layer) and four host layers (transport layer, session layer, presentation layer and application layer). The first level consists of physical devices and controllers that send and receive information. Second level involves connectivity and communication both within and between different networks, using gateways for older non-IP devices. Third level is edge/fog computing, which processes data close to the source with minimal latency. Fourth level handles data collection and storage, converting information from dynamic to static. Fifth level aggregates and simplifies access to data from multiple devices by creating schemas and views. Sixth level provides outputs through applications that interpret available data. The final level involves people and business processes to make applications useful by facilitating collaboration. Technologies such as Bluetooth and Wi-Fi use the lower communication layers while DDS or MQTT use, for instance, the application layer.

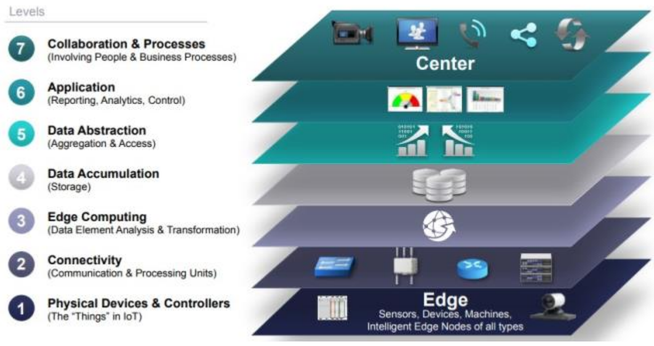

Figure 4: IoT Reference Model presented at IoT World Forum by Cisco, IBM and Intel.

2.2.1. IoT Devices

The foundation of an IoT network consists of devices with varying capabilities, as categorized by the International Telecommunication Union (ITU) based on their computational and connectivity features. These devices can be grouped into three classes (Bormann et al., 2014): 1) class 0: devices with minimal memory and processing capabilities that cannot securely communicate directly with the internet. These devices rely on other devices, such as proxies, gateways, or servers, to facilitate communication; 2) class 1: devices with limited capabilities that can communicate with other nodes on the internet but cannot use full-stack protocols like HTTP, TLS, and related security protocols. They can, however, use specific protocols like COAP and participate in conversations without relying on gateways; 3) class 2: less limited devices capable of supporting the same protocol stack as servers or notebooks. These devices can benefit from using lighter and more energy-efficient protocols, and examples include Arduino and Raspberry microprocessors.

The classification of IoT devices into three categories based on their capabilities highlights that not all devices can connect to the internet or process data on their own. To facilitate data transfer and reduce computational load, gateways are used. These gateways are not limited to connecting devices but also process data in situ. The data collected by IoT devices is transmitted to a gateway, processed, and then sent to the cloud. The use of gateways reduces latency and transmission size while providing an additional layer of security for data in transit. When data is processed locally by the device that collects it, it is called edge computing. When it is sent to a gateway for processing, it is called fog computing. Finally, when it is sent and processed within a cloud-based repository, it is called cloud computing. IoT applications can then be integrated with a data analytics engine for analysis and customized output

2.2.2. Protocols and connectivity

The realization of the Internet of Things (IoT) concept has been made possible by the development of various communication protocols, including Wireless Sensor Networks (WSN), used in particular for sensing operations (environmental sensors), Radio Frequency Identification (RFID), a system based on the use of radio-frequency waves, consisting of tags, readers and a back-end system that allows each ID to be associated with the corresponding physical object and any information relating to it, and Near Field Communication (NFC), produced by Philips, Sony and Nokia, used to transfer data from one device to another over short distances. These protocols have enabled the transfer of data between devices over short and long distances, leading to the creation of new standards that can be grouped into two main categories: short-range and long-range. Short-range protocols, such as Bluetooth, NFC, Wi-Fi, Z-Wave, and ZigBee, are typically used in smaller environments like homes or offices and are defined as Personal Area Networks (PAN). These protocols are low-power and have a short range, making them suitable for applications where energy efficiency is important. Long-range protocols, on the other hand, allow for communications over longer distances, up to 500 meters, with minimal energy consumption. Examples of long-range protocols include Low Power Wide Area Networks (LPWAN), LoRaWAN, and SigFox, as well as cellular IoT technologies like NO-IoT, LTE-M, and EC-GSM-IoT proposed by 3GPP. Within a specific network, devices communicate according to a set of rules, or protocols, that operate on different layers of a reference model. These protocols determine how data is transmitted and received along Internet backbones, and the IoT can be understood as a network that operates in parallel to traditional protocols used for the web (Figure 5).

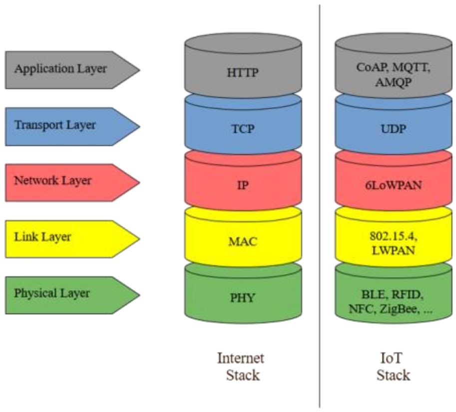

Figure 5: IoT and Internet architecture.

At the application level, there are several protocols that enable communication between devices and the web, including CoAP, MQTT, and AMQP. CoAP (Constrained Application Protocol) (Shelby et al., 2014) is designed for devices with limited capacity and uses a binary format for efficient communication, for whose integration it requires the use of an intermediary (proxy). MQTT (Message Queue Telemetry Transport) (Banks et al., 2019) is ideal for low-bandwidth connections and is used for small devices that require bandwidth efficiency and battery usage. AMQP (Advanced Message Queuing Protocol) (Godfrey et al., 2012), a specification for interoperable messaging for message-oriented middleware (MOM), provides interoperability between messaging middleware for a wide range of systems and applications, creating an asynchronous messaging system complementary to the http protocol.

At the transport layer, data transmission and communication between different layers are enabled and protected. Within this layer, we find two key protocols such as TCP and UDP. TCP (Transmission Control Protocol) (Eddy, 2022) is the dominant protocol for most Internet connectivity. It facilitates host-to-host communications by breaking down large data sets into smaller packets, resending and reassembling them as needed to ensure reliable communication. UDP (User Datagram Protocol), on the other hand, enables process-to-process communication and operates over IP. UDP improves data transfer rates compared to TCP and is ideal for applications that require lossless transmission of information.

The network layer enables communication between individual devices and routers. Within this layer, we find several protocols that facilitate device communication, including IP, 6LoWPAN and BACnet. IP (Internet Protocol) is a widely used protocol that has been updated to IPv6, which routes traffic over the internet and identifies and locates devices on the network. 6LoWPAN (IPv6 over Low Power Wireless Personal Area Networks) (Kushalnagar et al., 2007) is an IoT protocol conforming to the IEEE 802.15.4 specification that is optimized for low-power devices with limited processing capabilities. It allows for the creation of wireless networks with devices that use the IP protocol for communication, through an intermediate layer placed between the MAC and network layers. BACnet (Building Automation and Control Network) is a protocol developed by ASHRAE, and reported within ISO 16484-5, that is designed to manage building automation systems. It aims to create adaptable application protocols that can be transported across different physical network technologies.

The data layer (MAC) is responsible for transferring data within the system architecture and correcting errors found in the physical layer. Within this layer, we find several protocols that enable wireless communication, including IEEE 802.15.4 and LPWAN. IEEE 802.15.4 is an IEEE standard based on radio waves for low-power wireless connections. This standard is used in conjunction with other protocols like Zigbee and 6LoWPAN to create embedded wireless networks. LPWAN (Low Power Wide Area Networks) are designed to provide communication over long distances (up to 10 km) while minimizing power consumption. These networks are ideal for applications that require wide coverage but not high bit-rates. One example of an LPWAN network is LoRaWAN, developed by the LoRa Alliance, which is optimized for low power consumption.

The physical layer of a device ecosystem refers to the communication channel among devices in a specific environment. This layer includes various protocols and technologies that enable wireless and wired communication. Bluetooth, developed by Ericsson in 1994 and standardized by IEEE 802.15.1, is a wireless technology that enables high-speed data transfer over short distances (up to 10 m). Bluetooth Low Energy (BLE) is a newer implementation that reduces power consumption and cost while maintaining connectivity range. Ethernet is a wired connection that provides fast data transfer with low latency. LTE (Long-Term Evolution) is a wireless broadband communication standard for mobile devices and data terminals, which increases capacity and speed of wireless networks and supports multicast and broadcast streams. NFC (Near Field Communication) is a set of communication protocols that enables two devices to communicate at a maximum distance of 4 cm, typically used for contactless payments, ticket creation, and smart cards. PLC (Power Line Communication) is a technology that allows data to be sent and received over existing power cables, allowing an IoT device to be powered and controlled over the same cable. RFID (Radio Frequency Identification) uses electromagnetic fields to track unpowered electronic tags, and compatible hardware provides power and communicates with the tags to read their information for identification and authentication. Wi-Fi, standardized by 802.11, is a widely used technology in homes and offices, but it may not be suitable for all scenarios due to its limited range and 24/7 power consumption. Z-Wave is mesh network that employs low-energy radio waves for appliance-to-appliance communication. As a proprietary technology, it is built on a unique architecture at all layers. Zigbee is a specification developed by the ZigBee Alliance (now Connectivity Standards Alliance) based on the IEEE 802.15.4 standard for a collection of high-level communication protocols used to create personal local area networks with small, low-power digital radios. It is commonly used in the context of the smart home, where battery-powered devices are prevalent. The total uptime is limited, and most of the time, the device is in a power-saving state (sleep mode). Thread is a mesh connection protocol developed by Nest and other companies based on the 6LoWPAN protocol. Matter is an open standard for the Smart Home developed by the Connectivity Standard Alliance with the aim of improving the compatibility and security of IoT devices.

Table 1: Most common IoT protocols.

Protocol	Standard	Frequency	Distance
NFC	ISO/IEC 18092, ISO/IEC 21481, ISO/IEC 28361	13.56 MHz (universal frequency)	Max 10 cm (with other frequency you can obtain different distances)
Wi-Fi	802.11n (2009) – 802.11ac (2014)	2.4 GHz – 5GHz	50 m (indoor) – 100 m (outdoor)
BLE	Bluetooth v.5 (based on IEEE 802.15.1)	2.4 GHz	50 m
ZigBee	ZigBee 3.0 (based on IEEE 802.15.4)	2.4 GHz	10 – 100 m
Z-Wave	Z-Wave Alliance (proprietary technology)	800 – 900 MHz	10 m (indoor) – 100 m (outdoor)
6LoWPAN	Based on IEEE 802.15.4	Multiple physic support	20 m
LoRa	LoRaWAN (ITU-T Y.4480)	ISM 868/(915) MHz	10 km

2.3. Evolution of IFC standard

The rapid growth of digital technologies for acquiring data in the construction industry, for diverse uses and purposes within buildings and urban environments, has required an extension of traditional semantic domains. This is especially relevant to BIM-based information management processes, where BIM was originally designed to share information between various data silos, but now it's being considered in conjunction with big data, IoT, and AI for automation and broader environmental consideration (He et al., 2021; Tomalini, 2022). The progression of interoperability solutions, such as ISO STEP, IFC, and IFCOWL, is transitioning static BIM into a dynamic, web-based format.

BIM enables the semantic representation of all building-related information in a 3D model, allowing for better sharing compared to traditional methods. In addition, the IFC standard offers a data schema and a format for this information, facilitating interaction between various software applications. The IFC data model is defined in the EXPRESS language, defined by ISO 10303-11 standard, which includes terms and rules for constructing specific schemas and there are multiple versions of the schema, each providing a clear meaning and purpose for the objects they represent. buildingSMART also promotes other standardization efforts, such as MVD (Model View Definitions), which are subsets of the full IFC schema, IDM (Information Delivery Manual), IDS (Information Delivery Specification) and ICDD (Information Container for Linked Document Delivery). Additionally, PSD (Property Set Definition) should provide customized property definition schemes not tied to the IFC schema.

In this context, it is possible to observe how the IFC schema has limitations especially in terms of: *interoperability*, the IFC format is mainly used for information exchange but the compatibility of these files with the schema depends both on the import/export software and on the user's experience, thus sometimes resulting in semantic errors or incorrect geometric transformations; *adaptability*, encompassing different domains and software houses the development of the schema is very slow as it has to reach consensus among all the participants; *estensibility*, the same applies to the addition of new concepts, it is still possible to add proxy elements and custom psets but adding little at the semantic level as it would not be possible to make automatic queries on them (Pauwels et al. , 2017). To address these issues, an answer was sought in semantic web technologies by trying to equate the structure of an IFC file with the semantic structure of an RDF graph. The purpose of the EXPRESS language is in fact similar to that of OWL, the main differences lie in the domain to be represented and the technologies/languages used to represent that domain. IFC is limited to the construction sector while RDF is used for the representation of data on the web. The combination of the two standards makes it possible to publish IFC data as an RDF graph and leads to a cloud of Linked Open Data (LOD) that gathers a considerable number of interconnected datasets.

buildingSMART and W3C conducted a parallel effort to translate the original EXPRESS schema into an ontological structure (T-Box) that would respect the constraints imposed by the OWL2 DL language. Over the years, many initiatives have been proposed to formalise the IFC schema into an ontological language with the aim of providing a semantically rich and platform-independent software framework that could support the integration between the different tools used and the exchange of information in a knowledge-based system. Starting from more generic research such as the OntoSTEP project (Krima et al., 2009) for the conversion from EXPRESS to OWL, the definition of an ifcOWL ontology (Pauwels & Terkaj, 2016) was achieved, which was then published as a standard by buildingSMART within the ISO 16739-1 standard, thus making the data model available in EXPRESS, XSD and OWL and usable in IFC-STEP, XML and RDF formats. The main issue with ifcOWL is that its generation process does not take place from scratch but a faithful transposition of the EXPRESS schema into OWL language is maintained, considering that BIM models are produced in their own software environments and the most common process is to convert them into RDF graphs. These constraints led to the definition of a monolithic ontology, which is complex and not very usable in real use cases. In fact, we can observe subsequent research, such as SimpleBIM (Pauwels & Roxin, 2016) or IfcWoD (De Farias et al., 2015), in which its simplification is proposed, working on the optimisation of the semantic structure of the schema, with a main focus on the composition of the geometric component (Pauwels et al., 2017). Instead, the current line of research aims at producing ontologies that are simpler and more modular, as opposed to traditional monolithic ontologies, and that are adaptable to the specific use case. For this, applications have also been developed for the conversion of BIM models from IFC format into RDF graphs (A-Box) using modular ontologies such as BOT, for defining the topology of the building, PRODUCT, for the classification of building element, and PROPS, for building related properties (Bonduel et al., 2018).

The coexistence and linking of multiple ontologies thus makes it possible to represent the same element from several points of view and in the different phases of its life cycle. For example, in the field of Cultural Heritage, reference models have been developed to support the formal, shared and explicit representation of information concerning cultural heritage such as CIDOC Conceptual Reference Model (CIDOC CRM), now also recognised as an ISO standard (ISO 21127:2023), developed for the cataloguing of the documentation attached to a historical asset, and MONDIS (Cacciotti et al., 2013), which focuses on the documentation of damage in historical structures, their diagnosis and possible interventions. These have over the years become reference standards for the development of further frameworks for the analysis and interpretation of the historic built environment (Stasinopoulou et al., 2007; Alexiev et al., 2013; Pauwels et al., 2013, Acierno et al., 2017). Other researches, on the other hand, have proposed an ontology for the definition of a building's environmental data from the earliest stages of its life cycle, linking BIM methodology with semantic web technology (Djuedja et al. 2021), or the integration of hard data sources, such as BMS systems, and soft data sources, such as social networks, for the assessment of environmental comfort (Corry et al., 2014).

In parallel, the development of IoT technologies has taken the possibilities of managing a building to a further level of complexity. A smart building can no longer rely solely on the limited capabilities of traditional BMS systems, but requires numerous components that can handle the continuous flow of large amounts of heterogeneous data. As a result, an information model must be able to accommodate and store not only data-at-rest, produced in the survey and/or design phases, but also to manage data-in-motion, coming in real-time from devices for monitoring the environmental quality of architectural and urban spaces.The inclusion of IoT sensors within an asset should only be considered as a starting point for the implementation of a Digital Twin (Sacks et al, 2020), there is also the need for specific applications for operations such as training models for ML, forecasting energy demand, solving optimisation problems and performing predictive controls such as MPC (Model Predictive Control). These applications also need support services such as data cleaning, aggregation, extract-transform-load (ETL) tools to bring together and process data from different sources. Therefore, there is no single Digital Twin solution, as this may vary from time to time based on specific needs, just as its implementation is subject to evolve over time.

Thus, incorporating BIM methodology and its evolution into the Digital Twin concept can greatly benefit facilities management. This includes planning and cost estimation for asset management, predicting operational issues, enhancing maintenance activities, increasing information accessibility and security, reducing waste, and improving documentation (Singh et al., 2021). However, IoT devices have various communication protocols and semantic models for data exchange, but only partial integration with the IFC schema for buildings. For instance, certain research has concentrated on combining open protocols, like BACnet and the IFC schema, to develop specific MVDs for incorporating BAS data in BIM models during various building stages (Tang et al., 2020). However, even the use of IFC schema extensions for this integration is still an immature process and offers limited support (Wang et al., 2022). Furthermore, the IFC format is primarily intended for data transfer between tools, not for dynamic modification or transformation, so the introduction of Linked Data and semantic web technologies can lead to tackle these challenges.

Due to the IFC schema's limitations, some organizations have started to create alternative or supplementary data models based on RDF standard, making them compatible with Semantic Web standards and Linked Open Data. Many of these ontologies are based on the Basic Formal Ontology (BFO), which is a compact, top-level ontology developed to aid information search, analysis, and integration in scientific and other fields. It can be used as a foundation for organizing data and concepts in a structured manner (Arp et al., 2015). Then using the word 'building' as a filter in the Archivo platform, produced by the DBpedia Association, it is possible to search for some of the most widely used ontologies in the AECOO sector that can be used to relate BIM models to IoT devices. The Smart Applications REFerence ontology (SAREF) aims to promote interoperability between solutions from different providers and across various sectors in the Internet of Things (IoT). SAREF is a suite of individually versionned ontologies that contains a core ontology, a set of reference ontology patterns that provide guidelines on how to use and extend SAREF, and different extensions for vertical domains. The core ontology contains classes like *saref:Device*, *saref:Function*, *saref:Command* or *saref:Measurement*, which focus primarily on defining smart applications and give a basic model for IoT devices that can be extended to understand specific domains. The Semantic Sensor Network Ontology (SSN) is a framework developed by the Semantic Sensor Network Incubator Group (SSN-XG) at W3C (Compton et al., 2012). This ontology focuses on describing sensors and their properties to facilitate the organization, installation, management, understanding, search, and control of sensors and their data across various domains. The initial version of the ontology included four perspectives: sensor, observation/data, system, and feature. In October 2017, W3C and OGC released an updated version of SSN that also includes actuators, thereby differentiating SSN from SOSA (Sensor, Observation, Sampler, and Actuator). The latter includes concepts such as sosa:Sensor, sosa:Observation, sosa:ObservableProperty, sosa:FeatureOfInterest, sosa:Actuators, sosa:Actuation and others. SSN and SOSA offer diverse coverage and varying levels of axiomatization, enabling them to satisfy a broad spectrum of applications and use cases. These include satellite imagery, extensive scientific monitoring, industrial and residential infrastructures, social sensing, citizen science, observation-driven ontology engineering, and the integration of the Web of Things. Digital Construction Ontologies (DiCon) is composed of a collection of interconnected ontology modules that aim to capture various aspects of construction and renovation projects (Zheng et al., 2021). Since other data models and ontologies have already been established in these domains, the primary goal is to integrate with existing knowledge. A high-level ontology is used to categorize concepts in different modules, and a module is used to align terms with concepts in other ontologies. The ontology is modularized in two directions, following the approach established by the SSN ontology. On the vertical plane, each module provides specifications for the previous one based on the same domain, while on the horizontal plane, each new module expands the semantic domain by introducing complementary classes to the previous one and defining relationships between them. The Project Haystack is a widely-used system that employs tagging to characterize building components through the use of semi-structured sets of tags. It unifies semantic data models and web services, aiming to simplify the process of extracting useful information from the extensive data produced by smart devices in homes, buildings, industries, and cities. The Brick Schema (Balani et al., 2018), managed by the Brick Consortium, can be seen like an evolution of the Haystack Projcect ontology as represents the entities and relationships of buildings and their subsystems, describing different functional, structural and operational aspects. The classes of this ontology are the “things” inside a building and they range from equipment, points, locations and logical collections. From version 1.3, it also supports linking Brick models and sensor networks with communication protocols like BACnet, aiding in creating a digital twin. An IFC model can reference the Brick model through a unique identifier in the IfcLibraryReference instance, allowing an external platform to access data from both schemas. The Building Product Ontology (BPO) (Wgner et al., 2022) outlines a systematic approach to describe building products, excluding geometric and material details. It allows for the description of assembly structures and component linkages, and the ability to assign properties to any component, unrestricted by type, unlike typical template-based product descriptions. The Building Performance Ontology (BOP) aims to unify topological building data with static and dynamic properties, creating a consistent data environment for complex building assessments (Donkers et al., 2022). It helps building managers and software handle the large, varied data they encounter. Recognizing that static and dynamic property data are different but share a complex spatio-temporal context, BOP represents this complex context similarly for all data types. This enhances the use of linked data in complex calculations and improves machine-readability. The Smart Energy Aware Systems (SEAS) (Lefrançois, 2017) defines feature of interest, seen as an abstraction of a real world phenomena (thing, person, event, etc), and their properties, as an extension of the core classes of the SSN ontology. RealEstateCore (REC) is a collection of data schemas, developed as a modular ontology, that outlines the concepts and relationships found in data related to building and building systems. Property owners can utilize REC to describe, manage, store, and share data from their building interactions. This standardized language allows for easy connection between buildings and new services on a large scale, without the need to consider specific building or technology data formats. It was originally developed to be used with RDF-based graphs and SHACL queries, but it is also possible to use proprietary graph models available on the market such as Neo4j. Recently, a collaboration with the BRICK foundation has been launched to create an open source standard based on Semantic Web technologies. Both BRICK Schema and RealEstateCore will remain separate projects, managed by their respective consortiums, but the combination of the two ontologies can provide comprehensive coverage for various domains, including building management systems like HVAC and Access control, business administration systems such as CAFM and ERP, IoT devices including indoor climate and people counting, and blueprints like BIM and DWG. This is done with the compatibility with the new ASHRAE 223 standards in mind.

This research shows that the direction of development is not to replace existing technologies, but rather to combine building information with other semantic domains. The integration of these technologies with the methodologies already in use will allow better interoperability between the different parties involved in a construction process, simplifying the sharing of specific knowledge and introducing a higher level of process automation.

3. A FRAMEWORK FOR APPLYING DIGITAL TWIN TO BUILT ASSETS

Existing BIM methodologies, whether for historical or new structures, typically create a 'digital model' from 2D documents or tridimensional data like a point cloud. The same elements that make up the building or the assets inside it are modeled with the same methodologies and populated with parameters for their description and management. However, this methodology isn’t able to fully capture the rich semantics of individual objects, often resulting in oversimplified or redundant information spread across various silos.

The adoption of a true Digital Twin requires the adoption of an integrated system that allows the management of all these different types of data. However the development of custom software architecture become difficult in a setting where every building is unique. This issue is further compounded by the lack of solid architecture and clear APIs, which are crucial for connecting to other services in a smart building. Instead, a reference architecture is usually recommended, which can be customized for various domains, balancing the characteristics of scalability, reusability and modularity. Unfortunately, there is limited literature on this subject, with much of it being too theoretical, outdated, or lacking vendor impartiality (Chamari et al., 2023). The state of the art generally encompasses three main categories for system architecture: monolithic, service-oriented, and microservices-based architectures. The monolithic approch is the traditional one for creating a program as a single independent unit. The service-oriented approach (SOA) breaks down each process into a modular unit called »service«, which communicates via an Enterprise Service BUS (ESB), providing a standardized messaging approach. Meanwhile, microservices-based architecture, an evolution of SOA, consists of numerous specialized services accessible through APIs. As the system expands, these services can be individually updated and developed without affecting others, as they operate within containerized environments managed through service orchestration and management platforms like Kubernetes. This setup allows for greater scalability, both vertically and horizontally, than previous systems.

As part of the National Research Plan (PNR) - EU Next Generation - a problem-driven research project entitled, “BIM-to-Digital Twin: information management to support decision-making in the building life cycle”, has been initiated in collaboration with the Building Area of the University of Florence and Descor srl, company operating in the field of software tools for Facility Management, with the aim of developing information management of built assets belonging to the university's real estate stock through the implementation of BIM information models aimed at Facility Management (Biagini et al., 2023).

The Building Area is divided into three Process Units - Real Estate, Building Plan, Ordinary Maintenance - in addition to Administrative Support, to which are added two specialized services called “Fire System Management (GSA)” and “Control and Maintenance of Asbestos Containing Materials”. The Ordinary Maintenance Process Unit is responsible for planning and scheduling regular maintenance interventions, coordinating technical referents in various territorial offices, monitoring the need for programmed maintenance interventions and urgent repairs, and coordinating with the Property and Logistics Services Area for integrated interventions. The operational services managed by the Ordinary Maintenance Process Unit are divided into Maintenance services, Cleaning and environmental hygiene services, and Reception and porterage services. Each operational service includes various activities, such as ordinary activities (predefined or supplementary) and extraordinary activities (breakdown or on-demand). Maintenance Services encompass all activities aimed at maintaining the functional state and preservation of the building's systems and construction components. Specifically, the systems managed as different maintenance services are Electrical, Water, Heating, Air-conditioning, and Elevator, Firefighting, Security and access control and Network system as well as the minute building maintenance.

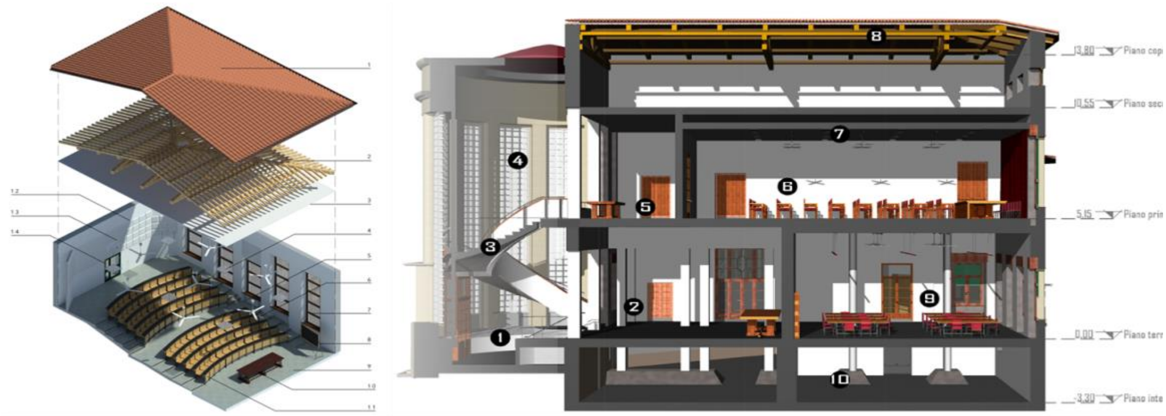

Figure 6: BIM models of university buildings.

The managed property portfolio consists of diverse assets, varying in function, structure, and historical-architectural value, each needing unique maintenance and management approaches. The Infocad.FM platform developed by Descor s.r.l., has been in use at the University for managing real estate assets, including a centralized Technical Registry with associated documents, data sheets, CAD plans, and photos. However, due to the varying formats of these documents, primarily being paper-based, there are challenges in managing this information. The goal is to transition to BIM methodologies for secure, dependable, and consistent data and information management within a Common Data Environment, which allows not only the uploading of files but also the writing of metadata related to them (Paparella & Zanchetta, 2020). In the research project, specific buildings were chosen as case studies and modeled following the organization guide lines. Each asset information model (AIM) is divided into domain-specific federated models for architectural, structural, and systems, to manage model information efficiently (Figure 6). The BIM creation process depends on the geospatial data type, using CAD-to-BIM or Scan-to-BIM methods. A BIM authoring tool is used to create the models, then exported to IFC format, aligning all elements with the correct schema class.

It is crucial the compilation of the OIRs (Organization Information Requirements) to create matrices based on the Level of Information Need concept. These matrices will help determine the required level of information for each type of asset within each building. Additionally, a library of general BIM objects can be established, which can be utilized in any building project. Each object in this library will be associated with the appropriate IFC schema class and the necessary psets to convey the required information. It is important to establish a naming convention for both individual instances (IfcObject) and their types (IfcTypeObject) right from the beginning. Furthermore, efforts should be made to align the organization's existing parameters with those provided by the IFC schema. This phase should be conducted simultaneously with the examination of technical registry documents prepared by the owner, following the guidelines of the COBie standard.

Next, an analysis of past maintenance actions carried out by the Ordinary Maintenance UP and the related costs and costs for each building was conducted. This helped outline improvement strategies in Facility Management (FM) using IoT devices for environmental monitoring, energy use, and overall efficiency. Specifically, this allowed identification of spaces within buildings that could provide valuable data through sensor monitoring (temperature, humidity, pressure, air quality, movement, brightness, etc.), considering their usage conditions.

Following this analysis, two case studies assets of university's real estate stock were chosen to begin the implementation of IoT systems for controlling the environmental quality of internal spaces: the Department of Statistics and the Department of Mathematics, Ulisse Dini.

3.1. Ongoing approaches to the implementation of IoT at university assets

Two different set up has been outlined for the two buildings in order to gather and organize data from IoT devices and merge them with data-at-rest in a BIM-based common data environment. The goal is to implement a Digital Twin of existing real estate properties, leading to advancements in big data analytics via AI applications. This framework aims to aid decision-making for various stakeholders in building operations, including owners, facility managers, technicians, and experts, by planning maintenance actions, creating content, providing recommendations, and predicting managed asset behavior. The paper also explores optimizing BIM-IoT integration using semantic web technologies, focusing on interoperability and data-set exchange, and enabling real-time visualization of monitoring data from BIM models for Facility Management. The proposed approaches involve the creation of BIM models using data and information from the real estate asset owner. This data includes geometric (2D/3D), alphanumeric, and documentary information, enhanced with additional semantic content for later management phases (Figure 6). However, before this operational phase, a thorough analysis of maintenance and asset functionality activities within the property must be conducted, focusing on actions taken, resources, and infrastructure. This analysis aims to define the organization's information requirements (OIR), informing all information exchanges that govern the various management processes. This should result in a BIM Guide for implementing the organization's asset information models, standardizing delivery processes among internal operators or external suppliers, following specific standards and best practices established by the company.

Once the modelling phase was completed, two different workflows were set up to connect BIM models with sensor data. The first approach involved the use of a DTH22 environmental sensors integrated through Node-Red to the open source platform Snap4City for data management (Biagini & Bongini, 2023); the second approach involved the installation of LORAWAN sensors within a building identified as a case study and the use of a property platform, Niagara Tridium, for data manipulation and sampling to be convolved within a BMS platform.

3.1.1. The Department of Statistics DT

The first DT project's implementation involved the building of the Department of Statistics (Figure 7). It is a three building stories composed by three blocks built in different periods. It has a total surface area of 4250 square meters with a prevalent use for classrooms and offices for teachers and administrative staff. The central body presents an interesting architecture inspired by the Finnish design of the 1950s, with the wooden structures of the main staircase connecting the floors and the roof declined in organic forms. The BIM model was based on the restitution of geo-spatial data extracted from heterogeneous documents provided by the Building Area, including the original 1958 project and regulatory adaptation of the 1990s, as well as from the direct and instrumental survey campaign to collect technical information on building components and installations.

The aim of this process was to create a federation of disciplinary models, subdividing the complex by category (architectural, structural, plant engineering and furniture). In particular, the plant modelling was performed based on a technical registry conducted only on the terminals detectable by visual inspection. As for the management side of the modelling, a set of shared parameters was created to reflect the information needs of the Building

Department, subdividing them into groups according to disciplines.

The implementation phase of the DT instead involved the use of environmental sensors, specifically DHT22, to collect temperature and humidity data and the Snap4City platform, an open-source tool developed by the DISIT Lab team of the University of Florence (Badii et al. 2019) for manipolating the data collected (Figure 8). This platform, originally designed for smart city management, has expanded to handle building management and BIM methodology. It caters to various domains, including mobility, energy, pollution, and more, and includes integrations like smart parking, smart waste, smart bed, and smart ambulance. The Snap4City platform offers customizable dashboard creation, historical data management using data aggregation and indexing systems, and is a data-driven solution that performs Data Analytics and Machine Learning operations based on incoming information. In addition it is an open-source project that adheres to major international standards, Fi-Ware certified, complies with GDPR, can handle diverse data types and supports multiple organizations working concurrently on the platform.

The initial step of the process involved creating a sensor device using a Raspberry Pi Zero 2 W (IoT Edge) microprocessor, which is able to process the data by itself without a gateway. Then the data can be trasmitted to the Snap4City platform by setting up a workflow in the Node-Red development environment, a visual programming tool. Besides the standard node library two additional palettes developed by the Snap4City team have been added: basic for end-users and advanced for developers. Simultaneously, an IoT Device instance was created on the Snap4City platform, representing the sensor, specifying its features, location, and expected data type. The sensor data was sent to an IoT Broker, which collected and indexed it. The data was then processed again via a new Node-Red workflow in an IoT App, utilizing the server's capabilities rather than the sensor's processors. Lastly, the data was displayed on a customized dashboard for an overview of the building's environmental conditions. The platform uses the combination of BIM Server and BIM Surfer, a web-based IFC model viewer, to input BIM models. The interface developed allows individual model elements to be associated, directly within the browser, with IoT Devices, previously created, and their related information. Once an IFC model is uploaded to BIM Surfer, it is added as External Content to the same dashboard that contains the previously collected data. This provides a comprehensive, real-time overview of the building's current state, both geometrically and sensor-wise.

Figure 7: BIM model of Department of Statistics of University of Florence. Main fronts (modeled by G. Manetti).

This approach for the implementation of DT through the integration of BIM information models and IoT systems aimed at the collection, processing and visualisation of environmental data using an open-source platform based on a microservices architecture. In particular, the methodology focused on interoperability, management and ownership of the data at each stage of the process.

However, this approach has limitations as the BIM model data integration, which can currently only be used at the geometric level, as the available interface cannot display all semantic contents of building components, only their hierarchical position within the IFC file.

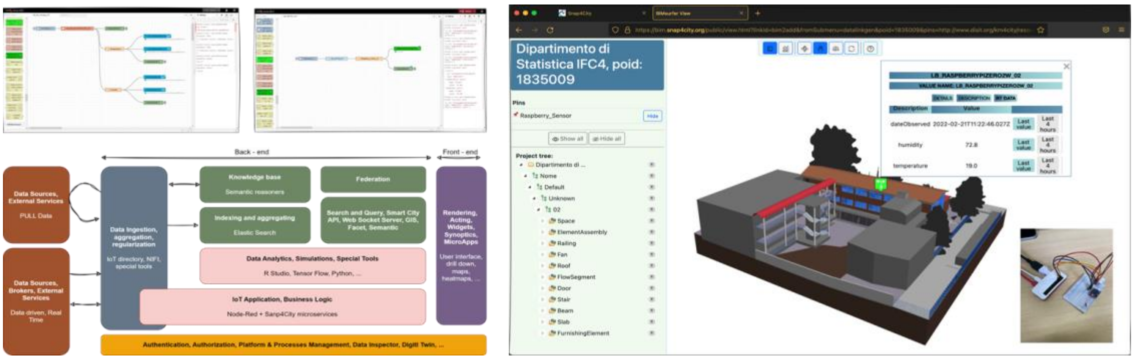

Figure 8: Snap4City workflow.

3.1.2. The Department of Mathematics, "Ulisse Dini", DT

The second DT project has used a different software architecture to gather, categorize, and process information from numerous LORAWAN devices situated within the built asset.

The building of the Department of Mathematics, “Ulisse Dini”, dates back to the late 1950s, based on the design by the Florentine professionals Casimiro Pagano and Silvano Cappelli, and built by the Guarducci company. It has a spatial configuration structured into three blocks which host different functions.

Block 1 consists of a basement and four floors in height, in which, among others, the main entrance, the classrooms, the offices of the teachers and researchers of the department and the auditorium are located. In the three-storey block 2 there are offices and classrooms. Block 3 houses the department's library. The overall gross surface area of the building is approximately 3750 mq. The largest rooms are the library (205 mq) and the great hall (235 mq) (Figure 9).

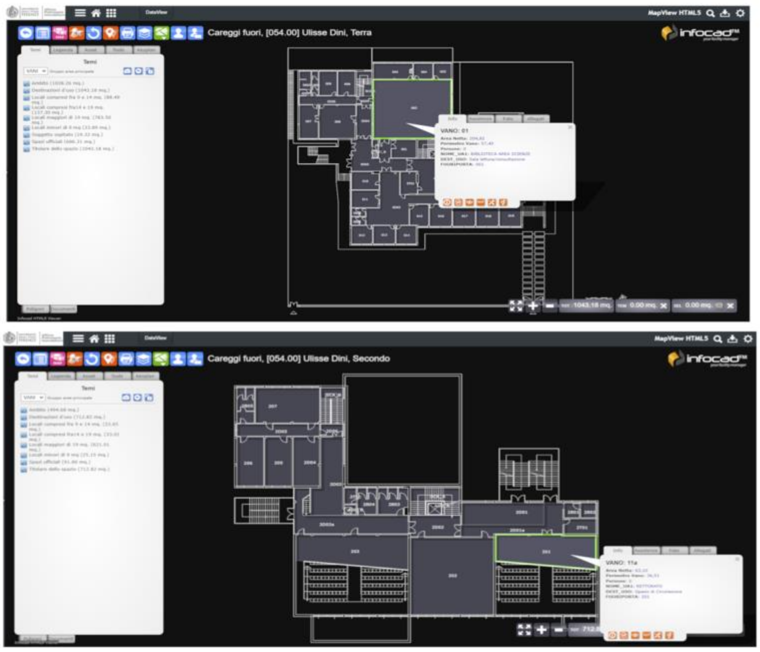

Figure 9: InfoCAD platform - 054.00 Ulisse Dini plans.

The information modelling of the building was developed through the coordination of federated disciplinary models in a completely similar way to the previous case (Figures 10-11).

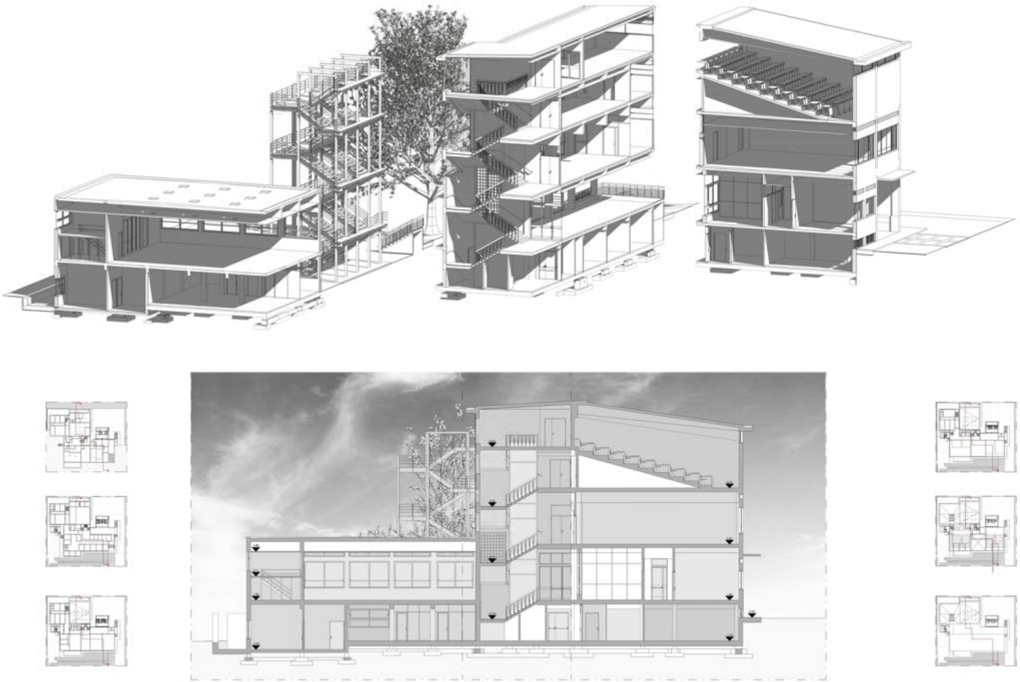

Figure 10: BIM model of Ulisse Dini.

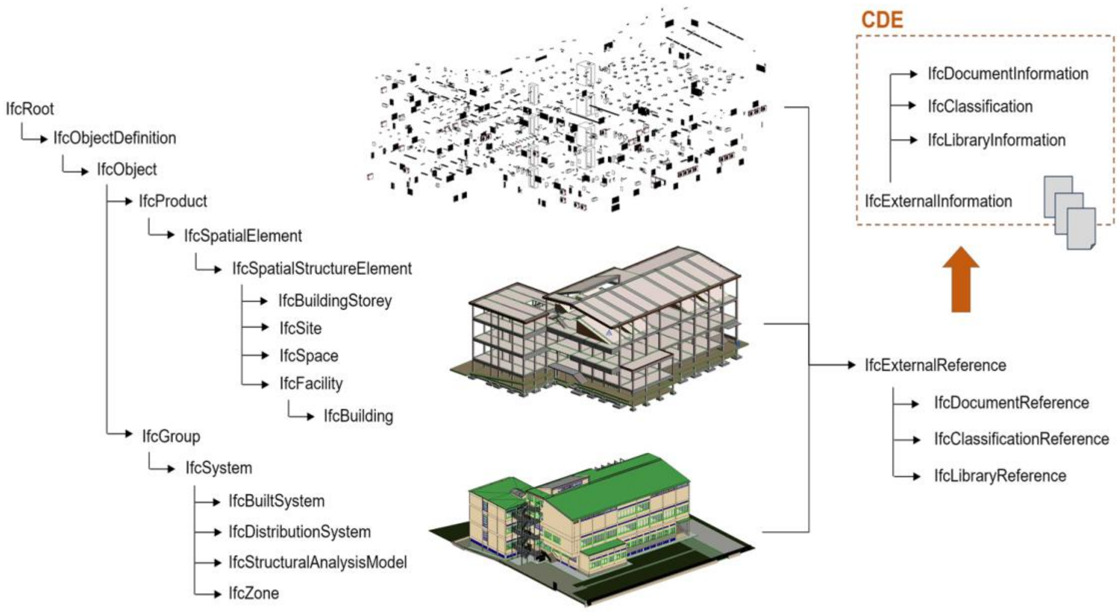

Figure 11: Federated models and IFC schema for object classification.

The device selection for IoT implementation has been based on the observations discussed in previous chapters, ensuring real-time data collection of environmental or other specified information. The physical layer consists of the device itself, which can transmit the collected data to a gateway or directly to the cloud for indexing and data aggregation (Data Storage Layer). Subsequently, the data, depending on the type, have been collected into a suitable platform (Data Integration Layer), and accessed through appropriate methods or APIs within software applications for real-time analysis and querying.

In this case the Niagara Framework, developed by Tridium - an independent Honeywell company born in 1998 - was utilized for the purpose of data manipulation. The primary focus of this framework lies in the automation of buildings, industrial plants, smart cities, and administrative management systems.

It brings forth several advantages, most notably its capacity to integrate various protocols, regardless of whether they are open-source or proprietary, and its ability to normalize data so that it can be processed uniformly. Additionally, the framework provides real-time information access, making it a good tool in the aforementioned fields.

The real situation today is that, as a result of successive installations over time or due to different brands, those who have to manage the building end up with many different applications. So Niagara acts as a layer that sits on top of all these verticals, capturing the information from the different protocols and, by normalising all this information, allowing the data to be correlated but also being able to regulate the installation.

Niagara uses a device called supervisor to receive and manipulate the incoming data from the gataway, with which one can dialogue either via a desktop application (Niagara Workbench) or via HTTPS protocol via a browser. After a first characterisation of the different types of input data, it is possible to set a data sampling according to an interval of one's choice, and subsequently aggregate and perform operations on the data via a node-based interface (wire-sheet). Since many technicians on different systems can work on a single building, the nomenclature of variables is often the responsibility of the person working on it.

To facilitate the use of the Analytics tool within the same platform, there is the possibility of using tags, which are labels that identify the type of data or other its characteristics. By default, either Niagara's proprietary dictionary or the open-source tagging system developed by the Haystack project are loaded; in addition, further custom dictionaries can be developed.

Organizations can use APIs to directly retrieve the end date or export it in various formats. In particular, exporting in CSV format can be used to store the data in an additional NoSQL database in case of need, so that the API call is made on a database like MongoDB instead of Niagara.

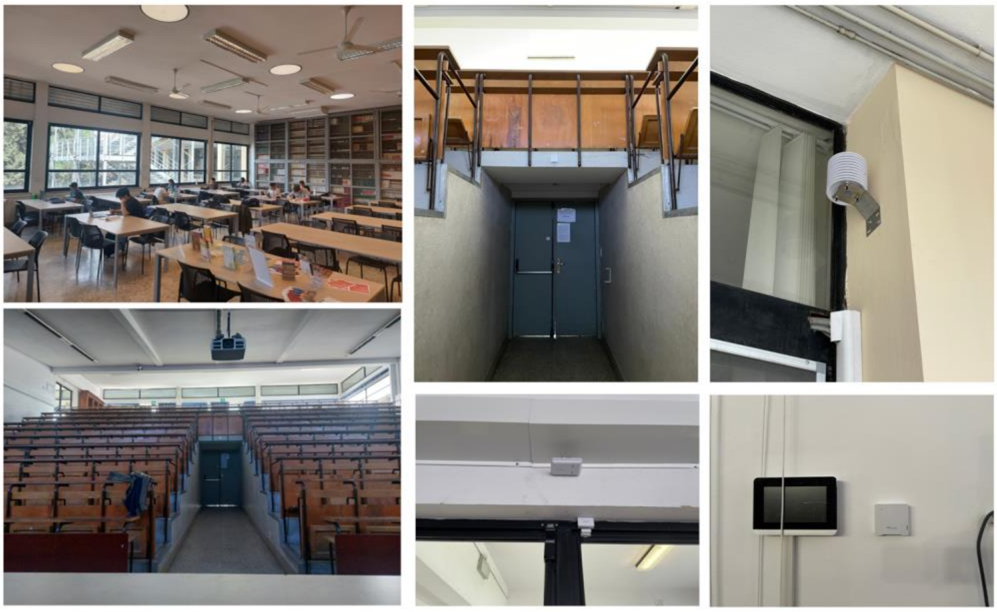

Figure 12: Devices installed in the Dpt. of Maths "Ulisse Dini".

In order to minimise the impact on the building in which students' teaching and staff work, battery-operated devices were chosen, which do not require electrical and masonry assistance for installation. Furthermore, taking into account the geometric and spatial characteristics of the locations where the devices are to be installed and the type of data to be collected, it was decided to use LoRaWAN as the data transmission protocol. This system allows us to minimise the costs of the equipment to be installed, minimising the impact on the existing building, and keeping the detection and security characteristics of the system within acceptable limits. The different types of sensors adopted allow the recording of data relating to: people counting, opening/closing windows, temperature, relative humidity and indoor and outdoor air quality (Figure 12). The data recorded by these sensors is then collected by a gateway installed in the building itself, which communicates with the external network via a dedicated SIM card so as to be independent from the university network. Every 5 minutes the data is transmitted from the gateway to the supervisor on which the Niagara platform is installed and which is located at the servers of the Descor organization. The information is transmitted according to the BACnet standard, which allows a more complex representation than standards such as Modbus. Subsequently, through the Niagara platform, the data is sampled and processed (Figure 13).

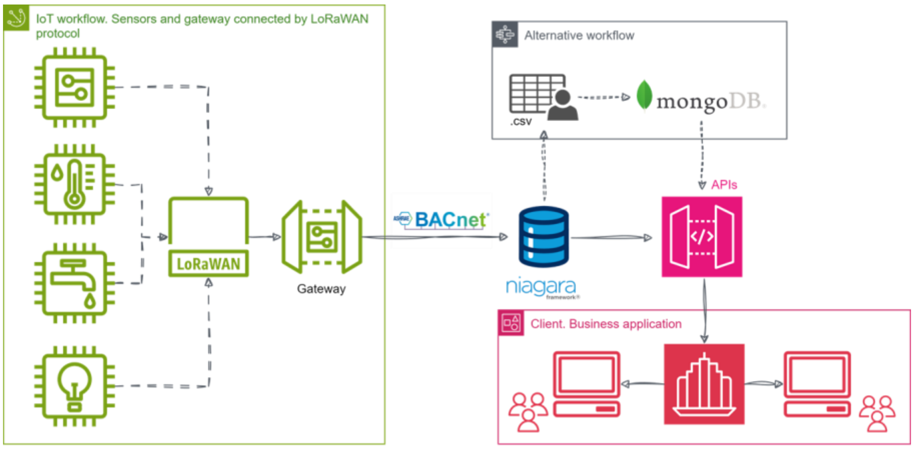

Figure 13: IoT framework.

Each sensor entity has been assigned a Tag following the standard defined by the Haystack Project with the aim of subsequently linking the classes of this dictionary with the other ontologies presented in the previous chapters. Moreover, by defining an automated workflow inside the Niagara platform, the daily automatic export of the different histories (Figure 14) associated with the different sensors in csv format has been set for subsequent use in NoSQL databases.

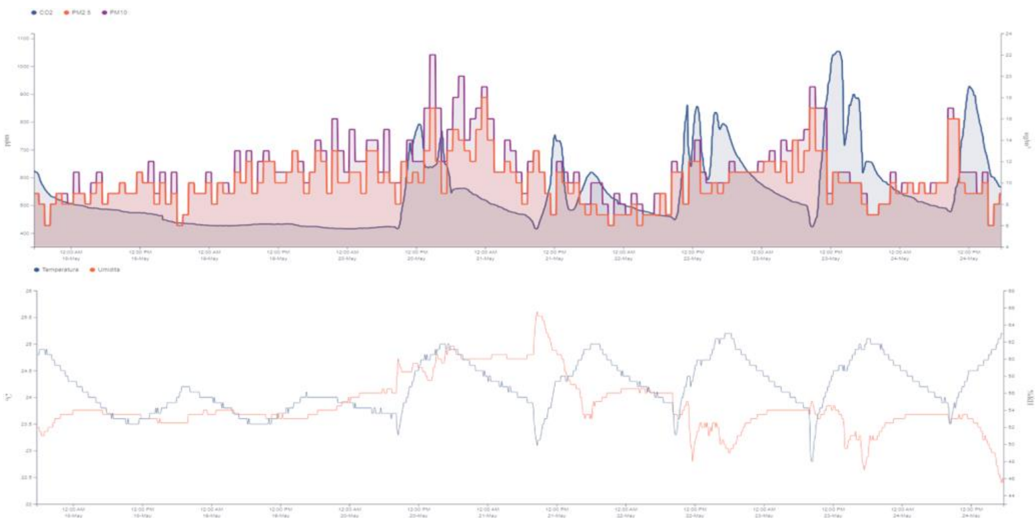

Figure 14: Example of histories for data collected in the »Library« room and visualized inside the Niagara platform.

As an ongoing project, the subsequent integration phases are still under development, but it is planned to achieve an integrated working environment in which IFC models, existing databases and sensor data can be combined in a way that is scalable to the different needs of the university. The next phase of the research will involve the use of semantic web technologies, in particular existing ontologies, to connect the information of the existing database used by the University, the BIM models and the data collected by sensors. The BIM model itself, which internally presents a representation of the sensors actually positioned in the actual environment, must be converted into an RDF graph and linked to the other information using some of the ontologies described above, which can be used to create an extensible semantic graph containing not only all contextual information about the building, but also references to external DBs or documents, thus offering an automated query methodology on the instances associated with the graph.

4. CONCLUSION AND FUTURE DEVELOPMENTS

The implementation of BIM tools and methodologies for the management of operational information for an existing asset can offer significant economic and managerial benefits for the asset's owner and particularly for facility managers. In fact, data are often scattered across different databases and specialized platforms such as CMMS, CAFM, BACS, or IWMS don't communicate each other. BIM can be regarded as a central data source for the representation of buildings and their components. It can be employed by data-driven applications for the correlation of heterogeneous data. Indeed, the extensive implementation of Internet of Things (IoT) devices facilitates access to dynamic data concerning a building's operational parameters, which is in addition to the considerable amount of static information accumulated throughout the lifespan of a building. This allows facility managers to enhance performance management, reduce energy consumption, optimise routine and non-routine maintenance, and improve user satisfaction and well-being. The integration of these two types of data enables the generation of a multi-domain, comprehensive digital representation of the building's components and their relationships, commonly referred to as the "digital twin". However, despite the wide range of communication protocols and semantic models for IoT device information exchange, there is still limited integration with the IFC scheme for building classification. IFC schema extensions offer limited and underdeveloped support for integrating this data, as it was not designed for real-time data transfer between tools. In addition BIM platforms are unable to comprehend implicit information regarding a building's topology, function, and behaviour due to a lack of expert knowledge in these areas. The objective of semantic enrichment is to enhance the intelligence of BIM models beyond that achievable through simple parametric modelling and extend the knowledge of a single BIM model beyond a specific domain. This is achieved by integrating additional contextual and relational data. This cannot be achieved merely by linking external data sources to the BIM model; instead, it requires the ability to reason about explicit knowledge in order to derive new information and provide an explicit representation of that information for user consumption. In light of the aforementioned considerations, a considerable body of research has been dedicated to the exploration of semantic web and linked data technology across a diverse array of domains, including not only the integration of sensor and actuators but also design, time and cost schedules, health and safety, and sustainability.

The 'BIM-to-Digital Twin' research project, currently in its initial phase, seeks to establish an operational framework for the collection and management of data essential for the implementation of Digital Twins (DTs) of existing real estate assets. This entails the integration of BIM platforms, existing databases, and IoT technology, with a view to subsequent developments in big data analytics and AI applications. This paper presented a comprehensive review of existing technologies and open challenges in creating an information technology architecture that supports this integration, in order to improve maintenance and operational activities for owners.

The research firstly present the current state of the art about semantic web and linked data technologies, where years of research led to the creation of the ifcOWL ontology. The complexity and monolithic nature of this schema, as the original one, have, over time, given rise to the development of additional, smaller and more modular ontologies. Ontologies like BOT, BPO, SSN/SOSA, Brick and REC facilitate adaptable and scalable information management, allowing for greater flexibility and responsiveness to organisational needs. After that n examination of the various layers and protocols that compose the Internet of Things (IoT) domain have been proposed. This knowledge has been very important in order to choose which kind of sensor were better for our goals in the environment presented.

The two case studies presented have shown an incremental approach to the realization of a digital twin solution which can be used by the technical office of the University of Florence. Starting from BIM models obtained by a

CAD-to-BIM process, two different framework were tested. The first framework started with the implementation an environmental sensors (DHT22) to collect temperature and humidity data, which were then transmitted to the Snap4City platform, an open-source tool developed by the DISIT Lab team at the University of Florence. Once the data was collected, it was processed using Node-Red workflows in both an IoT Edge device (Raspberry Pi Zero 2 W) and a server-based application. The processed data was then displayed on a customized dashboard for real-time monitoring of the building's environmental conditions. This integration of BIM models and IoT systems enabled a comprehensive understanding of the building's current state, both geometrically and sensor-wise. However, the implementation of DT through this approach has its limitations, particularly in terms of BIM model data integration. Currently, only geometric information is available for display, and not all semantic contents of building components can be shown due to limitations in the available interface. The second framework, which is still in progress, has seen the displacement of several IoT devices in two rooms inside the Department of Maths in order to collect not only the value of temperature and humidity but also other environmental data as CO2, PM2.5, PM10, sound level, … The data collected pass through a central gateway and are sent to the Niagara platform where they can be manipolated, visualized and extracted. In order to be more platform-independent all the data are exported periodically in an open format and used in other open source databases. As reported in the literature import all the data collected inside the BIM authoring software is useless and time consuming, using existing ontologies is possible create an RDF graph which contain all the information need about data and where they are eventually archived. The next step for this case study will be the creation of a RDF graph composed by the knowledge derived from the existing database of the university, the BIM model and the infrastructure used for the data collection. This graph will be used for making query, infer implicit knowledge and support the decision phase of the facility managers.

The research shown that the integration of BIM models and other kind of database is not straightforward and many domains and specific knowledge are involved. For this reason data interoperability assumes paramount importance in the industry. The shift from model-centric to distributed semantic approaches demands a more profound understanding of reality, one that transcends the confines of a single model. To address this challenge, it is essential to adopt a holistic approach that prioritizes interoperability and data exchange between disparate systems, models, and disciplines. This necessitates the development of standardized interfaces, data formats, and protocols that enable seamless communication and integration across various domains, while also accommodating the unique requirements and constraints of each discipline.

Author Contributions. Conceptualization: C.B., L.M.; methodology: A.B.; data acquisition: A.B..; data processing: A.B.; writing—original draft preparation: A.B.; writing—review and editing, A.B., C.B., L.M.; supervision, C.B. All authors have read and agreed to the published version of the manuscript.

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