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European Master in
Building Information Modelling

Visualizing Monitoring Data through BIM

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I appreciate you all.

STATEMENT OF INTEGRITY

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SOMMARIO

Uno dei campi che ultimamente ha acquisito molto valore nel mercato delle costruzioni è il Facility Management (FM), con un'attenzione particolare alle prestazioni degli edifici. La diffusione dell'uso del Building Information Modelling (BIM), come metodologia per la gestione dei processi di costruzione, porterà ad una gestione più digitalizzata degli asset. Facendo un passo avanti, il concetto di Digital Twin (DT) viene utilizzato per integrare gli asset dell'edificio con le tecnologie digitali per permettere l'analisi in tempo reale, oltre a fornire possibilità di simulazione dei processi. Ci si aspetta che il DT abbia un alto impatto nel facilitare la transizione sostenibile attraverso gli sviluppi tecnologici, secondo la missione europea del Green Deal.

L'integrazione del BIM con i dati in tempo reale dai dispositivi dell'Internet of Things (IoT) presenta un potente paradigma. Questa tecnologia potrebbe creare un ambiente di dati condiviso per la gestione incrociata dei dati dell'edificio e degli aspetti energetici. Dotare l'edificio di sistemi di monitoraggio significa che una grande quantità di dati collezionabili, sull'ambiente interno, deve essere monitorata e interpretata dai facility manager. L'integrazione dei dati dei sensori, derivati da più sensori, nel modello BIM, permette di combinare automaticamente i dati monitorati con il relativo spazio geometrico nel modello. Tuttavia, l'integrazione e la visualizzazione di questi dati di monitoraggio IoT in BIM è raramente senza soluzione di continuità e viene fatta con un'alta dipendenza dal server locale utilizzando strumenti di authoring BIM nativi.

Questa ricerca descrive un tentativo di sviluppare un DT utilizzando la piattaforma cloud-based Autodesk Forge non solo per integrare e visualizzare in tempo reale i dati dei sensori di monitoraggio interni in un modello BIM, ma anche per visualizzare un cruscotto decisionale del comfort termico interno utilizzando l'indice Predicted Mean Vote (PMV) rispetto agli standard di riferimento dell'edilizia verde per supportare decisioni complesse come alternativa significativamente migliorata rispetto ai modi tradizionali. Il quadro proposto è testato e verificato sul caso studio di una scuola, nell'ambito del progetto "SINCRO".

Parole chiave: Autodesk Forge, Building Information Modelling (BIM), Digital Twin (DT), Facility Management (FM), Internet of Things (IoT)

ABSTRACT

One of the fields that lately has gained a lot of value in the construction market is Facility Management (FM), with a special focus on building performance. The spread of Building Information Modelling (BIM) use, as a methodology for the management of the construction processes, will bring more to a digitalized asset management. Taking a step further, the concept of Digital Twin (DT) is being used to integrate building assets with digital technologies to allow real-time analysis, as well as provide simulation possibilities. DT is expected to have a high impact on facilitating sustainable transition through technological developments, according to the European Green Deal mission.

The integration of BIM with real-time data from the Internet of Things (IoT) devices presents a powerful paradigm. This technology could create a shared data environment for cross management of building data and energy aspects. Equipping the building with monitoring systems means that a large amount of collectible data, about the indoor environment, needs to be monitored and interpreted by facility managers. The integration of the sensor data, derived from multiple sensors, into the BIM model, allows to automatically combine the monitored data with the related geometrical space in the model. Nevertheless, integrating and visualizing this monitoring IoT data in BIM is rarely seamless and is done with high dependence on the local server using native BIM authoring tools.

This research describes an attempt to develop a DT using the cloud-based platform Autodesk Forge to not only integrate and visualize real-time indoor monitoring sensor data into a BIM model but to also display a decision-making dashboard of indoor thermal comfort using the Predicted Mean Vote (PMV) index in comparison to green building benchmark standards to support complex decisions as a significantly improved alternative compared to the traditional ways. The proposed framework is tested and verified on the case study of a school, within the project “SINCRO”.

Keywords: Autodesk Forge, Building Information Modelling (BIM), Digital Twin (DT), Facility Management (FM), Internet of Things (IoT)

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1. INTRODUCTION

Indoor air pollution has been ranked among the top five environmental risks to public health (Sun *et al.*, 2019). Monitoring the Indoor Environment Quality (IEQ) in real-time is particularly beneficial for health purposes, and is the future of healthy, smart buildings, especially in this post-COVID-19 period. According to data from the World Health Organization (WHO), more than 80 percent of people who live in urban areas, where air pollution is monitored, are exposed to air quality levels that exceed the limits of the WHO (i-scoop, no date d), and an essential part of tackling its effects is knowing how the air quality is at any given time. From a survey conducted on U.S consumers, 91 percent consider healthy indoor air quality (IAQ) important in the prevention of COVID-19 and 76 percent would feel more comfortable entering buildings knowing IAQ was being monitored (Harry Watson, 2021). Therefore to address this, technology such as the Internet of Things (IoT) offers a solution to monitor air quality.

IoT devices are increasingly being deployed in the built environment and can provide useful information related to the built environment to monitor and maintain the building performance. Combining this information with Building Information Modelling (BIM) would make it possible to transform our interaction with the built environment during its use and operational phase to improve the user's experience and better decision-making opportunity for the facility manager.

The Operational phase in the built environment where the Facility Management services commence is the longest in its lifecycle (Peng *et al.*, 2017). Yet, on a global scale, the implementation of digital information management at this stage compared to the others is not quite widespread (Parsanezhad, 2015). The interoperability between BIM and FM during this stage requires real-time data about the physical asset which can be implemented in three broad categories: tracking building performance, building maintenance, and emergency management (Xu, Ma, and Ding, 2014).

The integration of BIM with IoT devices creates a Digital Twin (DT) that combines the monitored data with the related geometrical space in the model to be used in FM by a facility manager. However, there is still a gap with the process of BIM-IoT integration through open standards and systems (Dave *et al.*, 2018), therefore using a non-proprietary file format or model or alternative solutions with less dependency on proprietary file formats could profer a solution.

The overall aim of this research is to improve the efficiency of facility management (FM) and utilize real-time data during the building's lifecycle. An integrated cloud-based framework is developed, that is capable of integrating models from open non-proprietary file formats such as IFC, gbXML, glTF as well as other industry proprietary file formats to visualize indoor monitoring data which is tested and validated on a real case study of an existing school building. The realization of this integrated framework includes: Integration which automatically collects data from physical sensors installed in a space, and maps the data in the BIM model; Visualization which automatically displays values based on the collected sensor data, and computationally visualizes the value with a color palette scheme; Analysis that interprets the collected data to guide in a better decision making process.

The dissertation starts with this present and first chapter, *Introduction* which presents a general overview of the research on the topic of creating a DT to be used for visualizing monitoring environmental data through a BIM-based model.

The second chapter, *Literature Review*, covers the review of existing literature and projects to explore the current knowledge and identify possible gaps. It comprises three main subsections, starting from providing relevant background information and key definition of the terms BIM and FM and its interoperability, followed by the introduction of DT, its concepts and application for a sustainable built environment, and the last part covers the transition from BIM to DT for indoor monitoring data exploring BIM to IoT (BIM-IoT) integration workflows, limitations, possible solutions, and cloud-based DT platforms.

The third chapter, *Methods*, addresses the strategic methodology for developing a cloud-based digital twin that integrates the indoor environment data collected by multiple sensors systems with a BIM-based model. The integration allows to automatically combine the monitored data with the related geometrical space in the BIM model. The implementation is a four-layer methodology following the workflow summarized from literature reviews on the topic of BIM-IoT integration for visualizing monitoring data. These four main layers are Data Acquisition; Data Integration; Data Visualization; and Data Analysis.

The fourth chapter, *Use Case*, describes the case study project, the IoT sensor parameters, the type of environmental data collected, the IoT devices installed, and the platform used for the BIM-IoT integration. The developed methodology for integrating the monitoring data with BIM was tested and validated on a real case study of an existing school building.

The fifth chapter, *BIM to DT - Visualizing Monitoring Data*, describes the detailed application of the proposed methodology on an existing school building, starting from the data collection process the database, using Forge to integrate the data with the sensor device family in the BIM-based model from Revit as the BIM authoring tool, visualizing the outputs as heatmaps in rooms within the model, and lastly analyzing the data against a decision-making dashboard with benchmark standards to identify the indoor thermal comfort using the Predicted Mean Vote (PMV) model.

The last and sixth chapter, *Conclusion*, summarises the contributions of the presented work, suggestions, and possible future work.

This research has been developed in collaboration with Fraunhofer Italia research s.c.a.r.l within the project “SINCRO”. Fraunhofer is an applied research company following an approach of digitization of construction processes through innovative information and communication technologies (BIM) to support the integrative collaboration of the various participants in the AECO industry.

2. LITERATURE REVIEW

This chapter covers the review of existing literature and projects to explore the current knowledge and identify possible gaps. It comprises three main subsections, starting from providing relevant background information and key definition of the terms BIM and FM and its interoperability, followed by the introduction of DT, its concepts and uses for a sustainable built environment, and the last part covers the transition from BIM to DT for indoor monitoring data.

2.1. BUILDING INFORMATION MODELLING AND FACILITY MANAGEMENT

2.1.1. BIM Definition

From the inception of digital drawing, back when drawings were done on computers using Computer-Aided Design (CAD) with the use of layer-based techniques and drawing software which allowed overlaying of multiple drawings. Over the years, this has evolved to the ability to include valuable geometric and non-geometric information needed at the design, construction, operation, and maintenance stages of buildings and infrastructure into the 3D digital models known as a BIM model. In the BIM Dictionary, “Building Information Model (BIM) is the object-based, data-rich, 3D digital model generated by a Project Participant using a BIM Software Tool” (BIM Dictionary, no date).

According to the NBIMS Initiative (National Building Information Modelling Standard), “Building Information Modelling (BIM) is the digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward” (NBIMS, 2013). Since BIM is known to start from the earliest conception, it enables an active collaboration of all participants from the beginning of a project based on an n-dimensional virtual presentation of the building, which can help to achieve an Integrated Project Delivery (IPD)

The information contained within a BIM model can be further categorized into different dimensions. These dimensions illustrate the levels of information inputted in a digital model, which also reveals the adaptability of the BIM process and relates to its uses throughout an assets’ life cycle at different stages. The BIM dimension workflow shown in Figure 1 starts from the inception of a project, the first dimension, 1D defines the Strategy or concept stage. At this level, the BIM strategy includes the Exchange Information Requirements (EIR), BIM Execution Plan (BEP), etc. The Second dimension, 2D defines the Drawings which are vector data such as 2D views and plans, documentations, etc. The third dimension which is the most known, 3D defines coordination, which is the geometry that gathers the graphical data, creates federated models for clash detections, etc. The fourth dimension, 4D defines the scheduling mostly assigned to construction management, which is the time factor, phase task management, etc. The fifth dimension, 5D defines the estimation, which covers the cost, automatic quantity extraction, etc. The sixth dimension, 6D defines Performance, which is the project lifecycle information, integrate with building processes and systems, IoT devices, sustainability, facility management, etc. (POWERBIM, no date).

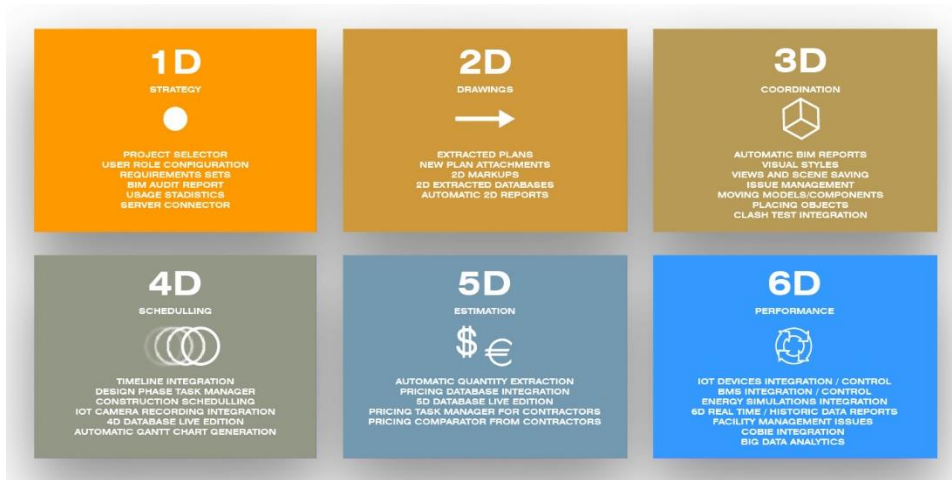


Figure 1 – Dimensions of BIM

Source: (POWERBIM, no date)

Throughout the asset’s lifecycle, the management of this information is also related to the maturity levels of BIM as seen in Figure 2, where the goal is to move from a two-dimensional approach to a fully integrated digital environment that encourages true collaboration (BSI, 2019).

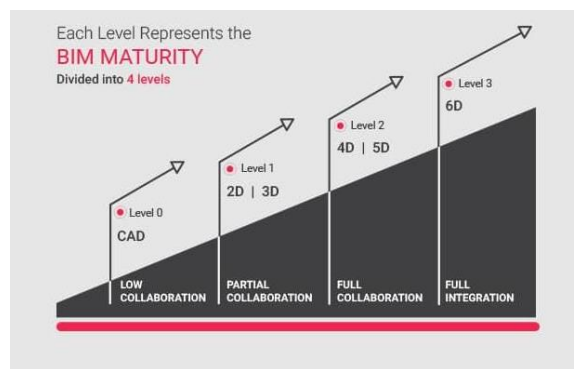


Figure 2 – BIM maturity level

Source: (United BIM, no date)

The amount of information added into a BIM model increases by each project stage (BIM Portal, no date a) as shown in Figure 3 aligning with BIM maturity level 2.

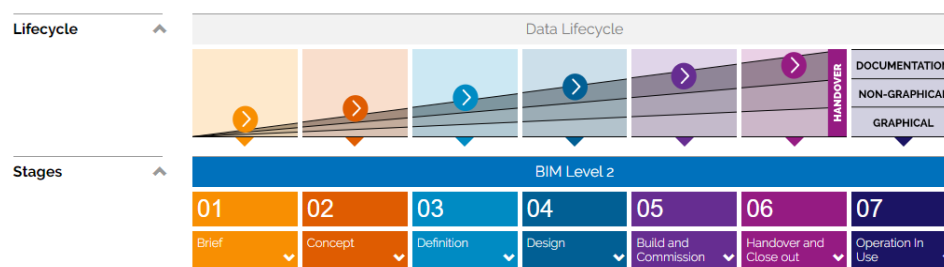


Figure 3 – Data lifecycle through project stages

Source: (BIM Portal, no date a)

2.1.2. FM Definition

After the project handover, the final stage, which is the operation in use, is where the hard and soft facilities management services commence. It gathers the most amount of information containing graphical, non-graphical, and documentation as an Asset Information Model (AIM) is used to help manage, maintain and operate the asset using data and information that relates to the asset (BIM Portal, no date b). This kind of information adds value as it is passed on to the end-user (NBS, 2017). This also translates to the overall life cycle cost (LCC) of a building, where the Operations and maintenance phase absorbs roughly 80% of the overall cost (ndBIM, 2016) and is the longest phase in its lifecycle (Peng *et al.*, 2017). Yet, on a global scale, the implementation of digital information management at this stage compared to the others is not quite widespread (Parsanezhad, 2015).

“The term Facility Management (FM) refers to the interdisciplinary activities performed during the Operation Phase of building, space, or infrastructure. FM activities typically include operation, leasing occupancy, maintenance, cleaning, etc.” (BIM Dictionary, no date). These different types of activities performed during the Operation Phase of a building are performed by the facility managers and are grouped under eleven core competencies Figure 4 which include: Occupancy and human factors; Operations and maintenance; Sustainability; Facility information and technology management; Risk management; Communication; Performance and quality; Leadership and strategy; Real estate; Project management; Finance and business (IFMA, 1998). The concept of FM covers various disciplines of the built environment by integrating people, place, process, and technology according to the International Facility Manager Association (IFMA).



Figure 4 – Core Competencies of Facility Management

Source: (IFMA, 1998)

The facilities management services that start in the operation stage are the ‘hard services’ or ‘soft services’ and are commonly known as components of FM (Figure 5). The hard services relate to the physical part of a building which is considered essential, while the soft services relate to the people and are mostly non-compulsory. (FTMaintenance, no date).



Figure 5 – Components of FM

Source: (FTMaintenance)

To achieve better efficiency of FM activities, it can be done using Computer Systems as supporting tools known as Computer-Aided Facilities Management (CAFM) with technical data that can be integrated with other platforms such as Computer-Aided Design (CAD), BIM models, and other types of numerical documents which allows Facility Managers to monitor the operational requirements of buildings (e.g. energy consumption, lighting, security, etc.), manage space utilization, track asset/equipment locations, and perform other related functions during the Operation Phase of a Facility. Other digital technologies that have been used to support FM include Computerized Maintenance Management System (CMMS), Building Automation System (BAS) or Building Management System (BMS), Energy Management System (EMS), etc (Alileche, 2018).

2.1.3. Implementation of BIM for FM (BIM-FM)

BIM implemented in FM is the ultimate step as this is the final stage where all information and data, accumulated over the project’s lifecycle becomes part of the management and maintenance of the building. This implementation can be divided into three categories: The first category is tracking building performance such as space management, controlling and monitoring energy, and facilitating real-time data access; The second category is building maintenance which includes locating building components and checking maintainability; and the third category is emergency management applied as a preventive measure to the occurrence of an emergency, such as a fire or other disaster (Xu, Ma, and Ding, 2014) where the BIM model acts as a repository of information of the whole building (ndBIM, 2016) enabling the owner to monitor its use and maintenance through a central control system.



Figure 6 – Advantages of BIM-FM implementation.

Source: (ndBIM, 2016)

Figure 6 shows some of the advantages of the implementation of the BIM-FM methodology. In summary, BIM for FM helps to gain control over every aspect of the facility, from operations to maintenance as an effective way to not only improve the quality of life but prevent any future problems. The simplest introduction to BIM for facilities managers is through digital twins.

2.2. DIGITAL TWINS – FROM CONCEPT TO APPLICATION

2.2.1. Industry 4.0 and the DT - The Digital Transformation

The “fourth industrial revolution” or Industry 4.0 has been known to define the current digital transformation and these technologies have brought complex industrial systems that are more autonomous, smart, and highly interconnected. As defined by i-scoop, Industry 4.0 is a broad vision with clear frameworks and reference architectures, mainly characterized by the bridging of physical industrial assets and digital technologies in so-called cyber-physical systems (i-scoop, no date b).

While it is safe to say that Industry 4.0 is only possible because of IoT as it plays a major role in the scope of Industry 4.0, however, it is not the only driver as there are eight other digital industrial technologies: Big data and analytics, cloud computing, augmented reality, etc Figure 7, that also play a key role (i-scoop, no date b).

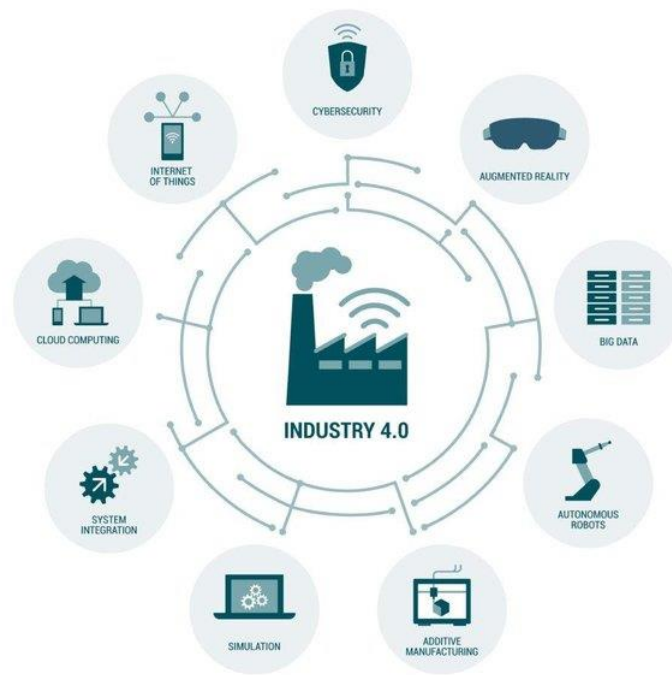


Figure 7 – Industry 4.0 – the digital transformation

(Source: i-scoop)

The Internet of Things, therefore, is the bridge that can connect people to the internet and digital networks through devices. Following the IoT challenge model developed by Tom Casaer, CEO of AllThingsTalk, comprised of two drivers, the cost driver: connect and collect, and the value drivers: visualize and use/share (i-scoop, no date c). This shows that the real value is in the use of this data which outweighs the cost challenge. That is why for instance, according to International Data Corporation (IDC) Worldwide Internet of Things Spending Guide, the European IoT spending is forecast to return to Double-Digit Growth and reach \$202 billion in 2021, an increase from 2020 despite the covid-19 pandemic (i-scoop, no date a; IDC, 2020).

The built environment which covers the main aspects of human existence where BIM processes are majorly used to achieve IPD provides significant opportunities for the implementation of digital technologies such as the Internet of Things (IoT) (Dave *et al.*, 2018). Integrating BIM with IoT results in the creation of Digital Twins (DT).

2.2.2. The concept of DT

In recent times, the application of DT has gained massive popularity, even though the idea of this technology was first introduced in 1991, with the publication of ‘Mirror Worlds’ by David Gelernter (IBM, no date a). However, the concept of DT was conceived and applied to manufacturing in 2002 by Dr. Grieves for the formation of a Product Lifecycle Management (PLM) center simply known as “Conceptual Ideal for PLM”. (Grieves and Vickers, 2016). This concept possessed similar elements of a DT: the physical space, digital space, and the bidirectional data/information flow between the two

spaces. Eventually, the first mention of the name “Digital Twin” was in 2010 by NASA’s John Vickers (IBM, no date a; Singh *et al.*, 2021).

Since the publication by NASA, DT has been defined by different authors in varying terms based on its application. Definitions such as virtual or digital model, layout, counterpart, doppelganger, clone, footprint, software analogue, representation, information constructs, or simulation of its physical counterpart. Most of the definitions agreed on one thing which is the bidirectional data flow in real-time between the physical and digital world (Singh *et al.*, 2021). A Digital Twin (DT) simply put, is a digital copy of a physical element that depicts its real-world attributes in real-time. This could be a model with regular updates continuously evolving or a sensor-enabled model to simulate the physical asset. The evolving profile of a DT achieved from cumulative, real-time data helps to provide important better-decision-making insights on system performance (Parrott and Warshaw, 2017).

Over the years, the use of DT has been applied in several industries from aerospace/aeronautics to manufacturing and beyond for different objectives. The manufacturing industry, for instance, has widely embraced a digital transformation with the emergence of the internet of things (IoT), its processes have increasingly become digital. An example of a model process Figure 8 focused on the manufacturing part of the product life cycle goes through enabling components from the physical world integrated and continuously updated to the digital model is explained by Parrott and Warshaw (2017):

Sensors – Devices installed in the physical world to measure and collect data such as environmental data (temperature, humidity, occupancy, etc).

Data – The data captured by the sensors in the physical world that are aggregated and integrated with external data such as bill of materials (BOM) and user feedback logs.

Integration – Integration technology enhances a bidirectional interaction of data between the sensors in the physical world and digital world.

Analytics – Insights produced by the digital twin through analytical techniques that analyze the data using algorithms and visualization.

Digital Twin – The digital replica of the physical world, where components and processes can be aligned in real-time to achieve greater efficiency and generate a decision-making action that can be implemented in the physical world.

Actuators – Devices that translate the action from the digital world to instigate automatic or manual interventions or responses in the physical world.

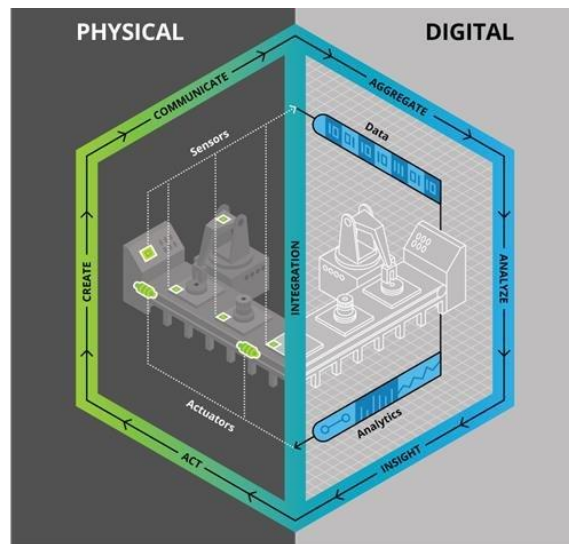


Figure 8 – Manufacturing process digital twin model

(Source: Parrott and Warshaw (2017))

The author further described a sequence of six steps to follow as a DT conceptual architecture to create a DT. This architecture is used in the manufacturing process but may also apply to the creation of any other digital twin in different industries. These steps flow in a physical-digital-physical loop and are as follows:

1. **Create** – The sensors are deployed in the physical world and continually updating data is measured to be used as input for its analysis. The measurement collected by the sensors is broadly classified into two groups: operational measurements and environmental data.
2. **Communicate** – The bidirectional integration/connectivity between the physical world and digital world in real-time through Network communication.
3. **Aggregate** – The support for data ingestion into a data repository or database, which are processed and prepared for analytics.
4. **Analyze** – Data is analyzed and visualized using advanced analytics technologies to create insights to inform decision-making.
5. **Insight** – Insights generated from analytics are visualized using dashboards and highlighting focus areas in the performance to verify.
6. **Act** – The feedback actions from the insights sent back to the physical world. This step completes the loop connection between the physical world and the digital world.

It is also recommended that this DT conceptual architecture should be designed flexibly and have the ability to be scaled to allow its evolution as the available technology continuously evolves (Parrott and Warshaw, 2017). The flexibility of DTs allows for the creation of different maturity types Table 1,

defined by five levels of sophistication requiring a greater degree of maturity and digital transformation and offering increased value (Autodesk, no date).

Table 1 – Digital Twins Maturity Levels

Levels	Description
Level 1: Descriptive twin	The descriptive twin is a visual replica with live, editable design and construction data, including 3D models and BIM.
Level 2: Informative twin	The informative twin uses increased integration with sensors and operations data for insights at any given time.
Level 3: Predictive twin	The predictive twin captures real-time data, contextual data, and analytics to identify potential issues.
Level 4: Comprehensive twin	The comprehensive twin leverages advanced modeling and simulation for potential future scenarios as well as prescriptive analytics and recommendations.
Level 5: Autonomous twin	The autonomous twin can learn and make decisions through Artificial Intelligence (AI) while using advanced algorithms for simulation and 3D visualization.

2.2.3. The Gemini Principle

Digital technologies can enhance the quality of our lives and help make better-informed decisions to achieve cost savings and improved performance in the built environment through effective information management (Rogers and Kirwan, 2019). The importance of DT in the creation of a unified ecosystem, using connected sharing data to achieve even greater value, was identified by the Centre for Digital Built Britain (CDBB), leading to the creation of guiding values to aid in the development of a National Digital twin (NDT) and information management framework across the built environment.

To achieve an aligned national resource for improving the performance, quality of service, and value delivered by assets across the built environment, a set of guiding principles for the framework needs to be followed to create the NDT to make it purposeful, trustworthy, and functional. These principles are the Gemini Principles, as the first deliverable from the Digital Framework Task Group (DFTG) (Bolton A, Enzer M, 2018).

The Gemini Principles have three key statements: Purpose, Trust, and Function. Purpose.

Purpose - must provide benefit to the general public, enabling improvement in performance while creating value, and must provide real insight into the built environment.

Trust - must enable security and be secure in itself, it must be as open and transparent as and be built using the appropriate quality of data.

Function - must be based on a standard connected environment, there must be clear ownership of the digital asset, as well as clear governance and regulation, and be adaptable as the available technology continuously evolves.

Table 2 – The Gemini Principles

Key Statements	Principles		
Purpose: Must have a clear purpose	Public good	Value creation	Insight
Trust: Must be trustworthy	Security	Openness	Quality
Function: Must function effectively	Federation	Curation	Evolution

2.2.4. The Ecosystem of Digital Twins

The implementation of digital technologies is widely seen in industries like automotive, aerospace/aeronautics, manufacturing, but still, rare tangible examples are implemented in the built industry (buildingSMART *et al.*, 2020). This gap was identified by the Digital Twins Working Group of buildingSMART International to explore ways to maximize the full potential of economic, social, environmental, and business value through the use of digital technologies in the built industry spanning through all the phases of the Plan-Build-Operate- Integrate (PBO-I) lifecycle

The information management in the built industry is still fragmented and lack of interoperability is still a key constraint (Bolton A, Enzer M, 2018) and the buildingSMART International (bSI) believes that the concept of DT can be achieved through alignment with common open digital solutions and standards such as ISO 55000:2014 for asset management and the expected benefits from adopting asset management to enable a better decision-making process (buildingSMART *et al.*, 2020).

The DT can be created in parallel to its physical twin or as an as-built replica after the physical version already exists and be digitized during the operation phase of the PBO-I lifecycle. While the creation of a DT per physical asset is valuable, the integration of multiple DT from several physical assets would yield even higher value and create an ecosystem of digital twins on a broader scale. The PBO-I lifecycle particularly focuses on this broader network which is an overall connected system (buildingSMART *et al.*, 2020).



Figure 9 – PBO-I lifecycle

(Source: buildingSMART, *et al.*, 2020)

Creating the DT and this ecosystem requires gathering and integrating of data, buildingSMART International (bSI) has identified three focus areas that are closely related to standardization to bridge the gap and enable interoperability:

Standards for data models – Standards to create interoperable systems data between different layers of data model ranging from geospatial information for urban planning to digital engineering models for construction, or even operational data models for asset performance.

Standards for data management and integration – Standards that allow the integration of data between two related fields together such as data science and information management, with a focus on semantic precision on a common basis while retaining its true meaning.

Data security and privacy – Standards to define data security and privacy requirements such as hosting of data, data ownership to allow data flow effortlessly between projects, lifecycle phases, levels of scale, and tools.

The concept of a digital ecosystem, particularly when focused on the “Digital Twins of the Earth” will also help address global change challenges, facilitate the European Green mission, and contribute to realizing the goals of the UN Sustainable Development Goals (SDG) for decision-makers (Nativi, Mazzetti and Craglia, 2021).

The continuous expansion of the DT markets indicates the demand for digital twins will continue to escalate for some time. In 2020, the digital twin market was valued at USD 3.1 billion with some industry analysts speculating it could continue to rise sharply until at least 2026, reaching an estimated USD 48.2 billion (IBM, no date b).

2.3. FROM BIM TO DIGITAL TWIN FOR INDOOR ENVIRONMENT MONITORING

2.3.1. BIM to IoT (BIM-IoT) Integration

The integration of BIM with digital technologies such as the Internet of Things (IoT) in the built environment is still in its early stages but offers a lot of potentials and can be helpful for in-time decision-making. Previous research reviewing several related articles on BIM to IoT (BIM-IoT) integration summarized the research domains based on their specific implementations in building projects. The domains include Construction Process Monitoring; Energy Performance Management; Indoor Environment Monitoring; Indoor Thermal Comfort; Space Management; Hazards Monitoring; and Community Monitoring (Editors *et al.*, 2021), Construction Operation and Monitoring, Health & Safety Management, Construction Logistics & Management, and Facility Management (Tang *et al.*, 2019).

The common methods for IAQ monitoring include continuous or real-time indoor air quality monitoring which is the process of gathering IAQ data 24 hours per day, 7 days per week, by using IAQ sensors that collect minute-by-minute readings of your indoor air; and Indoor air quality testing which is a one-off occurrence where a professional typically uses a handheld probe, getting a snapshot of the air quality at a single point in time (Harry Watson, 2021).

For this study, the domains focused on Indoor Environment Monitoring; Indoor Thermal Comfort; for Facility Management. BIM-IoT integration takes advantage of the geometric and parametric properties of BIM models and the real-time streaming of environmental data (temperature, humidity, etc.) collected by IoT sensors to create a Digital Twin for visualization monitoring data in real-time.

2.3.1.1. BIM-IoT Integration - Workflow

Based on the literature review found on the topic of BIM-IoT integration for visualizing monitoring data. Figure 10 summarizes the workflow commonly used starting from deploying and collecting the sensor data from the physical building and stored in a database, to mapping this data to elements in the BIM model, to visualizing this data within the BIM model as color fills or text, and analyzing or utilizing the data.







Figure 10 – BIM-IoT Workflow

The Data Acquisition processes differed as sensor data retrieved from the devices were linked/stored in different databases such as Microsoft Excel, Google sheets, InfluxDB, MongoDB, etc. These databases were then integrated into the BIM model for visualization. The Data Integration and Data Visualization were more similar across and the data analysis differed as the researchers mostly had different goals.

From the various workflows and software identified in the literature reviews, Table 1 presents the software used, and Figure 11 and Figure 12 summarizes the processes/steps followed focusing on Data Integration and Data Visualization processes.

Table 3 – Softwares

Software	Description	Reference
 Revit	BIM authoring tool	(Autodesk, 2021e)
 Dynamo	Visual Programming Tool	(Dynamo, 2021)
 Navisworks	3D Model Review Tool	(Autodesk, 2021c)
 Microsoft Visual Studio	Integrated Development Environment (IDE)	(Microsoft, 2021)

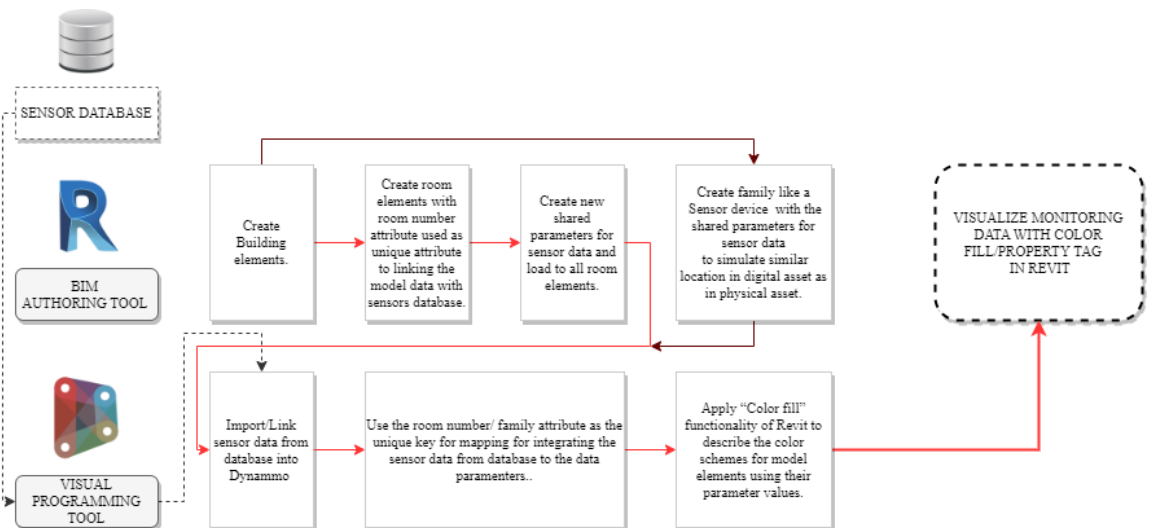


Figure 11 – Sensor Database – Dynamo – Revit workflow

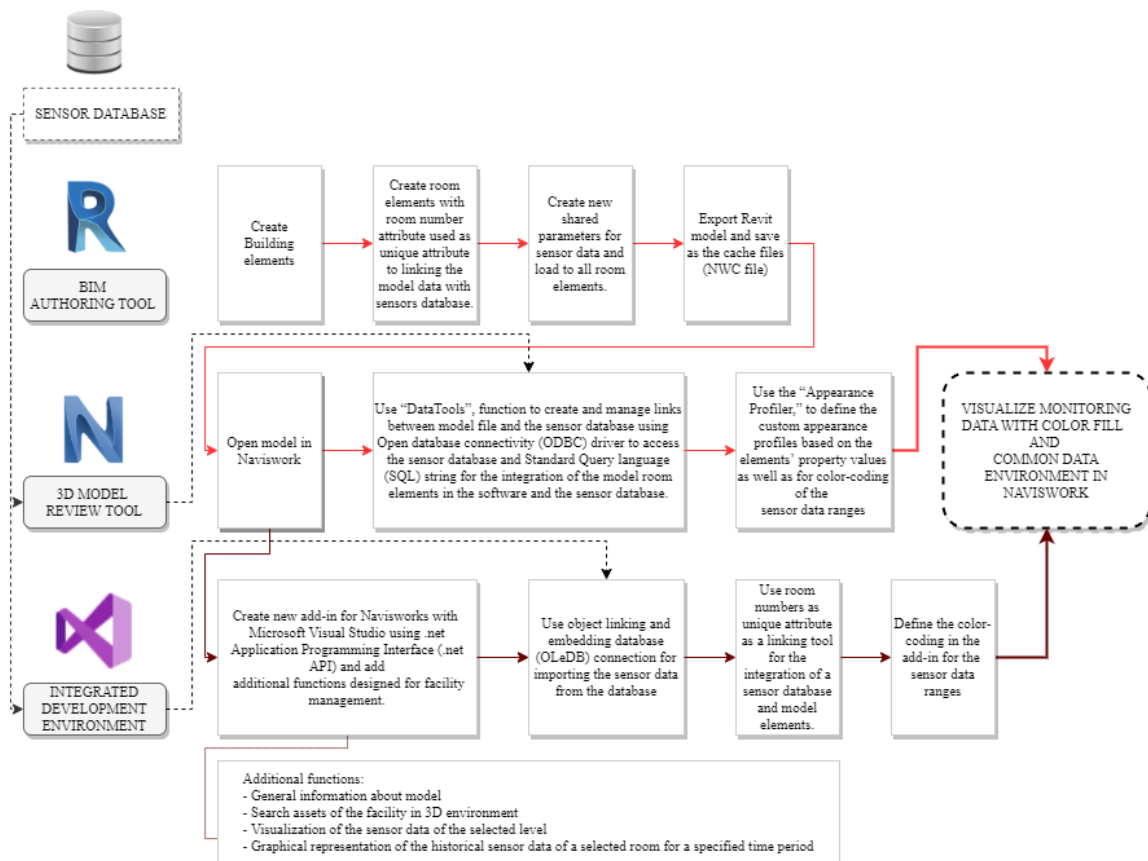


Figure 12 – Sensor Database – Revit – Navisworks - API workflow

1. **Figure 11** - The integration of the sensor data to be visualized in the BIM model was integrated through Dynamo into Revit mapping to different elements/unique keys with shared parameters similar to the parameters in the database for linking the data. This data was visualized within Revit in different forms. For instance, (Chang, Dzung and Wu, 2018), (Kazado, Kavagic and Eskicioglu, 2019), (Penna *et al.*, 2019) integrated the data using properties of the rooms, while (Malheiro *et al.*, 2020) used a sensor device family. Visualization of this data was done using color fills in the rooms, except for the last two authors who used room tags/familiar tags respectively to show the data.
2. **Figure 12** – This presents two different approaches using the functions of Autodesk Navisworks Manage software such as visualization, database connectivity, and appearance profiler. The first approach integrates the data directly in Navisworks while the second approach uses Visual Studio.Net platform and software development kits (SDK) for the development of a new add-in that is compatible with a BIM software solution. Both approaches used a Revit model exported and imported into Navisworks. The mapping of the data from the database is linked to room properties and the visualization is done using color fill in the rooms. The second approach, adds and visualizes an additional Information interface about the facility. (Kazado, Kavagic and Eskicioglu, 2019).

2.3.1.2. BIM-IoT Integration - Limitations

The integration of sensors with the Revit model Figure 11, is an easier approach but with several limitations such as enables accidental model changes, does not allow viewing of the historical data, and does not allow a search of the building assets. The first approach of integration of sensors in Naviswork Figure 12, addresses the limitation of accidental model changes but it also does not allow viewing of the historical data or searching for individual building assets. However, to address limitations associated with Figure 11 and Figure 12 first approach, using the open-source add-in enabled real-time display of the sensor data, viewing of historical data over the specified period, and search of the individual assets within the building. In addition, Naviswork can be used to visualize large models and even models created by other BIM software vendors such as ArchiCAD, GRAPHISOFT, Nemetschek Allplan, AECOsim, and Rhino (Kazado, Kavgic and Eskicioglu, 2019).

2.3.1.3. BIM-IoT Integration – Possible solutions

However, a facility manager as an end-user, that needs the model only to visualize and utilize the data, who may not be familiar with BIM authoring tools or need all its other functionality, not to mention the high licensing cost that comes with owning these tools. There is a gap in the BIM-IoT integration through open standards and systems (Dave *et al.*, 2018), therefore using a non-proprietary file format or model or alternative solutions that do not rely heavily on proprietary file formats could address some of these issues.

The interoperability issues through open standards can be addressed by adhering to the openBIM process defined by (buildingSMART International, 2021). openBIM is a collaborative process that permits digital workflows based on vendor-neutral formats such as IFC, BCF, COBie, CityGML, gbXML, etc. It extends the benefits of BIM by improving the accessibility, usability, management, and sustainability of digital data in the built asset industry and facilitates interoperability to benefit projects and assets throughout their lifecycle. OpenBIM has principles that recognize that: Interoperability is key to the digital transformation in the built asset industry; Open and neutral standards should be developed to facilitate interoperability; Reliable data exchanges depend on independent quality benchmarks; Collaboration workflows are enhanced by open and agile data formats; Flexibility of choice of technology creates more value to all stakeholders, and Sustainability is safeguarded by long-term interoperable data standards. Therefore, openBIM enables an accessible digital twin which provides the core foundation to a long-term data strategy for built assets.

(Pasini *et al.*, 2016; Ciribini *et al.*, 2017), developed a framework Figure 13 using an interoperable BIM environment based on the neutral data format of Industry Foundation Class (IFC). To exchange data between the Building Management System (BMS) and the BIM, taking advantage of a wide set of definitions of classes in IFC that represent almost every object that can be found in a building, a BMS-IFC converter was developed written in python to access the data in the BIM model and BMS through its web services and outputs the IFC format.

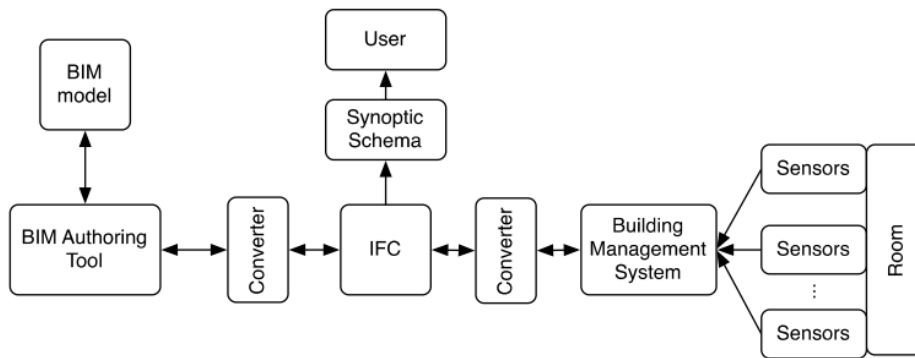


Figure 13 – BIM-IoT integration through IFC framework

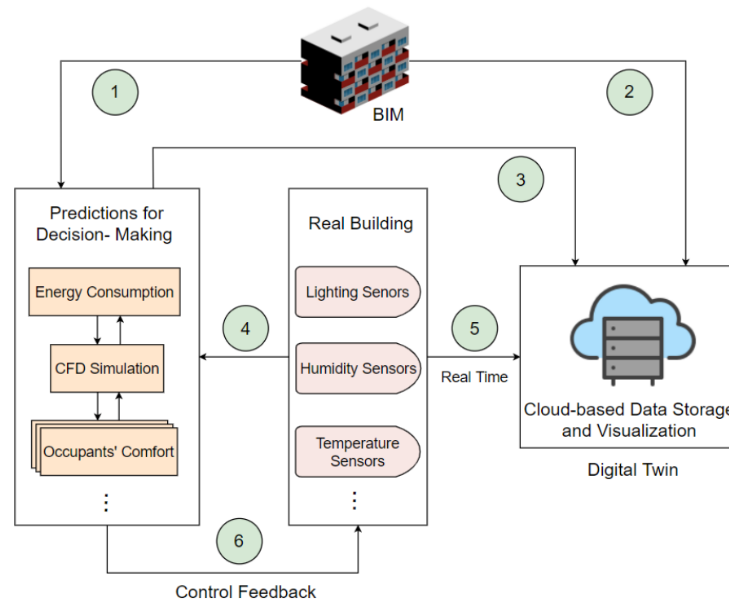
(Source: Pasini *et al.*, 2016)

In another study done by Dave *et al.*, (2018), A campus-wide, web-based system platform called Otaniemi3D was developed to integrate the built environment data with IoT sensors and ensure that open standards are used in the deployment and integration of both IoT and BIM standards. The platform integrates Building Information using IFC with wireless sensor nodes through standardized Open APIs which are the Open Messaging Interface (O-MI) and the Open Data Format (O-DF). Otaniemi3D system architecture is made up of three main components: IoT devices used to measure and collect sensor data; Backend Server, the layer that deals with the interpretation of the built environment data through standard formats such as IFC either through directly stored local data or through data stored in servers and accessed through APIs; and the Front end(s), the interface for users interaction that consumes data from the backend, transforming into a human-friendly form and can be implemented as websites, WebApps or smartphone apps.

2.3.2. Cloud-based Digital Twin

Learning from the limitations and possible solutions of the BIM-IoT integration, which highlighted the need to identify a technological solution to integrate a BIM model viewer window inside the web application UI. The proposed platform should be cloud-based and be capable of integrating models from open non-proprietary file formats such as IFC, gbXML, glTF as well as other industry proprietary file formats. Since the Facility Manager is the proposed end-user who is not a model author but needs an updated 3D model of the building to visualize information based on the data sensors.

Editors *et al.*, (2021) proposed an example of the expected ideal Digital Twin as a cloud-based data storage and visualization for building indoor environment management Figure 14. Where the indoor environmental data should be collected adequately without any time delay through IoT techniques such as Wireless Sensor Networks (WSN) and the sensor data should be used to predict the real-time indoor environment or the occupant's comfort as the basis for decision making in the building management process. Therefore, by using BIM models, real-time visualization of the ongoing status of the indoor environment can be shown, which could provide a better insight of the building status to the managers, thus significantly improving the efficiency of the building system control, facility management, and maintenance.



- ① BIM model for supporting simulations and predictions
- ② BIM model visualization on cloud
- ③ Visualization of simulation/prediction results on cloud
- ④ Real-time indoor sensing data to support simulations and predictions
- ⑤ Real-time sensing data visualization on cloud
- ⑥ Simulation/prediction results feedback to support automatic building system control

Figure 14 – Example of the ideal Digital Twin for a single building indoor environment

(Source: Editors *et al.*, 2021)

Cloud-based solutions cover a huge part of the digital space. According to Cisco, IoT connections were estimated to reach 13.7 billion in 2021, up from 5.8 billion in 2016 and the cloud will host over 94% of workload and computing processes (Cisco, 2018). Cloud services are infrastructure, platforms, or software that are hosted by third-party providers and made available to users through the internet. These cloud solutions are categorized into three primary models with different levels of control, flexibility, and management of as-a-Service solutions: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). They are sometimes referred to as the cloud computing stack because they build on top of one another (Microsoft Azure, no date).

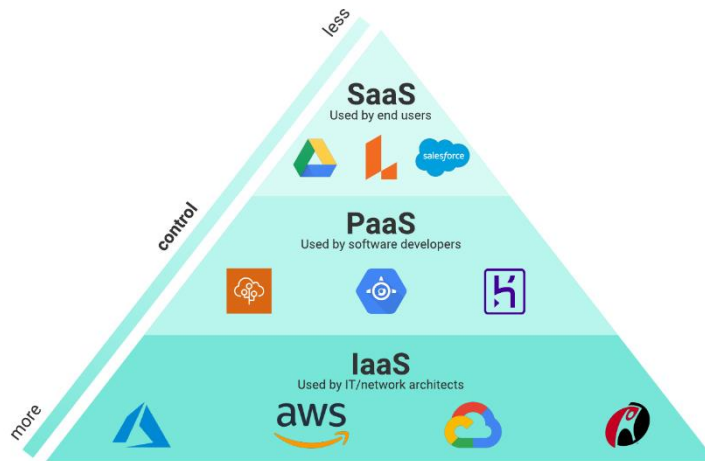


Figure 15 – Cloud service models

Source: (Lucid, no date)

IaaS – used by IT/network architects for Internet-based access to storage and computing power. IaaS lets you rent IT infrastructure - servers and virtual machines, storage, networks, and operating systems - from a cloud provider on a pay-as-you-go basis. IaaS provider examples include Microsoft Azure, Amazon Web Services (AWS), Google Compute Engine, Rackspace.

PaaS – used by software developers to build and host web applications. PaaS is designed to give users access to the components they require to quickly develop and operate web or mobile applications over the Internet, without worrying about setting up or managing the underlying infrastructure of servers, storage, networks, and databases. PaaS provider examples include Heroku, Forge, AWS Elastic Beanstalk, Microsoft Azure App Services, Salesforce, Google App Engine, Apache Stratos.

SaaS – used by end-users for web-based applications. SaaS is a method for delivering software applications over the Internet where cloud providers host and manage the software applications making it easier to have the same application on all of your devices at once by accessing it in the cloud. SaaS provider examples include Google Apps, Slack, Microsoft Office 365.

To create a cloud-based DT for visualizing monitoring data, it is essential to choose a model that would enable developing a web application that can be easily used and accessible over the internet. The PaaS cloud service model is currently the most popular especially among developers as it offers a flexible platform for developers to build unique, and customizable software or applications without the need to start from scratch or taking on all the responsibility, saving a lot of time and cost-effective. Some advantages of PaaS platforms are that they are accessible by multiple users, scalable, flexible, and easy to run without extensive administration knowledge.

2.3.2.1. Cloud-based Digital Twin Platform for BIM visualization

This research aimed to identify a digital platform that would enable the development of a web application to integrate a BIM model and IoT sensor data for visualization. An example of such a platform is Autodesk Forge. Forge is Autodesk's cloud-based development PaaS. It is a set of web service application program interfaces (APIs) that allow you to integrate Autodesk SaaS products (such as Fusion Team, BIM 360 Docs, etc.) to build innovative, cloud-powered applications that connect construction workflows with visualization, engineering, and design. It is based on web standards such as RESTful APIs, HTML 5, CSS, and JavaScript.

In addition to being a collection of APIs, Forge is an ecosystem that operates in a common data environment and leverages Autodesk industry expertise, technology, and a global network, enabling companies to get started quickly and focus on developing customized and scalable solutions to solve design, engineering, and manufacturing challenges.

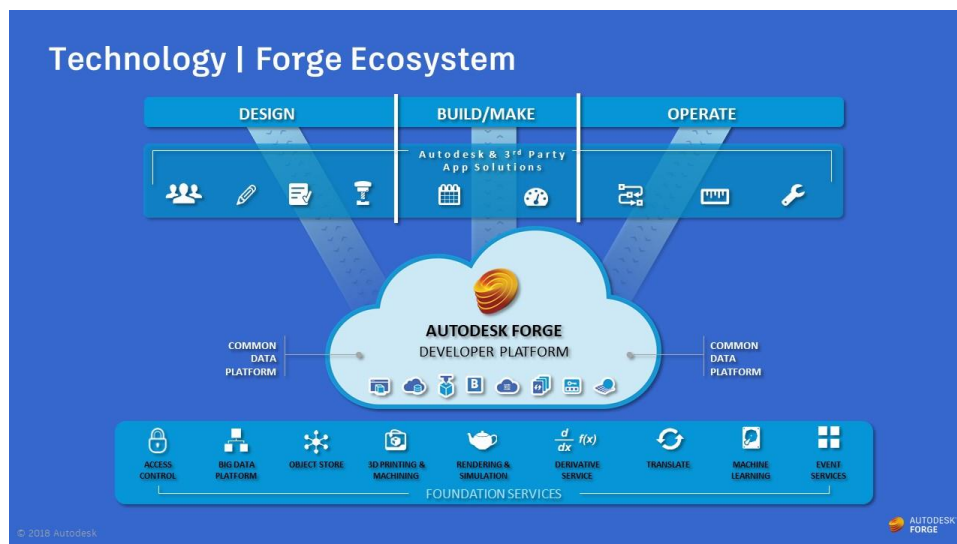


Figure 16 – Autodesk Forge ecosystem

Source: (Forge, 2019)

The potential of using Forge web services to develop a Digital Twin for advanced IoT visualization is implemented in a proprietary beta ongoing project named Project Dasher 360. Project Dasher is an Autodesk research project using a BIM-based platform to provide building owners with greater insight into real-time building performance throughout the life cycle of the building. It integrates sensor data with model data from Autodesk's Forge platform to contextualize IoT data in 3D.

Figure 17 shows the UI of Dasher 360 as a building performance management tool that displays historical and real-time sensor data inside a building model as a timeline component at the bottom of the screen. It also has other clickable buttons to display the sensors, sensor list, dashboard with the sensor data, and other model viewer tools to explore the properties of the BIM in the viewer.

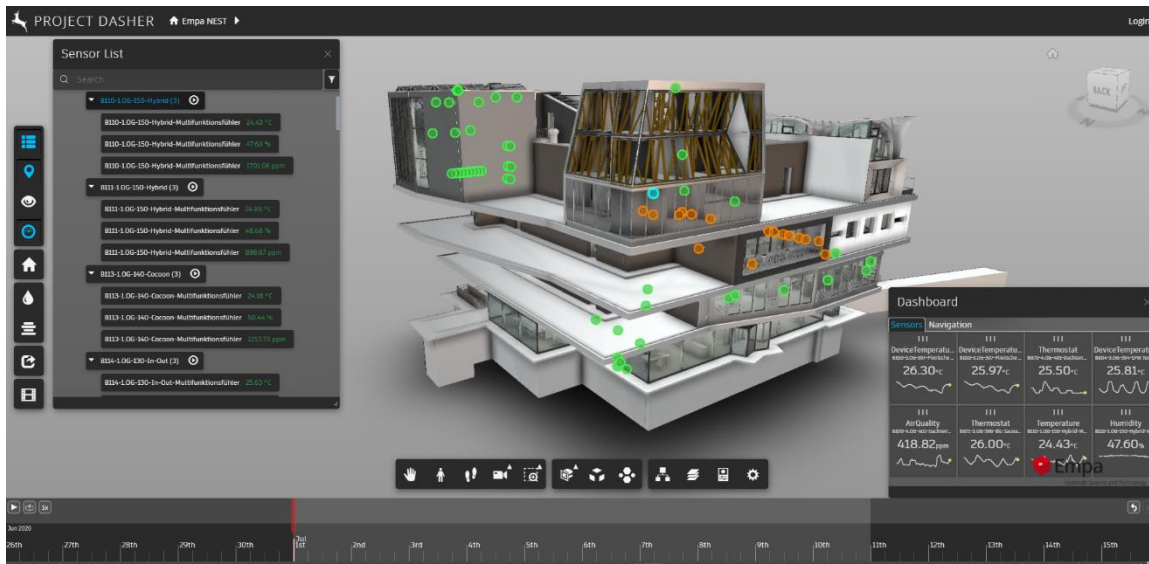


Figure 17 – Project Dasher 360 UI

Source: (Dasher360, 2021)

Today, several companies have adopted Forge for developing Digital Twin for visualization, facility management, and all other purposes, some case studies include:

Moicon - uses the Forge platform to build digital twin solutions for customers, collecting and organizing their valuable facility data and combining it with sensor data in a visual, intuitive, and automated manner. Their easy-to-use, predictive software systems for end customers reduce costs, labor, and unplanned downtime (Moicon, 2021).

FaciliCAD - uses the Forge platform to build a computer-aided facilities management (CAFM) software package that offers two complete CAFM software solutions: faciliCAD Desktop and faciliCAD Web, that play role in Facility Management. Now, with faciliCAD Web, non-CAD users, facility and office managers, IT, human resources, accounting, and more can collaborate in real-time on any device (faciliCAD, 2021).

VINCI Facilities - uses the Forge platform to build TwinOps, a facility management software system based on BIM that delivers actionable insights into building operations that help building owners in Europe and Morocco manage their facilities more efficiently and provide managers with an operational dashboard for buildings (TwinOps, 2021).

Another platform by Autodesk is the Autodesk Tandem (originally known as Constructwin) recently released and now made commercially available on July 12, 2021, as a cloud-based Digital Twin technology platform that enables projects to start digital and stay digital, transforming rich data into business intelligence. By harnessing BIM data throughout the process, AEC firms can create and hand over a digital twin to building owners and operators (Tandem, 2021). Although it is relatively new in the market, it shows a lot of potentials for the built asset lifecycle management and could be worth exploring in future research.

3. METHODS

This chapter addresses the strategic methodology for developing a cloud-based digital twin that integrates the indoor environment data collected by multiple sensors systems with a BIM-based model. The integration allows to automatically combine the monitored data with the related geometrical space in the BIM model.

This research is presented in two phases. The first phase introduces the use case which describes the case study building, the selected domains for implementing the proposed framework, and the DT visualization platform with a basic step-by-step process on getting started. The second phase is the actual implementation of the framework of BIM to DT for visualizing monitoring data on the case study.

Following the workflow summarized from literature reviews on the topic of BIM-IoT integration for visualizing monitoring data (Figure 10), Figure 18 shows the implementation workflow schema made up of four main layers starting from the physical asset to the digital asset, briefly described below:

DATA ACQUISITION – Layer one, which are inputs comprising of the BIM model of the existing school building using Autodesk Revit 2020 used as the BIM authoring tool, and the collection of indoor environment data from IoT sensor readings (such as temperature, humidity, co2, tvoc, and illumination) retrieved from the existing school building stored in the InfluxDB database and graphically visualized in Grafana.

DATA INTEGRATION – Layer two, which is the process of matching properties of the sensor data parameters with the sensor device family parameters in Revit, and then mapping the sensor data from the database to the sensor family device from Revit in a cloud-based integrated model in Autodesk Forge.

DATA VISUALIZATION – Layer three, which are outputs that combine the BIM model and sensor data, visualized in Autodesk Forge using heatmaps and other UI components. This is where the user interacts with the application.

DATA ANALYSIS – Layer four, which adds a decision-making dashboard of environment data thresholds and indoor thermal comfort from green building benchmark standards and uses the data inputs provided to simulate and visualize the thermal comfort level (PMV).

The end-user of this visualization dashboard which is the energy manager can identify the visual thermal comfort level for decision making in real-time. However, this visualization dashboard can be used and understood by anyone with a less technical background because it allows users to interpret the indicated values simply since they are represented by colors different from the usual way to present data in dashboards such as bar graphs, tables, and graphs. It is simpler for a layperson to interpret data through color than a large volume of numbers.

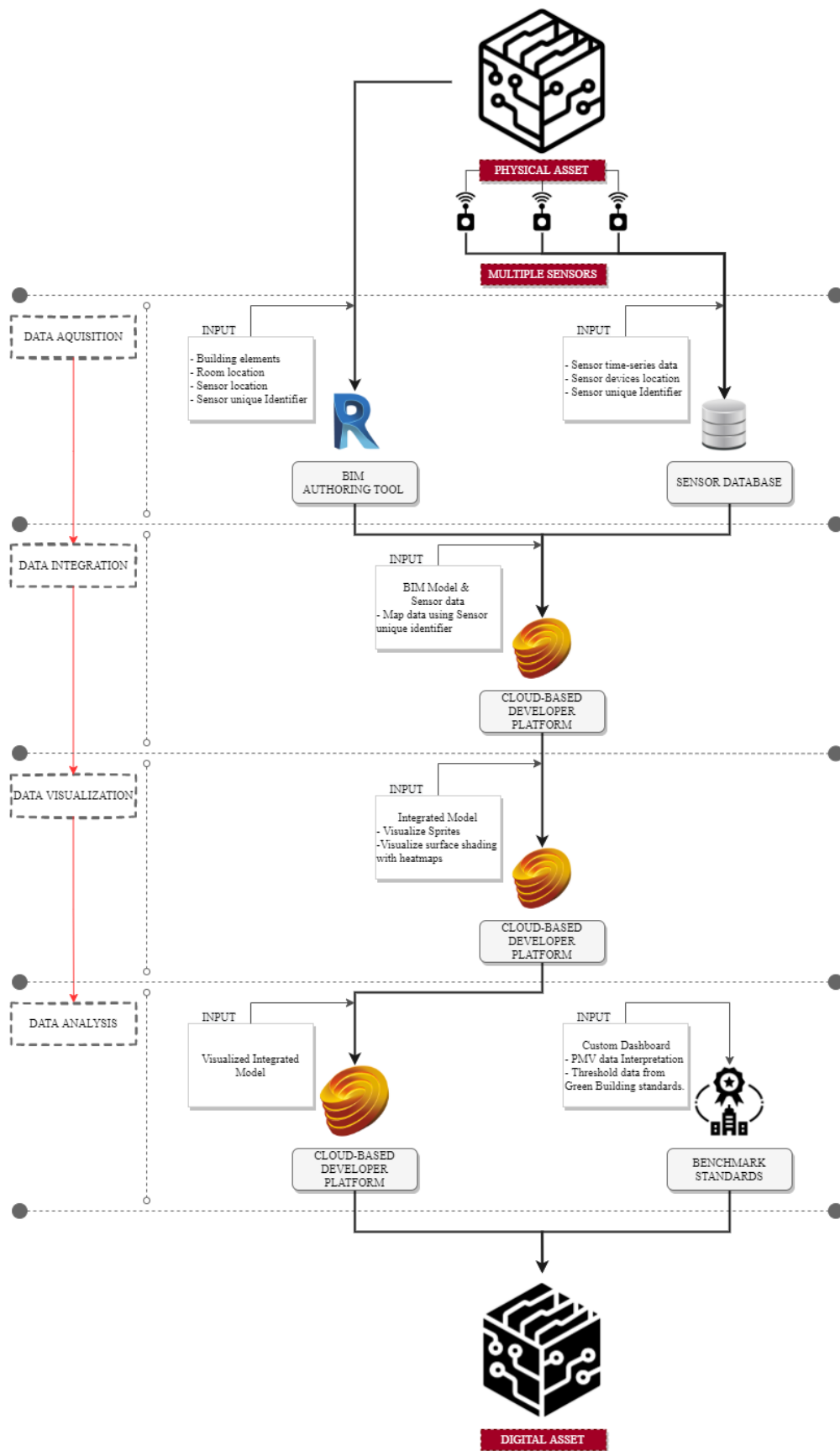


Figure 18 – BIM-DT framework process of implementation

4. USE CASE

This chapter describes the case study project, the IoT sensor parameters, the type of environmental data collected, the IoT devices installed, and the platform used for the BIM-IoT integration. The developed methodology for integrating the monitoring data with BIM was tested and validated on a real case study of an existing school building.

4.1. DESCRIPTION OF THE USE CASE

The project adopted for this case study is based on an existing school building, located in the South Tyrol province of Northern Italy. The building has a total area of approx. 1,450 m² comprising of two floors with a vast number of spaces used for different functions. The BIM model was developed using Autodesk Revit 2020. Figure 19 shows the general view of the 3D model in Revit. Furthermore, the present dissertation took advantage of an Architectural BIM model, which was provided by the SINCRO team of Fraunhofer.

For this study, there were two types of implementation domains: Indoor Environment Quality and Indoor Thermal Comfort.



Figure 19 – School Building 3D model in Revit

4.1.1. Indoor Environment

Indoor environmental quality (IEQ) refers to the quality of a building's environment relating to the health and wellbeing of those who occupy space within it and it is determined by many factors such as the air quality, lighting, and damp conditions (CDC, no date). Therefore, to monitor the indoor environment quality within the school building, IEQ parameters were measured such as temperature, humidity, CO₂ concentration, total volatile organic compound concentration (TVOC), and illumination.

4.1.2. Indoor Thermal Comfort

As cited in (Guenther, 2021), according to ASHRAE-55, Thermal comfort is defined as “that condition of mind that expresses satisfaction with the thermal environment”. Therefore, to assess this condition, these comfort limits can be expressed by the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indices Figure 20.

Indoor thermal comfort is generally assessed using the PMV or the adaptive model. However, the most widely used thermal model for indoor environments is the PMV model created by Povl Ole Fanger which aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale and has been adopted by many international standards, such as ISO 7730, ASHRAE 55, (Zahid, Elmansoury and Yaagoubi, 2021). To predict PMV, the level of satisfaction of the occupants in a space needs to be considered. PPD essentially gives the percentage of people predicted to experience local discomfort (Guenther, 2021). Within the PMV index, +3 translates to hot, while -3 translates to cold. The comfortable range for PMV is between -0.5 and 0.5, and a corresponding PPD below 10%.

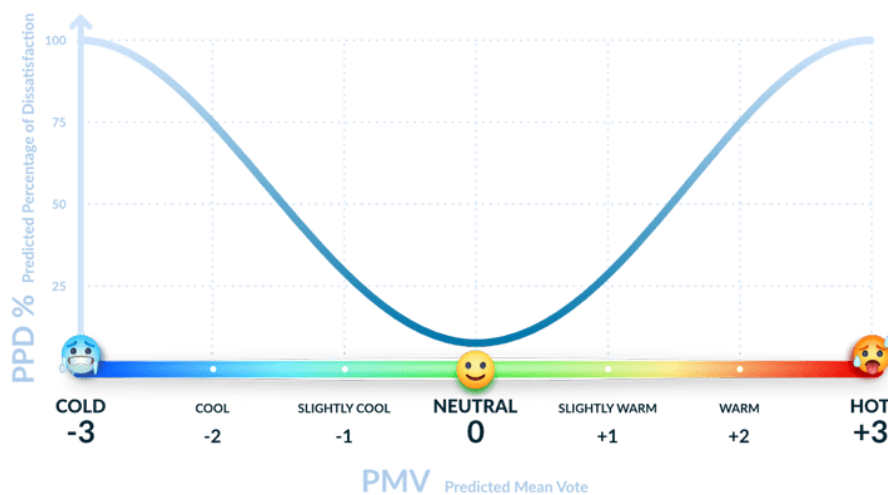






Figure 20 – PMV and PPD indices

Source: (Guenther, 2021)

This study used the PMV model to assess indoor thermal comfort. Previous studies (Chang, Dzeng and Wu, 2018; Zahid, Elmansoury and Yaagoubi, 2021) conducted PMV analyses on the sensor data collected using Python programming language or other simulation methods.

Multiple sensor devices were deployed in indoor spaces of the school building to perform environmental data collection. In total, there were seven sensor types used and placed at different instances in the building. The sensor data collected were grouped into four categories: Indoor Air Quality (IAQ), Illumination, Occupancy, and Consumption, and an additional category called Comfort calculated to analyze the PMV and PPD data from all sensor devices. For this study, the sensor data visualized focused on three of the categories; IAQ, Illumination, and Comfort comprised of four sensor types and twenty-four instances in the building. Table 4 describes the different sensor devices, the category, sensor data parameters, unit of measurement, and the number of instances in the building.

Table 4 – Indoor environment sensor devices

Sensor Type	Category	Sensor Data	Unit of measure	No. instances
URSALINK AM102 	IAQ	Temperature	°C	10
		Humidity	%H	
		CO2	ppm	
		tvoc	ppb	
Illumination	illumination	lux		
	Comfort	PMV	-	
ELSYS ERS-CO2 	IAQ	Temperature	°C	7
		Humidity	%H	
		CO2	ppm	
		tvoc	ppb	
Illumination	illumination	lux		
	Comfort	PMV	-	
ELSYS ERS-EYE 	IAQ	Temperature	°C	4
		Humidity	%H	
Illumination	illumination	lux		
	ELSYS ERS-LITE 	IAQ	Temperature	°C
Humidity			%H	
Total No. of sensor instances visualized				24

4.2. DT VISUALIZATION PLATFORM

The subsection introduces the cloud-based platform to be used to create the DT for visualization which is the Autodesk Forge, its application frameworks, and functionalities.

4.2.1. Autodesk Forge

Forge is Autodesk's cloud-based development PaaS. It is a set of web service application program interfaces (APIs) that allow you to integrate Autodesk SaaS products (such as Fusion Team, BIM 360 Docs, etc.) to build innovative, cloud-powered applications that connect construction workflows with visualization, engineering, and design. It is based on web standards such as RESTful APIs, HTML 5, CSS, and JavaScript (Autodesk, 2021a).

Just as humans use a computer program through a User Interface (UI). Similarly, computer programs communicate to other computer programs through an Application Program Interface (API). The Forge Platform offers APIs and services that help you access and use your design and engineering data via the cloud. From automated processes to alerts. 3D in-browser to virtual reality. Forge APIs can be combined with existing software systems to innovate how you work and get more from your data (Autodesk, 2021b).

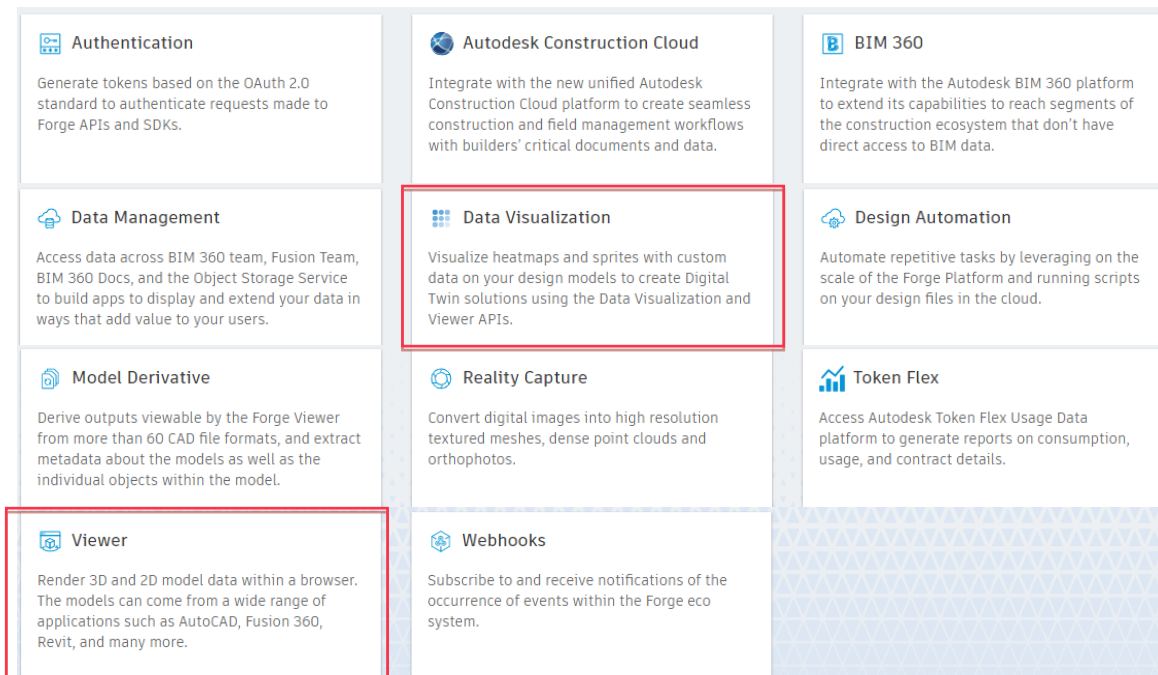


Figure 21 – Autodesk Forge APIs

Source: (Autodesk, 2021b)

For this study, the APIs focused on was Data Visualization to visualize heatmaps and sprites with custom data on your design models to create Digital Twin solutions using the Data Visualization and Viewer APIs to render 3D and 2D model data within a browser. The models can come from a wide range of over 60 different types of non-proprietary and proprietary file formats (IFC, gbXML, 3DS, DWG, NWC, RVT, and many more.) into derivatives (output files).

4.2.1.1. Data Visualization API

A new Data Visualization extension called Hyperion Reference App using the Data Visualization API was recently released on May 3, 2021, as an IoT toolkit to integrate sensor data from any preferred database service (Azure, AWS, others) into BIM models (Autodesk, 2021d). This toolkit lets you easily create a Digital Twin using the Forge Viewer with features ranging from adding sensors into the model to allow for equipment maintenance status, to adding heatmap shaders on objects that help visualize temperature, CO2, or people movements. By leveraging these components Figure 22, heatmap and sensor data are easy to incorporate into your Digital Twin solution.

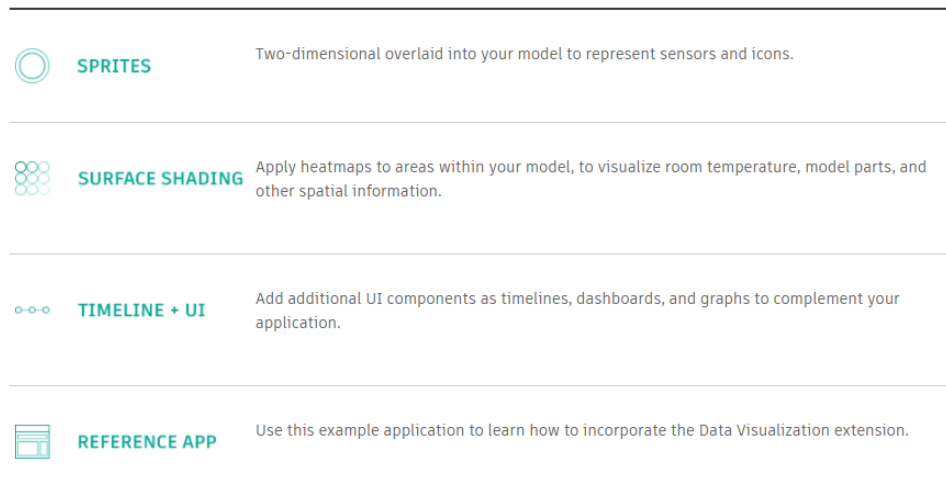
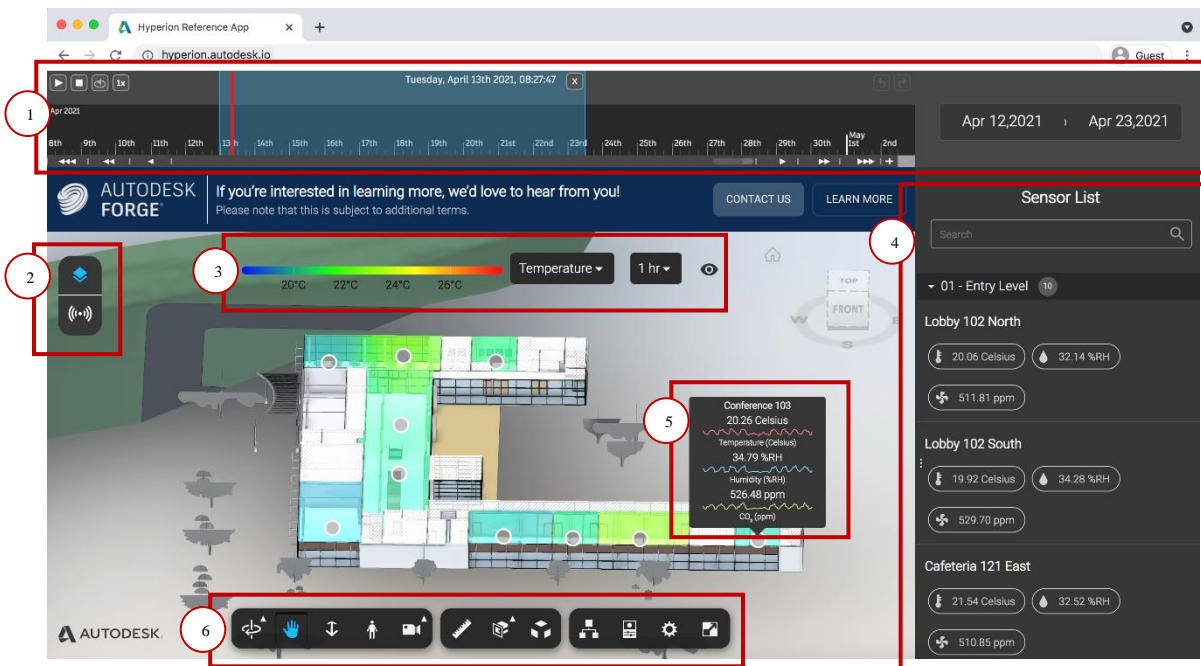


Figure 22 – Data Visualization Extension Components

Source: (Data visualization, 2021)

Figure 23 shows the sample Hyperion Reference Application (Hyperion Reference App, 2021). The project is made up of two NPM modules (React.js client code or front-end as the User Interface (UI) framework, which is everything the user sees and interacts with, and Node.js server code or back-end which enables the interface to work) and a Reference-Application that demonstrates how they work together.



- 1 - Chronos TimeSlider
- 2 - Layers, Sensor and Heatmap types selector
- 3 - Sensor parameter and interval selector
- 4 - Sensor list
- 5 - Sensor data
- 6 - Viewer extension tools bar

Figure 23 – Hyperion Reference Application

Source: (Hyperion Reference App, 2021)

To get started, it is necessary to create a Forge account, install Node.js – version 12 or higher – including NPM and it is recommended to have some knowledge of using the Forge Viewer API. A developer’s guide/documentation is provided on the Forge website to leverage the Data Visualization extensions to integrate IoT data with a BIM model and the Forge viewer API.

4.2.1.2. Viewer API

Before starting with the Data Visualization, it was necessary to explore the Viewer to have a base knowledge of how the Forge platform works and the possibility to finally deploy the DT Visualization app on the web that can be easily accessible.

The Forge viewer API is a WebGL-based JavaScript library that allows rendering/viewing high-performance interactive 3D and 2D model data directly within any compatible web browser (Viewer API, 2021). It makes it possible to interact with and retrieve metadata about design files in over 60 formats right in your browser, without having to install extra software (Model derivative API, 2021). The tutorial steps on the developer’s guide (Learn Forge, 2021) were followed to set up and activate the Forge account, install development tools needed to create a web app, setup OAuth an open

standard used across the Forge Platform for token-based authentication, and authorization, upload & show 3D models on the web which can be done by uploading & translating model directly from the local storage or granting access to show model from BIM 360 & Fusion, adding viewer extension buttons and panels, and lastly deployment, this is when the app finally goes live.

The languages available on the viewer API to choose from are Node.js, .NET Framework, .NET Core, Go, PHP and Java. For this project, Node.js was the selected language and Visual Studio code was used as the IDE.

1. Create a Forge account

The use of Autodesk Forge requires the payment of a cloud credit subscription. You can start with 90 days free trial and get Free access to all Forge APIs, 100 Cloud Credits, and 5 GB storage.

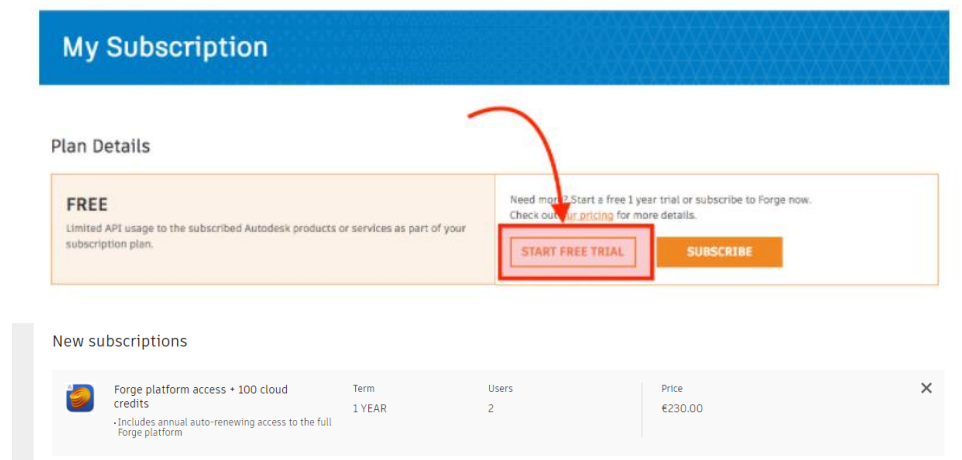


Figure 24 – Forge Subscription

2. Create an App

Select APIs to be used. Client ID and Client Secret are generated on the newly created app page. These are needed in all other OAuth flows.

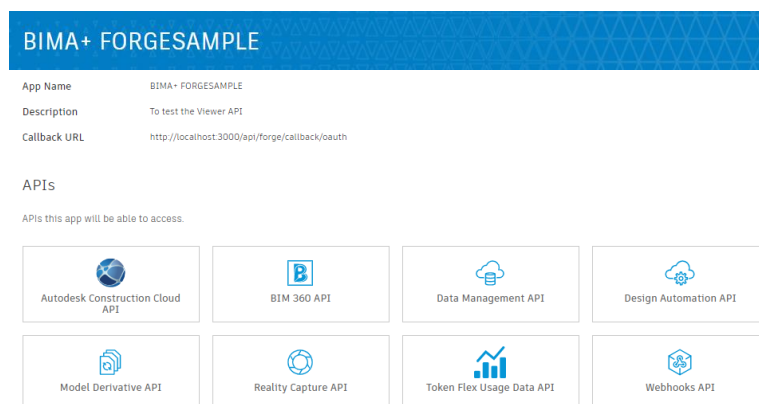


Figure 25 – Creating an app in Forge

3. Create a local development server

The languages available on the viewer API to choose from are Node.js, .NET Framework, .NET Core, Go, PHP and Java. For this project, Node.js was selected and Visual Studio Code (VSCode) was used as the Integrated Development Environment (IDE). Follow tutorials to create a server or download from the GitHub repository.

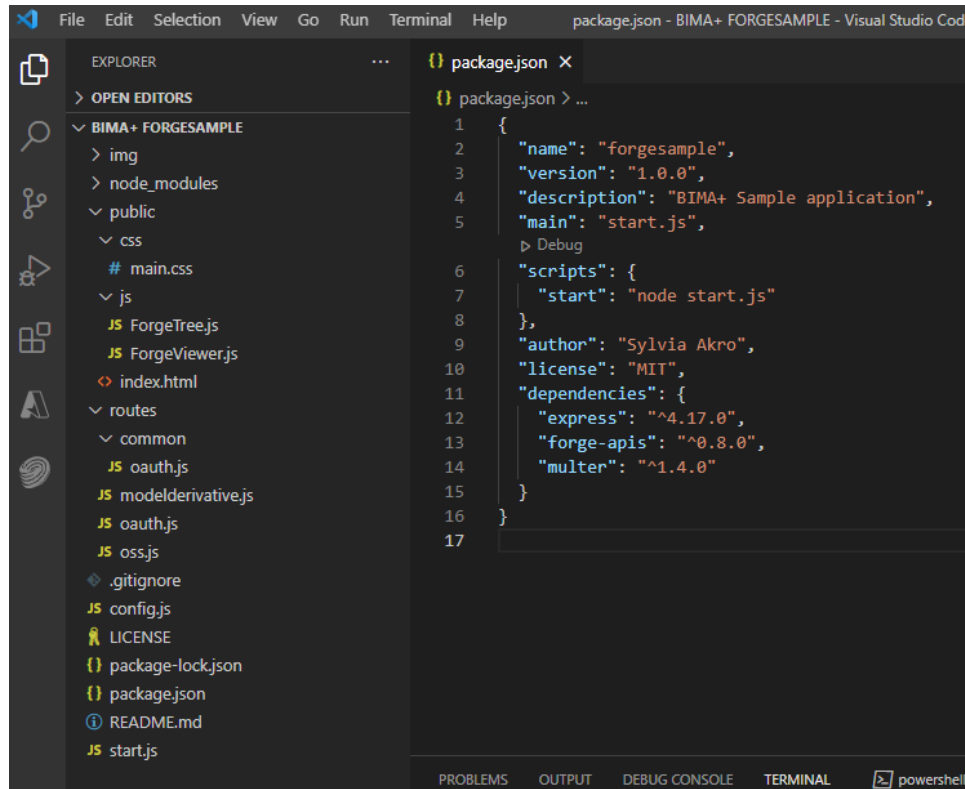


Figure 26 – Local development server in VSCode

4. Add OAuth credentials for authentication

This means that your app directly communicates with the Forge Platform for authentication and access to resources. Set environment variables by adding the Client ID and Secret credentials from the created app to obtain an Access Token.

5. Upload, Translate & show 3D models on the web

You can either upload models from the local drive or view models directly from BIM 360 or Fusion. For this tutorial, the model was uploaded from the local drive. Upload file to Object Storage Service (OSS), which are stored as objects in buckets and each bucket has a retention policy that determines how long the files would be retained: Transient - cache-like storage for 24 hours; Temporary – Storage for 30 days; Persistent – storage until it is deleted. To show the model in the viewer, execute the code in the local server and open the local port in the browser: <http://localhost:3000>. Figure 27 shows the model uploaded to the viewer.

The model used for this tutorial is a model that was used in the previous modules of this course, designed and modeled by the author using Autodesk Revit version 2021.

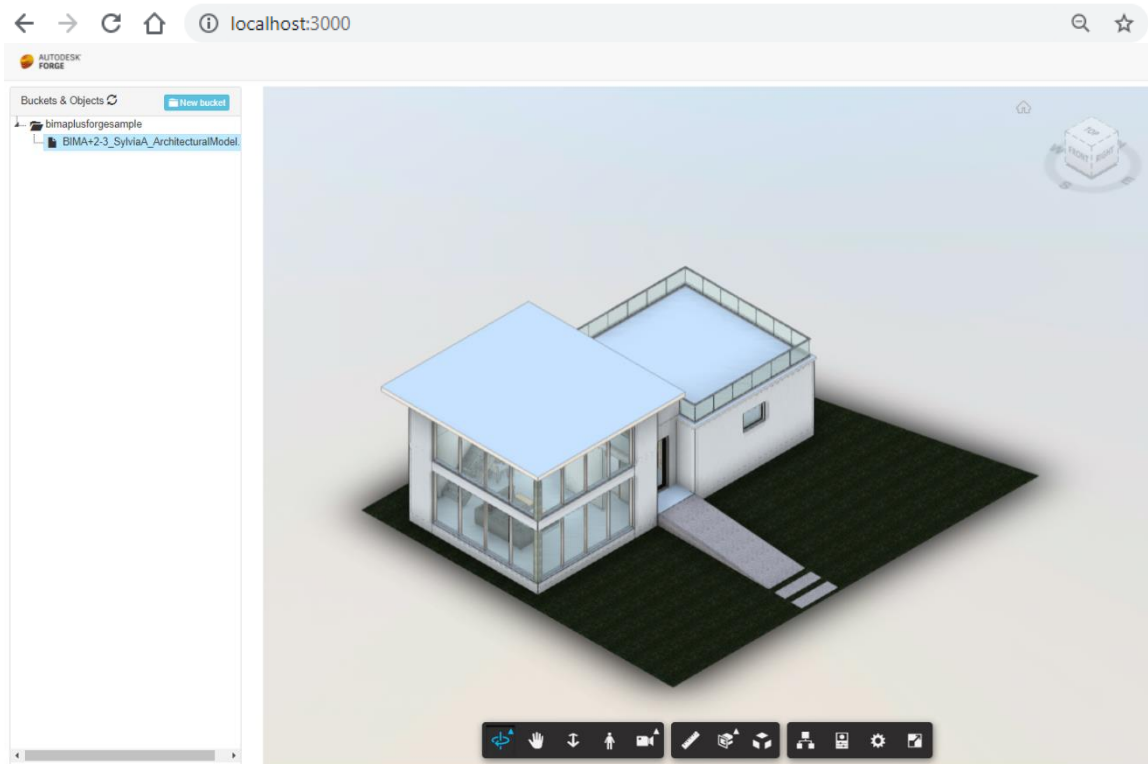


Figure 27 – 3D model uploaded on the browser in Forge viewer running locally

6. Add viewer extensions and Dashboards

The viewer makes it possible to add more built-in or custom extension tools and dashboards. Extensions provide a mechanism to write custom code on the client-side that adds buttons and panels that interact with the Viewer. These extensions could either act within the viewer or pop up as a docking panel within the viewer.

To illustrate this, the new extensions added to the viewer were: two built-in extensions - Document Browser and Visual Clusters; three custom extensions – Nested Viewer, Model info, and Model Summary.

The dashboard added shows a bar chart and pie chart that could be used to display any details according to the selected property from the model within the viewer.

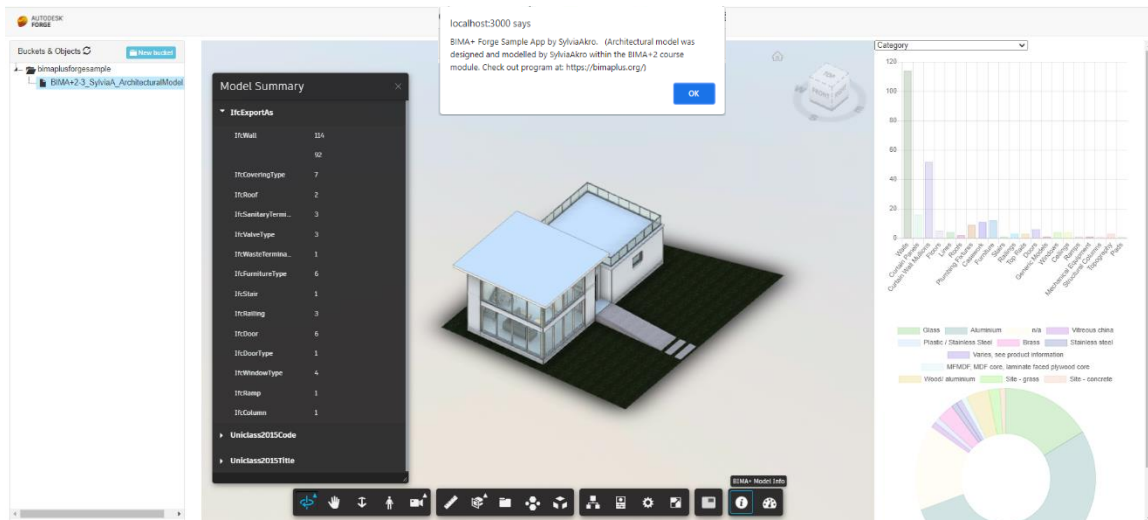


Figure 28 – Viewer with added extension and dashboard

7. Deploy as a web app

The deployment of the app, which is the last step was done using Heroku. Heroku is a cloud-based application, platform-as-a-service (PaaS) based on a managed container system for building, running, and managing modern apps. Deploying the application means putting it on a Web server to be used either through the Internet or an intranet. Currently, there are four (4) options (Figure 29) to select from for deployment, which are through Amazon Web Services (AWS), Microsoft Azure, Heroku, or AppHarbor.

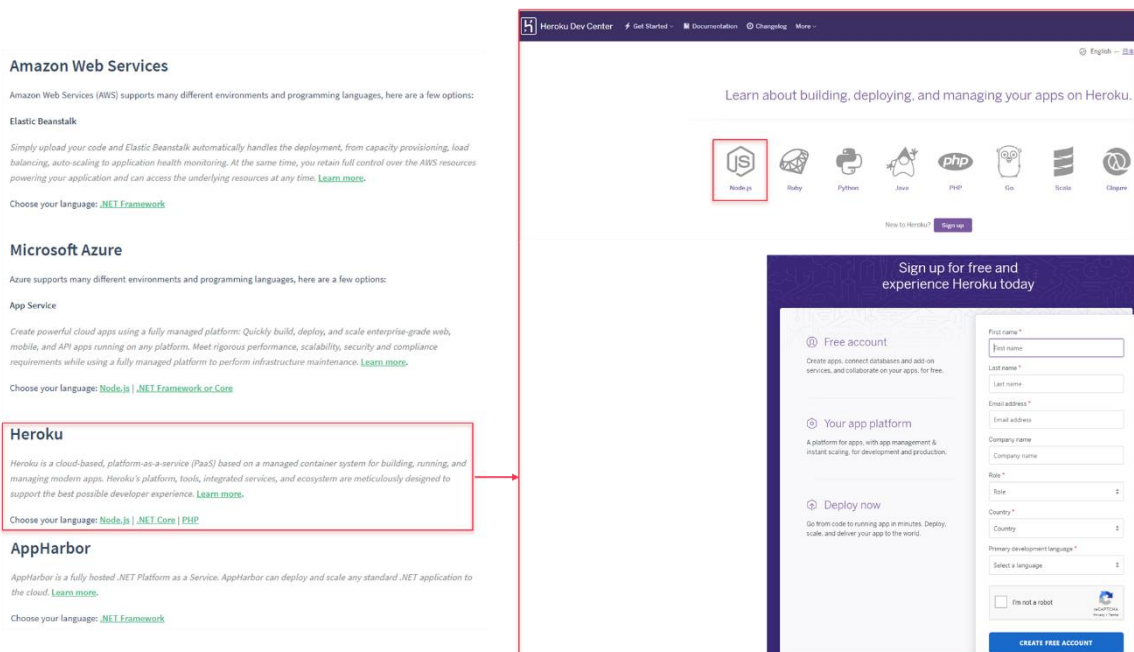


Figure 29 – Forge Deployment options (left) and Heroku (right)

Source: (Learn Forge, 2021)left and (Heroku, 2021) right

Figure 30 shows the web app deployed through Heroku and can be viewed within the browser on a computer or mobile device. It can be accessed through the address: <https://bimapius-forgesampleapp-sylvia.herokuapp.com/> or scan QR code. Available until December 03, 2021.

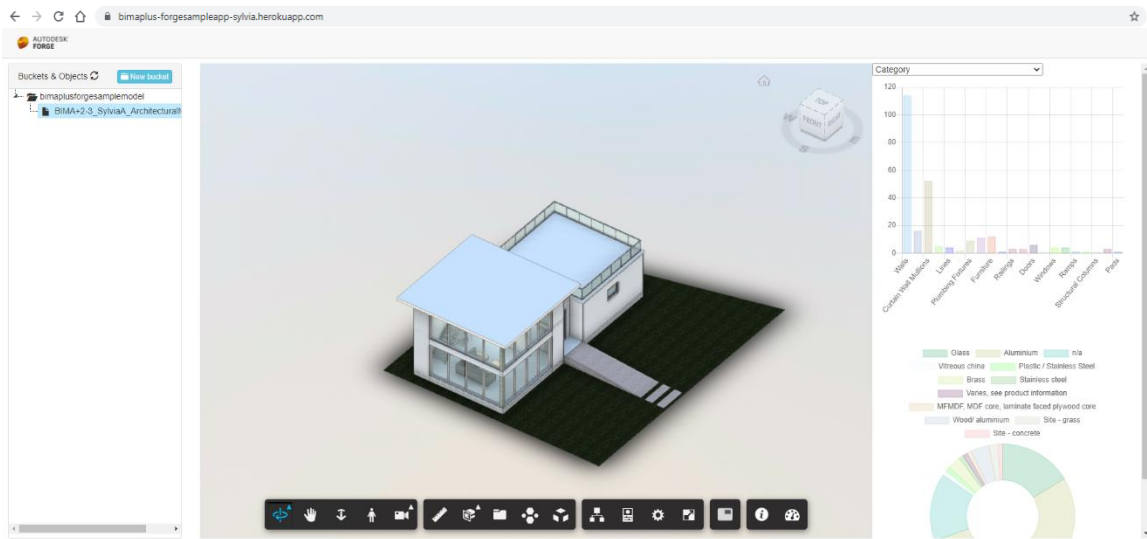


Figure 30 – Deployed web app on browser through Heroku



Figure 31 – QR code and information to access deployed web app on browser

In summary, after going through the basic tutorial of Forge using the viewer API to successfully create and deploy a sample web app, Forge has shown its potential. Therefore, the next part would illustrate the process of leveraging the Data Visualization API to visualize monitory data within a BIM model.

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5. BIM TO DT - VISUALIZING MONITORING DATA

This chapter describes the detailed application of the proposed methodology Figure 18 on an existing school building, starting from the data collection process into the database, using Forge to integrate the data with the sensor device family in the BIM-based model from Revit as the BIM authoring tool, visualizing the outputs as heatmaps in rooms within the model, and lastly analyzing the data against a decision-making dashboard with benchmark standards to identify the indoor thermal comfort using the Predicted Mean Vote (PMV) model.

5.1. DATA ACQUISITION

The process of the data collection was outside the scope of this research but to give an overall context, it introduces briefly the process of sensor data acquisition from the Data producer to the Database and graphically visualized in a Dashboard. A data producer is known to be a user interface, automation, service, or device that collects data that is relevant to a business (Spacey, 2016). In this case, the data producers are the IoT sensor devices deployed in the physical asset to collect the sensor data. They have accumulated data from the beginning of April this year and still running. This monitoring data is stored using the InfluxDB database, a time-series database built specifically for storing time-series data and then visualized in Grafana, a visualization dashboard tool for time series data. This dashboard only works as a graphical representation of data (Figure 33).



Figure 32 – Indoor Environment Data Acquisition schema

Table 5 – Sensor Data parameters

Parameter	Unit of measurement
Temperature	°C
Relative Humidity	%H
CO2	ppm
Total volatile organic compounds (VOC)	ppb
Illumination	lx
Predicted Mean Vote (PMV)	Not Applicable
Percentage of Dissatisfied (PPD)	%



Figure 33 – Sensor data dashboard graphical represented in Grafana

5.2. DATA INTEGRATION

Creating a dynamic integrating process between the IoT sensor data and BIM model was done within Forge. but first, it is of essential importance to have matching properties of the sensor devices with data from the database and the BIM model sensor family in Revit using a unique identifier for integrating the BIM model and Sensor data from the database into Forge. In this study, the **sensor name** was used as the unique identifier. The IoT sensor devices have a unique sensor name in the real world (Figure 37), the database (Figure 38) which matched the sensor device family in the BIM model in Revit (Figure 39).

5.2.1. Sensor Device Family Creation in Revit

A family called ‘sensor’ was created as a Generic model in Revit to represent the real sensor devices. The different sensor devices (Table 4) were created as types under the sensor family with varying type and instance properties. This sensor family was placed in the BIM model simulating the real position of the asset in the physical building. Figure 34 shows the sensor device family type and instance properties of device type “Ursalink AM102”.

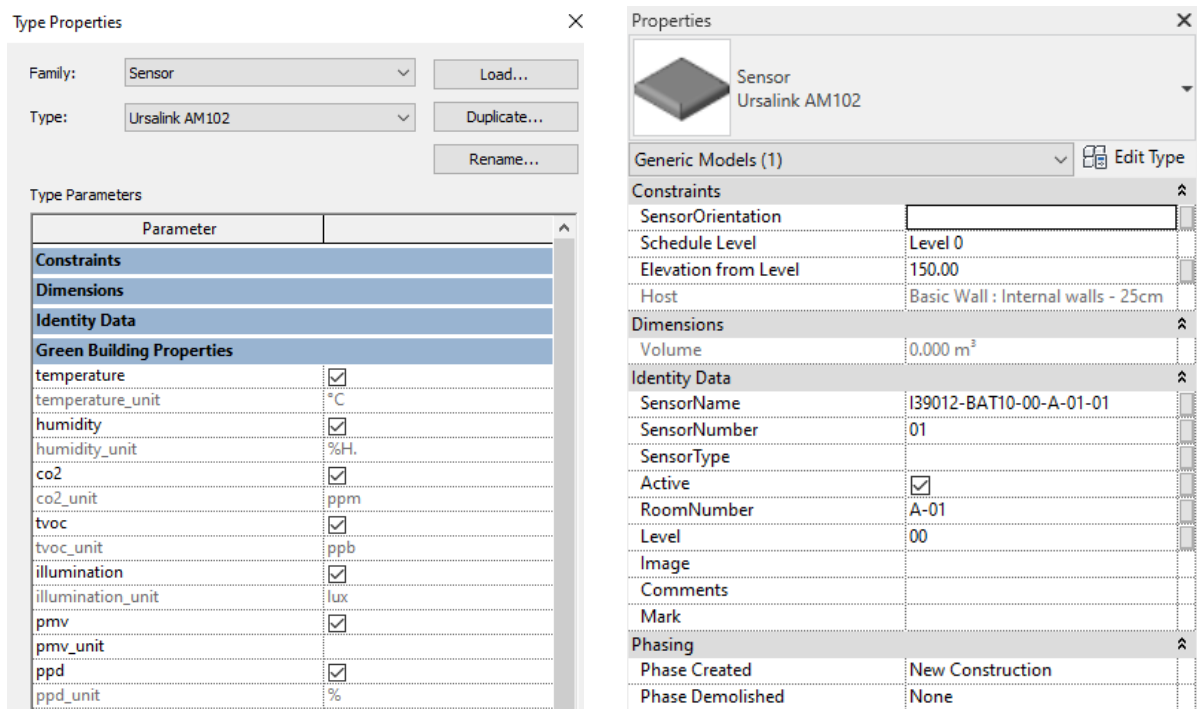


Figure 34 – Sensor device family type (left) and instance properties (right) in Revit

The parameter group called ‘Green Building Properties’ was created to represent the sensor data and the unit of measurement to which the data from the database is going to be assigned in Forge. The sensor data is created as a Yes/No type of parameter with its corresponding unit of measurement as a text type of parameter. This information is manually checked and inputted following the real case scenario. For instance, Figure 35 shows the Yes/No parameter “*temperature*” and its corresponding unit of measurement as a text type of parameter “*temperature_unit*”.

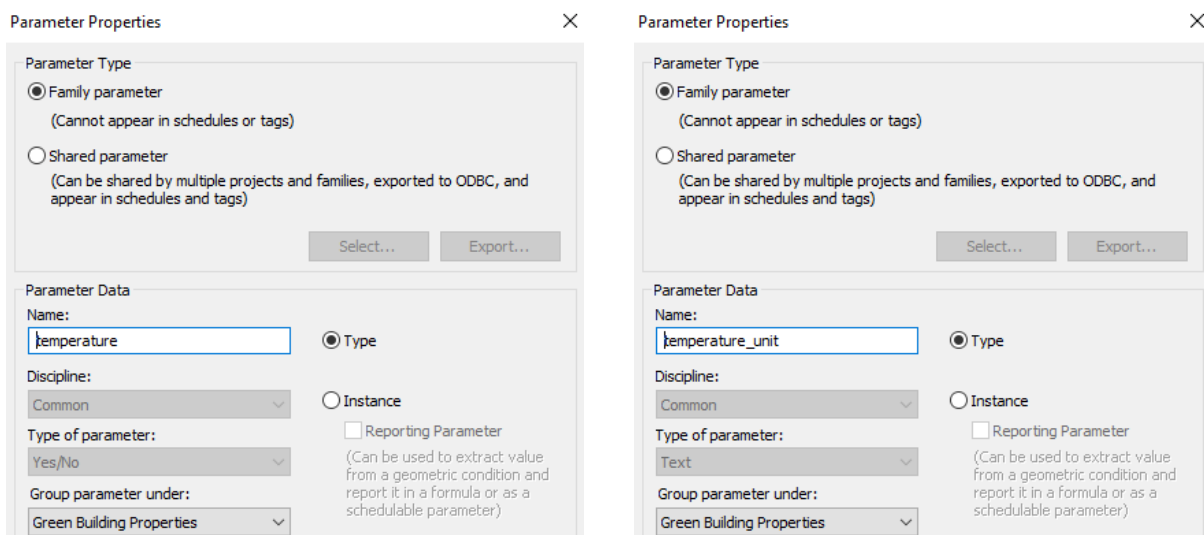


Figure 35 – Green Building Parameter types in Revit

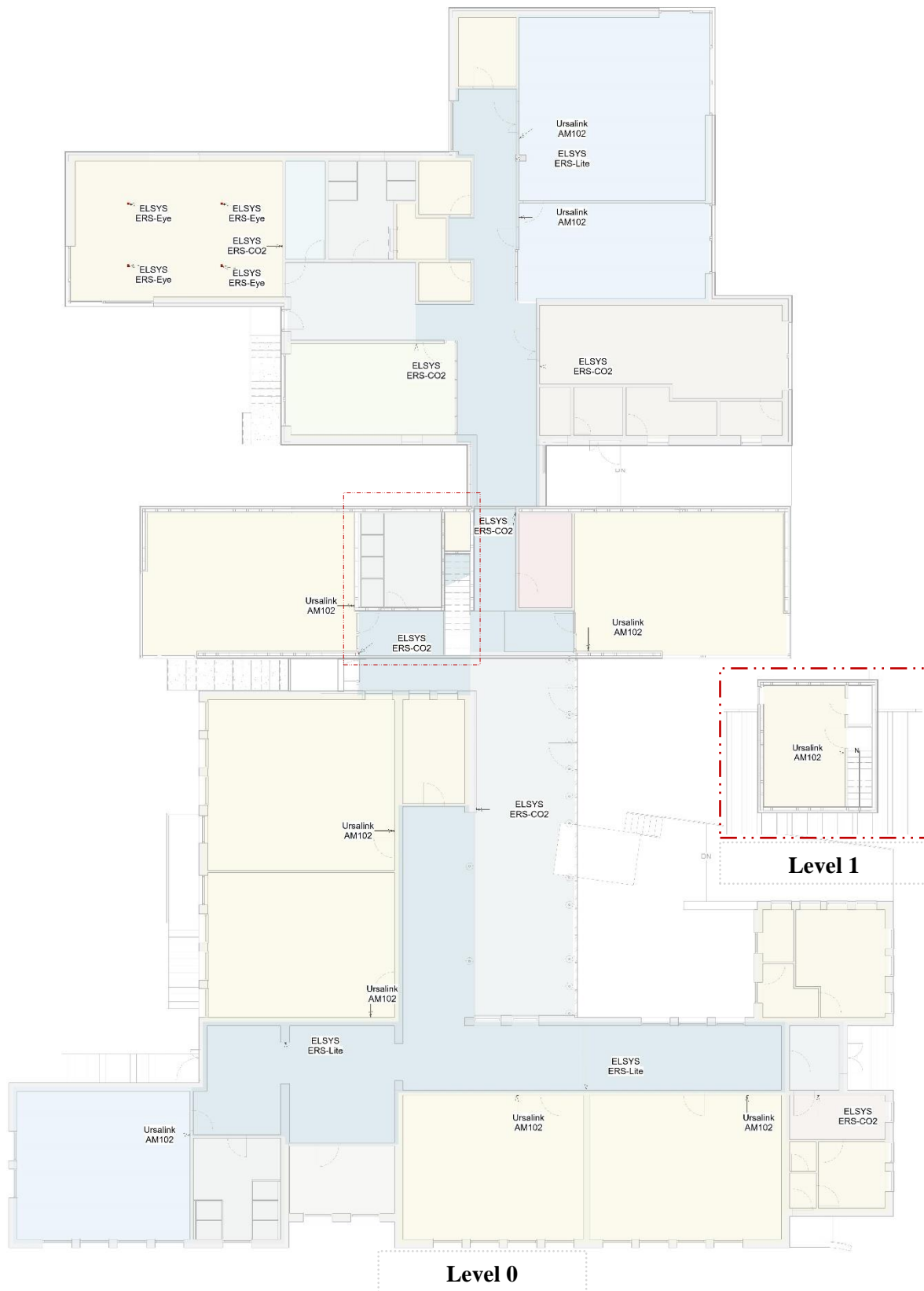


Figure 36 – Level 0 and Level 1 floor plans showing sensor device instances tagged in Revit

Selecting one sensor, for instance, the unique identifier which is the **sensor name** “I39012-BAT10-00-A-01-01”, is the same in the physical asset, the database, and in the BIM model in Revit.

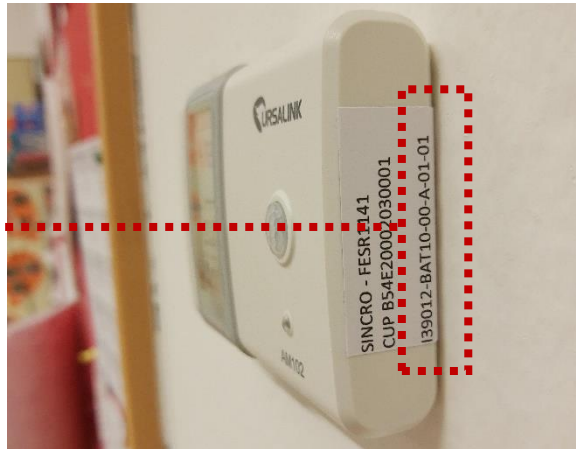


Figure 37 – Unique identifier labeled on device in Real-world

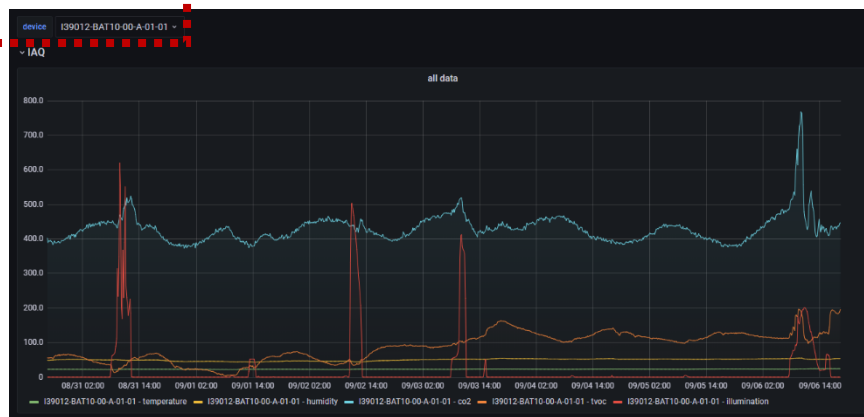


Figure 38 – Unique identifier in the database in Grafana

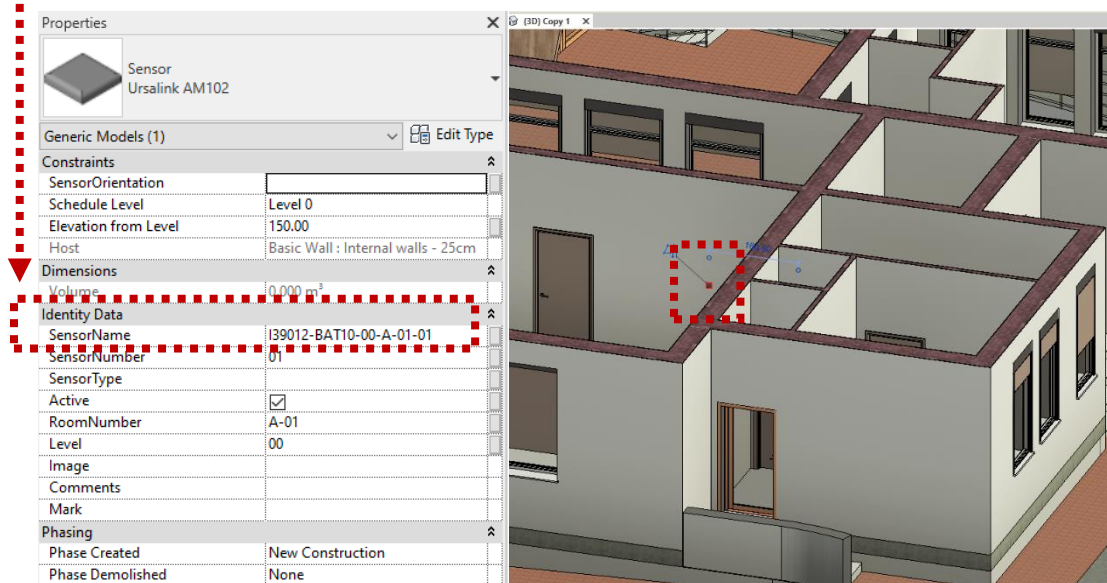


Figure 39 – Unique identifier in the instance parameter and model in Revit

5.2.2. Reference Application setup in Forge

After going through the prerequisite for using the Data Visualization extensions to integrate IoT data with a BIM model as illustrated in 4.2.1.2, by creating a Forge account, installing Node.js – version 12 or higher – including NPM and gaining some knowledge of using the Forge Viewer API. The next steps followed the procedure described in the developer’s guide from running the reference application to deployment. Most of the process to set up the Reference App was done in Visual Studio Code (VSCode) as the IDE.

1. Installing and launching the Reference Application

To install and launch the reference app, in a console or terminal window, a directory was selected to install the Data Visualization Reference Application and clone the GitHub repository: `git clone https://github.com/Autodesk-Forge/forge-dataviz-iot-reference-app.git`. Then install and run npm to launch an instance of the reference app in the web browser on the local port 9000 on the computer through this address: `http://localhost:9000`.

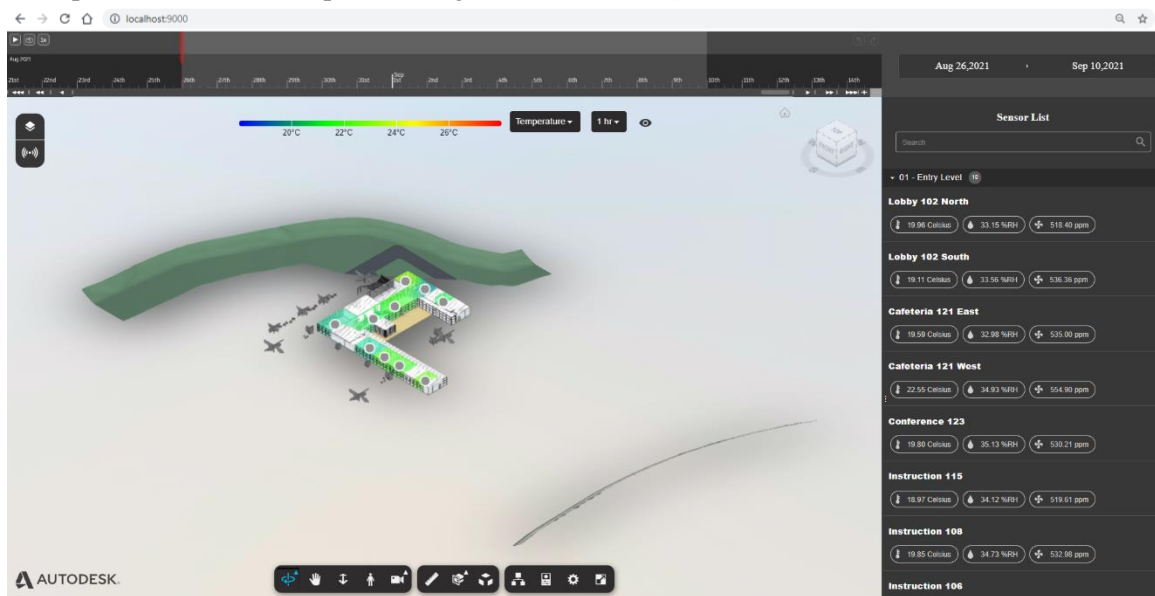


Figure 40 – Reference app launched on the local port in the web browser

2. Replacing the default model

After running the Reference Application, the default sample model was replaced with our model using the Forge storage. First, by creating a new .env file using the template provided with the Reference Application and edited it by adding values for `FORGE_CLIENT_ID` as `Client_Id`, `FORGE_CLIENT_SECRET` as `Client_Secret` from the App details created in the Forge account, and `FORGE_BUCKET` as a 'unique URL'. Set the `ENV` variable to `local` and then run the development server.

Next, select, upload and translate our model in the web browser using the address: `localhost:9000/upload` (Figure 41).

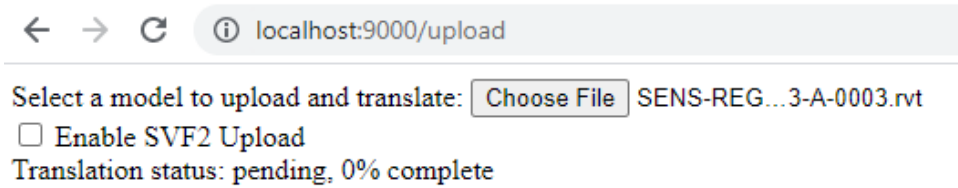


Figure 41 – Uploading file in the local server in the web browser

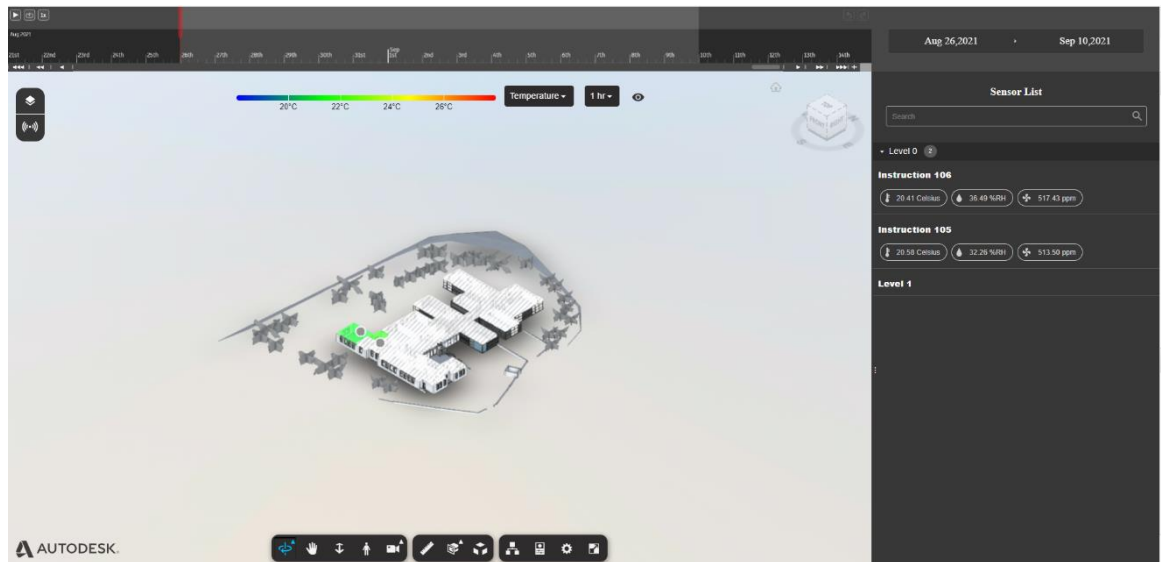


Figure 42 – Uploaded 3D model in the local server in the web browser

After uploading and replacing the default model, the sensor devices from the default app is not all visible because it uses synthetic data that is set to work only with the default sample project, therefore to visualize the sensors in our model, the sensor devices should be mapped to the position of the sensor device family added in the Revit model.

The following next steps below required more programming skills and were developed in the back-end in VSCode and the source code had to be modified to achieve the implementation.

3. Mapping devices and properties to sensor device from the model positions

Sprites are the two-dimensional objects overlaid into the model to represent sensors and icons. This was done by using the location of the sensor device family in the BIM model from (Revit) to place the sprites in Forge using the function *generateDevicesFromModel*. This checks the model and finds elements with the property *SensorName* which is the unique identifier. From the selection, it filters and returns defined properties, which are used to define the sensor types.

```

async function generateDevicesFromModel(viewer, model, dataHelper) {
  var defer = Q.defer();

  let devices = [];

  await model.findProperty("SensorName").then((res) => {
    model.getBulkProperties(
      res,
      [
        "SensorName",
        "dbId",
        "externalId",
        "temperature",
        "pmv",
        "ppd",
        "tvoc",
        "illumination",
        "co2",
        "Schedule Level",
        "name",
        "humidity",
      ],
      function (e) {
        let sensors = e.filter((obj) =>
          obj.properties.find(
            (x) => x.displayName === "SensorName" && x.displayValue
          )
        );
      }
    );
  });
}

```

Figure 43 – Code snippets showing sensor devices generated from BIM model in VSCode

4. Defining the devices models according to the properties of each parameter

A device model describes a type of device, such as a sensor in this context. Every device model contains an id, a name, and a description, as well as a list of device properties that this type of device supports. Each device property includes the following values: id, name, description, type, unit, minimum range value, and maximum range value. For example, Figure 44 shows an example of the temperature device property. The device models are used together with the property gradient.

```

[
  {
    "deviceModelId": "d370a293-4bd5-4bdb-a3df-376dc131d44c",
    "deviceModelName": "Human Comfort Sensor",
    "deviceModelDesc": "Monitors indoor air quality by measuring levels of",
    "deviceProperties": [
      {
        "propertyId": "Temperature",
        "propertyName": "Temperature",
        "propertyDesc": "External temperature in Fahrenheit",
        "propertyType": "double",
        "propertyUnit": "°C",
        "rangeMin": "15.00",
        "rangeMax": "35.00"
      }
    ]
  }
]

```

Figure 44 – code snippets of device model properties in VSCode

5. Defining the property gradient

The default reference app came with only three device properties (Temperature, humidity, and CO2), therefore more properties for tvoc, illumination, PMV, and PPD were added. The gradient map was set to have a three-color gradient for the properties defined in the device models.

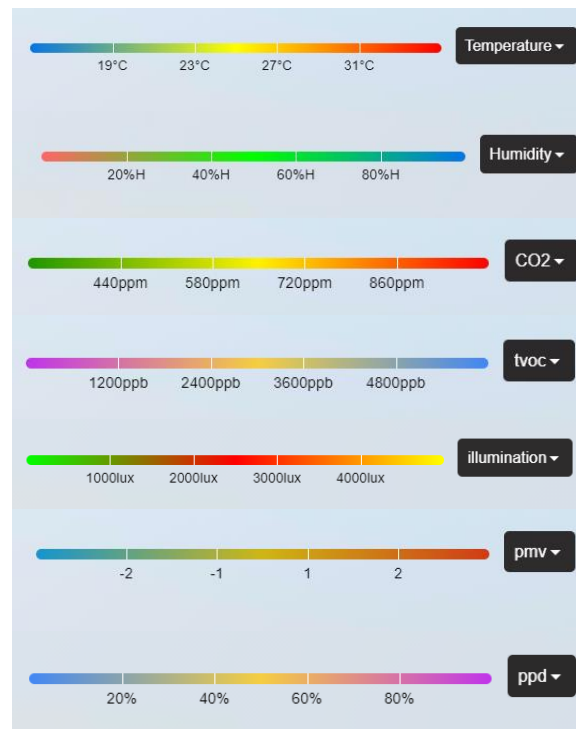


Figure 45 – Property gradient and device properties

6. Defining the property icons for the added properties.

The property icons were also updated to represent each property in the sensor list which can be viewed alongside Figure 45 for better understanding.

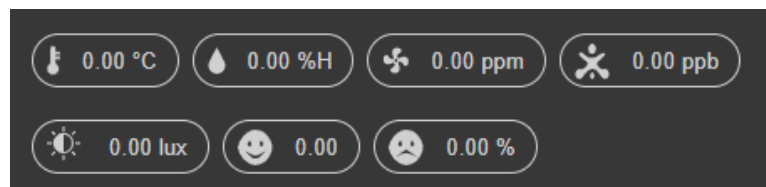


Figure 46 – Property icons for all parameters

7. Adding our sensor data

The default Reference App works with synthetic data which are randomly generated data. To add our sensor data from the database in real-time, this is done using a data gateway, and a data adapter, that is specific to an individual data provider. The job of a data gateway class on the server-side is to retrieve sensor data from a target data provider, before returning it to the client-side data adapter that converts the data into the target normalized data format. Therefore, for the sensor data located in InfluxDB, a custom data adapter and gateway for InfluxDB was created. The *GetMeasurement* was set to query data from the database returning *sensor_name* and *sensor_value* starting from the current time to the last 7 days.

```

GetMeasurement(sensor_name, sensor_value) {
  // sensor_name = sensor_name;
  console.log(sensor_name);

  let influxQL = `select mean(value) from ` + sensor_value + `
    where device_name = ` + sensor_name + `
    and time > now() - 7d
    group by time(10m)
    fill(linear)`;
}
    
```

Figure 47 – code snippet for getting sensor data from database in VSCode

Also, it is possible to use CSV files as a time-series data source for the Data Visualization over a certain timeframe. This option was also explored using a CSV file exported from Grafana for a timeframe from June to July to visualize the historical data for the summer season. To do this, configuration values such as the device models, start date and start time, etc were added to the .env file.

The CSV file is structured according to each sensor device containing columns for its Timestamp and the sensor data for all properties and all the files are added to the CSV folder on the server-side. It is important to note that the CSV file should be named with a unique identifier to make it possible to read the data. For example, the CSV file below is saved as “I39012-BAT10-00-A-01-01” which is a sensor name.

	A	B	C	D	E	F	G	H
1	Time	Temperature	Humidity	CO2	tvoc	illumination	pmv	ppd
2	6/1/2021 0:00	21.8	42.5	418	153	0	-0.31	6.98
3	6/1/2021 1:00	21.8	42.5	422	149	0	-0.32	7.1
4	6/1/2021 2:00	21.7	42.5	427	144	0	-0.33	7.4
5	6/1/2021 3:00	21.6	42.5	428	140	0	-0.35	7.65
6	6/1/2021 4:00	21.6	42.5	431	136	0	-0.37	7.8
7	6/1/2021 5:00	21.6	42.5	440	141	30.8	-0.37	7.8
8	6/1/2021 6:00	21.8	42.3	578	219	153	-0.32	7.15
9	6/1/2021 7:00	22.5	42.4	784	261	383	-0.16	5.55
10	6/1/2021 8:00	22.8	42.7	765	228	391	-0.11	5.23

I39012-BAT10-00-A-01-01

Figure 48 – The structure of CSV file exported from Grafana

Switching between the InfluxDB data source and the CSV data source can be done by setting the Adapter Type variable in the .env file to either CSV or Influx in VSCode.

8. Mapping Sensors to Rooms to generate the Heatmap surface shading data

This step can be done automatically when there is room information and device position information. However, if this information is not available, it is possible to manually map the devices to rooms. In this case, it was done automatically, from the room and level information already placed and defined in the Revit model, the position and size of each room was obtained in the form of a bounding box and is mapped to the position of each device to determine which room contains what device. The Heatmap surface shading is rendered following the property gradient.

5.3. DATA VISUALIZATION

5.3.1. Visualization

After going through the process of creating the data integration, the next part is the data visualization which is the output that combines the BIM model and sensor data, visualized in Autodesk Forge using heatmaps surface shading and other UI components. This is where the user interacts with the application and it was viewed in the web browser on the local port 9000 on the computer through this address: *http://localhost:9000*.



Figure 49 – 3D model displayed with heatmap surface shading data in Forge viewer

5.3.2. Data Verification

It is essential to verify if the right data has been successfully integrated into the Digital Twin. To check the validity of the data visualized, compare the data between the database and the visualized data in Forge. This also helps to check whether the IoT devices are working properly or not by identifying the devices that have not collected data for a certain period.

In this implementation, it was easy to perform this verification because some sensor devices were returning no data values and on comparing with the database within the same timeframe, those sensors also had no data. Examples of such sensor devices: “I39012-BAT10-00-B-01-01” and “I39012-BAT10-00-A-14-01”. The verification timeframe used to check was from September 03, 2021, to September 09, 2021.



Figure 50 – Sensor data in Forge



Figure 51 – Sensor data in Grafana

5.4. DATA ANALYSIS

5.4.1. Data Interpretation

With historical data, you can get a snapshot of the information visualized that can be used for predictive analysis and simulation. However, with real-time data, you can use data visualizations to effect changes within the building as they occur in real-time.

At this point, visualizing the historical and real-time environmental monitoring data through BIM with heatmaps in the digital twin was done successfully. However, to make sense of this data for the end-user, it is important to compare it to green building benchmark standards. This was done by adding a decision-making dashboard of the indoor environmental and thermal comfort data thresholds to

support complex decisions. Note that PMV is a common metric for assessing the comfort level of an indoor environment.

Table 6 – Standard and Comfortable values for monitored parameters

Parameter	Unit of measure	Summer Threshold	Winter Threshold
Temperature	°C	23 - 26 °C	20 – 25 °C
Relative Humidity	%H	40 - 70%H	40 - 70%H
CO2 concentration	ppm	400 - 1000 ppm	400 - 1000 ppm
(tvoc)	ppb	300 - 500 ppb	300 - 500 ppb
Illumination	lux	100 - 500 lux	100 - 500 lux
PMV	Not Applicable	-0.5 - +0.5	-0.5 - +0.5
PPD	%	<10%	<10%

Temperature - Based on CEN, EN 15251:2006 Table A.3, comfortable temperature in winter is between 20 °C and 25 °C, while in summer, it is between 23°C and 26°C. (EN15251, 2006)

Humidity - According to the WHO as cited by (Mataloto *et al.*, 2021), Humidity recommended for the human body varies between 40% and 70% and can be harmful outside this range.

CO2 – Based on CEN, EN 13779 as cited by (Penna *et al.*, 2019), CO2 concentration varies between 100 ppm and 100 ppm.

TVOC – The recommended levels for TVOC between 300 ppb to 500 ppb is considered acceptable (Airmex, 2020)

Illumination – The illumination values are the same in summer and winter and the comfortable range is between 100 lux – 500 lux based on UNI EN 12464:1:2004.

PMV – According to ISO 7730 as cited by (Guenther, 2021), when PMV = 0, the indoor environment is in the best thermal comfort state, moreover the PMV comfortable scale should be between -0.5 and +0.5.

PPD - According to ISO 7730 as cited by (Guenther, 2021), the PPD values correspond with the PMV, therefore for a PMV scale between -0.5 and +0.5, the corresponding PPD would be below 10%.

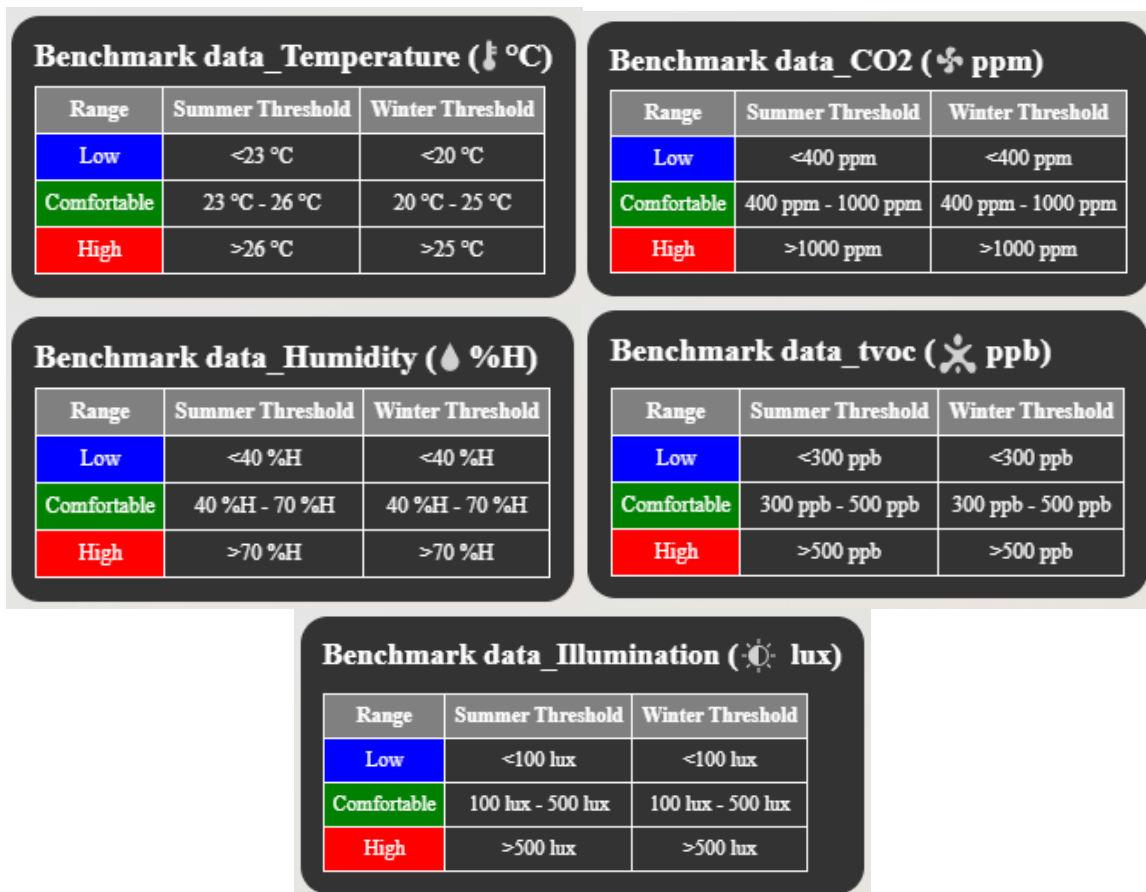
5.4.2. Data Dashboard

The decision-making dashboard was added to the viewer to compare it to green building benchmark standards and Comfortable values for monitored parameters Table 6. This was done by creating a custom panel for the data, which changes on click with the parameter selected from the device models.

The parameters for temperature, humidity, CO2, tvoc, and illumination had a similar dashboard structure with column headers: Range, Summer Threshold, and Winter Threshold. The Range was categorized as Low, Comfortable, and high with their corresponding values under the respective threshold. The color scheme applied is Blue for Low, Green for Comfortable, and Red for High.

The dashboard structure for PMV follows the seven-point scale within the PMV index, with two column headers: Vote and Scale. The color scheme applied on the scale uses a gradient from Blue to Green to Yellow to Red corresponding to the scale values from -3 translates as cold to +3 translates as hot.

The dashboard structure for PPD is structured to have two column headers: Vote and Threshold. Where the vote is either satisfied or dissatisfied with the color scheme Green and Red applied respectfully.



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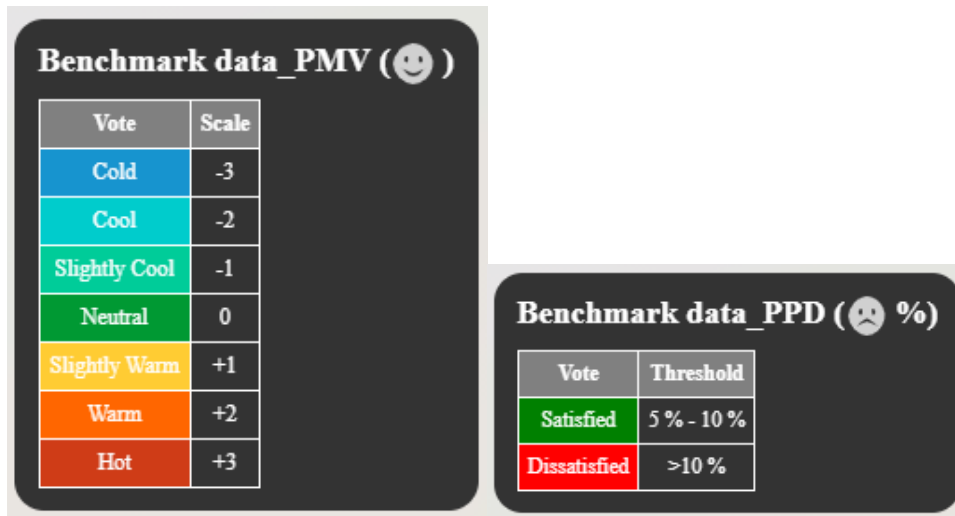


Figure 52 – Benchmark data dashboard for all parameters in Forge

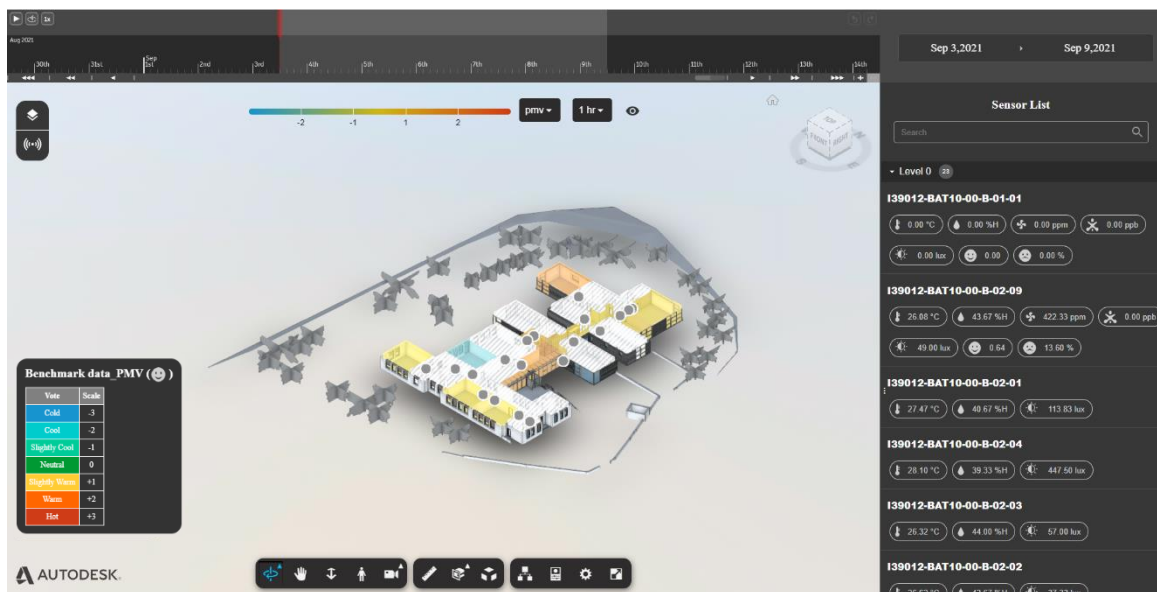


Figure 53 –Digital Twin developed with Hyperion Reference Application in Forge

The color scheme applied to the dashboard parameter range was intended to also be applied to the text of the sensor data values in the sensor list depending on the range the sensor values fall to enable easy identification of the data thresholds within the sensor list. That was not possible to achieve within the scope of this study. Probably, with more development time and a wider scope, it would have been possible to set an alert system to notify the manager when the monitoring parameters fall within an unacceptable threshold for quicker response. However, the color schemes in the dashboard still serve the purpose of highlighting and interpreting the data of the indoor thermal comfort using the PMV index.

5.4.3. Deployment of the Digital Twin

The deployment of this app on the cloud to be viewed as a web app is the final goal of the implementation. However, due to privacy reasons from Fraunhofer on the project, the application was not deployed.

Nevertheless, after going through the deployment of the basic forge viewer app (Figure 30), it is safe to say that it would have also been possible to deploy this Digital Twin with the Data visualization extension to be viewed on the browser for easy accessibility from anywhere.

6. CONCLUSION

BIM-IoT integration to create a DT in the built environment provides useful information to monitor and maintain the building performance during its use and operational phase that improves the user's experience and better decision-making opportunity for the facility manager.

This dissertation was aimed to propose an implementation framework oriented to visualizing monitoring environmental data through a BIM-based model to improve the efficiency of facility management (FM) and utilize real-time data during the building's lifecycle.

To promote openness and interoperability between disciplines and different BIM authoring platforms used in the AEC industry, Autodesk Forge was used as the cloud-based developer's platform to creating the DT based on its capability to integrate models from open non-proprietary file formats such as IFC, gbXML, glTF as well as other industry proprietary file formats to visualize indoor monitoring data.

The implementation framework integrated the indoor environment data collected by multiple sensors systems with a BIM-based model to automatically combine the monitored data with the related geometrical space in the BIM model. It was implemented through a four-layer methodology following the workflow summarized from previous studies on the topic of BIM-IoT integration for visualizing monitoring data. The four main layers were Data Acquisition; Data Integration; Data Visualization; and Data Analysis.

A use case study of an existing school building was used to test and validate the implementation framework, by leveraging a set of web services APIs from Forge. It was possible to start by exploring the basic Forge viewer to develop and deploy a web app. It allowed for custom modification according to the intended use and this demonstrated the potential of the platform as a cloud service.

Moving forward to the process of data integration, visualization, and analysis, a Reference application was used as the base to develop a DT. It was possible to implement the connection between the visualization dashboard for time-series data (Grafana) and Forge. To integrate the sensor data collected with the sensor device in the BIM model with a Unique Identifier. The UI components and other features such as heatmap surface shading in the reference app allowed for visualizing the monitoring data in real-time as well as historical data. And finally, it was possible to add a custom dashboard referencing benchmark standards to highlight, compare, and interpret the sensor data and most importantly define the indoor thermal comfort using the PMV index.

Along with the benefits of this framework, there are also limitations. During the development of this project, several challenges and limitations were encountered. There is a performance and dependency issue such as managing bulk sensor data from the database, which causes lagging returning errors like *load canceled due to load timeout*. As well as the lack of sufficient resources and support available due to the platform being relatively new, although this seems to be improving since there have been regular updates thereby increasing the community of users.

Another challenge is the level of programming knowledge required for this process, which is subjective depending on your skills. Moreover, the platform is created for developers. The app had to be modified to fit the use case, and this was done by hard coding some processes. The desirable goal is to achieve an optimized and more dynamic workflow. To efficiently develop a DT using this reference app, it is recommended to have a collaboration of a design team developing the BIM model and a Developers team to manage the back-end processes.

An alternative to this platform could be the recently released Autodesk Tandem for developing DT since it requires little or no programming background. It is a cloud-based Digital Twin technology platform that enables projects to start digital and stay digital, transforming rich data into business intelligence. By harnessing BIM data throughout the process. Although it is still in its early commercial phase, it shows a lot of potentials.

Further researches and improvement on the implementation framework could focus on the Data analysis part of a DT for the integration of Forge and analytics tool such as PowerBI to provide better insights and predictive analysis, allowing for constant update of accurate information of the building's performance. Further, to align with the increasing rise of digital transformation, the development of advanced visualization methodologies of the monitored data through a Standalone visualization system using a game engine such as Unity 3D or Unreal engine for advanced digital support such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR).

Although, there is still a significant amount of research and work to overcome the limitations that are present in this research work for BIM-IoT integration to create a DT for visualizing monitoring data in the built environment. To the best of the authors' knowledge, this is the first paper that utilizes the Data Visualization reference application for the development of a DT. This implementation framework has exhibited great benefits and potentials. Therefore, there is a need for a framework that integrates some of the raised subjects for future research.

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LIST OF ACRONYMS AND ABBREVIATIONS

AECO	Architecture, Engineering, Construction, and Operations
AI	Artificial Intelligence
AIM	Asset Information Management
API	Application Programming Interface
BEP	BIM Execution Plan
BIM	Building Information Modelling
BIM-FM	Building Information Modelling and Facility Management
BIM-FM	Building Information Modelling to Internet of Things Integration
BoM	Bill of Materials
bSI	buildingSmart International
CAD	Computer-Aided Design
CAFM	Computer-Aided Facilities Management
DT	Digital Twin
EIR	Exchange Information Requirement
FM	Facility Management
IaaS	Infrastructure as a Service
IAQ	Indoor Air Quality
IDE	Integrated Development Environment
IEQ	Indoor Environment Quality
IFC	Industry Foundation Classes
IoT	Internet of Things
IPD	Integrated Project Delivery
JSON	JavaScript Object Notation
NDT	UK National Digital Twin
O&M	Operations and Maintenance
PaaS	Platform as a Service Solution
PBO-I	Plan-Build-Operate- Integrate
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SaaS	Software as a Service
TVOC	total volatile organic compound concentration
UI	User Interface

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APPENDICES

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