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DIGITAL TWIN PROTOTYPING AND SIMULATION PIPELINE PROPOSAL THROUGH THE INTEGRATION OF BIM AND IOT

Marwa ABDELFATTAH

Master's Thesis

Supervisor

Asst. Prof. Dr. Can UZUN

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The thesis titled DIGITAL-TWIN PROTOTYPING AND-SIMULATION PIPELINE PROPOSAL THROUGH THE INTEGRATION OF BIM AND IOT prepared by MARWA ABDELFATTAH and submitted on 11.06.2024 has been **accepted unanimously** for the degree of Master of Science in Architecture.

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Marwa ABDELFATTAH

ABSTRACT

DIGITAL TWIN PROTOTYPING AND SIMULATION PIPELINE PROPOSAL THROUGH THE INTEGRATION OF BIM AND IOT

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[In recent years, the notion of building information modelling (BIM) has expanded beyond 3D geometric representations to encompass seven more dimensions. Time, cost, sustainability, and facilities management are some of these aspects. These measurements can be combined using BIM into a single digital model to provide a complete picture of a building project at every stage of its life. In this industry, decision-making, goal-achievement, teamwork, and speed will all be greatly facilitated. The concept of a digital twin is based on the utilization of BIM and real-time IoT data, which may be leveraged to improve building and operational efficiency. Nevertheless, there are few levels of research performed about BIM-IoT integration for the digital twin approach in the construction field, especially environmental monitoring. Further examination of the positives and negatives of this integration becomes a very important issue. The position of the IoT sensors in this chain is to assist the BIM models in data gathering and interpretation, thus enhancing the precision of project monitoring and predictive maintenance processes, which is for sure one of the demands for sustainable development.

With the use of building information modelling technologies and the internet of things, this study seeks to develop a pipeline for creating digital twins that deviates from previous research in terms of automated data collection and visualization techniques. Furthermore, increased automation and real-time asset visualization are provided by the combination of building information modelling and the internet of things. The experiment consisted of simulating and prototyping to assess the proposal pipeline, and a prototype was built with data collection using IOT sensors, Arduino, modelling in BIM, and automation using the Dynamo platform. The prototype of a 35 square-meter room was virtually tested out, and the results demonstrated that application of the predicted mean vote parameters of environmental convenience might restrict the amount to which the available findings can be spread to other regions with different climates. Furthermore, in addition to predictive maintenance, the building can be continuously monitored and modified to improve its energy efficiency and comfort level thanks to API capability based on IoT devices and real-time sensor data. It will additionally provide the evaluation with the quality of assessment via its practice of both maintenance and measure planning for the future.]

Keywords: Building Information Modelling (BIM), Internet Of Things (IOT), Digital Twin, Dynamo, Arduino, Real-time Sensors, Automated Visualization.

ÖZET

DIGITAL TWIN PROTOTYPING AND SIMULATION PIPELINE PROPOSAL THROUGH THE INTEGRATION OF BIM AND IOT

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[Son yıllarda yapı bilgi modellemesi (BIM) kavramı, 3 boyutlu geometrik temsillerin ötesine geçerek yedi boyutu daha kapsayacak şekilde genişledi. Zaman, maliyet, sürdürülebilirlik ve tesis yönetimi bu yönlerden bazılarıdır. Bu ölçümler, bir bina projesinin ömrünün her aşamasında tam bir resim sağlamak için BIM kullanılarak tek bir dijital modelde birleştirilebilir. Bu sektörde karar verme, hedefe ulaşma, takım çalışması ve hız büyük ölçüde kolaylaşacaktır. Dijital ikiz kavramı, bina ve operasyonel verimliliği artırmak için kullanılabilecek BIM ve gerçek zamanlı IoT verilerinin kullanımına dayanmaktadır. Bununla birlikte, inşaat alanında dijital ikiz yaklaşımı için BIM-IoT entegrasyonu, özellikle de çevresel izleme hakkında çok az düzeyde araştırma yapılmıştır. Bu entegrasyonun olumlu ve olumsuz yanlarının daha detaylı incelenmesi çok önemli bir konu haline geliyor. IoT sensörlerinin bu zincirdeki konumu, BIM modellerine veri toplama ve yorumlama konusunda yardımcı olmak, böylece sürdürülebilir kalkınmanın taleplerinden biri olan proje izleme ve tahmine dayalı bakım süreçlerinin hassasiyetini arttırmaktır.

Bina bilgi modelleme teknolojilerinin ve nesnelerin internetinin kullanımıyla bu çalışma, otomatik veri toplama ve görselleştirme teknikleri açısından önceki araştırmalardan ayrılan dijital ikizler oluşturmaya yönelik bir süreç geliştirmeyi amaçlamaktadır. Ayrıca bina bilgi modellemesi ile nesnelerin internetinin birleşimi sayesinde artan otomasyon ve gerçek zamanlı varlık görselleştirmesi sağlanıyor. Deney, teklif hattını değerlendirmek için simülasyon ve prototip oluşturmayı içeriyordu ve IOT sensörleri, Arduino, BIM'de modelleme ve Dynamo platformu kullanılarak otomasyon kullanılarak veri toplama ile bir prototip oluşturuldu. 35 metrekarelik bir odanın prototipi neredeyse test edildi ve sonuçlar, çevresel uygunluk için tahmin edilen ortalama oy parametrelerinin uygulanmasının, mevcut bulguların farklı iklimlere sahip diğer bölgelere yayılabileceği miktarı kısıtlayabileceğini gösterdi. Ayrıca, kestirimci bakımın yanı sıra, IoT cihazları ve gerçek zamanlı sensör verilerini temel alan API yeteneği sayesinde bina sürekli olarak izlenebiliyor ve enerji verimliliğini ve konfor seviyesini iyileştirecek şekilde değiştirilebiliyor. Ayrıca geleceğe yönelik hem bakım hem de önlem planlaması uygulamasıyla değerlendirmeye değerlendirme kalitesi sağlayacaktır.]

Keywords: Yapı Bilgi Modellemesi (BIM), Nesnelerin İnterneti (IOT), Dijital İkiz, Dinamo, Arduino, Gerçek Zamanlı Sensörler, Otomatik Görselleştirme.

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ABBREVIATIONS

AEC	:	Architectural, Engineering, and Construction.
BIM	:	Building Information Modelling.
BEM	:	Building Environment Monitoring.
CPS	:	Cyber Physical System.
CAD	:	Computer Aided Design.
DT	:	Digital Twin.
DAS	:	Data Acquisition Equipment.
DAE	:	Data Acquisition Equipment.
FM	:	Facilities Management.
IoT	:	Internet of Things.
MSC	:	Multisensory chip.
NDT	:	Non-destructive Testing.
PMV	:	Predicted Mean Vote.
SHM	:	Structural Health Monitoring.
SHT	:	Sensor, Humidity and Temperature.
TC	:	Thermal Comfort.

1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Building information modelling (BIM) is a vital tool for enhancing the methods used in project delivery. It provides highly precise geometry and building component data sets (Eastman, 2008). However, real-time data and information cannot be updated into a BIM 3D model, which contains a wealth of information about the structure and materials used in construction, without outside assistance (Tang et al. 2019). Conversely, the Internet of Things (IoT) is a cross-platform network of networked sensor and actuator devices. Sensors, identity and recognition, cloud platforms, software, hardware, communication, algorithms, orientation advances, data management solutions, thermal and energy-efficient storage, and safety precautions are among the technologies that make up the Digital Twin technological concept (Gubbi et al. 2013). These technological advancements allow the Digital Twin to continuously update its knowledge and gather real-time data from several sources, providing more precise and current insights into the construction process. Although real-time and recordable status from actual construction and activities is provided via IoT data, BIM models offer extremely accurate project representations at the component level. Real-time data or point samples of the continuous sensor flow over lengthy periods of time, is a systematic definition for the wide range of data collected from the sensors (Deng et al., 2021). To create a digital twin strategy, several business sectors are integrating BIM and IoT, including energy supervision, building management, health and safety management, and construction monitoring.

Most of the studies with the objective of integrating both the BIM and the IoT applications into the digital twin concept are still theory based with less practical applications. Yet, the web of advantages offered by the mixture of BIM and IoT to create digital twins is universally acknowledged. Real-time and updated representation of the physical asset's state can be shown in BIM models using live data from IoT devices. This improves operational performance and allows for better decision making.

With the use of automated sensors and data analysis, this strategy will focus research on the integration of BIM and IOT for digital twin prototype design and development. This project will use an Arduino board connected to Dynamo (a free Revit plug-in) to integrate BIM and

IoT technology sensors to construct a digital twin prototype that can accurately imitate real-world settings. Subsequently, visual computer programming and Python scripts will combine to collect data from temperature and humidity sensors and assign tasks to perform the necessary computations to determine the interior thermal comfort index. Using this strategy will govern the research, which will be primarily cantered on creating a digital twin prototype that integrates IoT sensors and data analysis.

Not only will the most significant advancements that may result from the use of IoT and BIM technologies in energy resource and performance optimization be analysed, but significant new developments as well, such as the efficiency of decision-making by signers and stakeholders, may also arise from the deployment of these technologies. The digital twin prototype can gather vital information that aids in the designer's decision-making on the optimal plan for design, power, and upkeep. Modern, highly developed equipment and analytics will produce data that is immediately usable, offering crucial and practical insights into the manufacturing, facilities management, and construction sectors.

1.2 REASERCH AIM AND OBJECTIVES

The project aims to investigate whether BIM and IOT systems can be integrated to create a digital twin prototype. The objective is to create a virtual representation of a physical facility that can operate, gather data from IOT sensors in real time, and analyse its efficiency. Combining the two technologies for the digital twin approach, the digital twin prototype may offer recommendations for an improved maintenance decision-making process in addition to the precise modelling offered by BIM and the data-gathering ability of IOT sensors.

The main objectives of the thesis project are:

a. By utilizing dynamic approaches and methodologies to model the physical asset's digital twin from the BIM model, the team can monitor and evaluate the physical asset's performance in real time. Conversely, the dynamic approach ensures that the digital twin is always current and appropriately reflects the actual asset, considering all modifications or updates made to it.

b. Dynamo (BIM modelling plug-in) script automation is the most important step in the project to create an automated visualization tool to be used to reflect all the data collected using the IOT sensor directly in the BIM model and to automatically extract it simultaneously from the Arduino installation.

c. Thermal comfort calculation, which will be performed using the Dynamo script, will automatically visualize all the sensor data (temperature and humidity values) into the BIM model with the colour palette scheme.

d. Explore the most automated method of integrating the IOT sensor with the BIM model that avoids data loss and conflicts by utilizing powerful synchronization algorithms and data transfer protocols.

e. Evaluating the value and effectiveness of integrating BIM technology integration and digital twins for sustainability and decision-making

f. Examine areas for improvement in the combination of BIM and IoT technology for a digital twin strategy to streamline construction processes and increase efficiency.

2. LITERATURE REVIEW

2.1 INTRODUCTION TO BUILDING INFORMATION MODELING (BIM)

2.1.1 Definition of BIM

Building information modelling, or BIM, has garnered a lot of interest lately in the architectural, engineering, and construction (AEC) sector due to the expanding usage of information technology. BIM also improves the infrastructure's value, productivity, sustainability, and efficiency while providing a clearer picture of constructability challenges that are resolved early in the development process. (Doumbouya, Guan, and Gao, 2016). It saves a significant amount of time and money while increasing project productivity. Building information modelling has the potential to save a large portion of the $15.8 billion in waste that the US building industry produces each year (Park, 2008). Building information modelling (BIM) helps with communication and coordination among the construction stakeholders, which facilitates construction and reduces problems and mistakes during the building phase. It enables the designers to test the designs virtually and check all their elements before implementing them into practice, as well as solve all the clashes between the building's different systems. (Mihindu and Arayici, 2008). BIM is a unique technology that facilitates collaboration between the architect, the engineers, the contractors, and others who take part in the construction. It helps in decision-making, visualizing, developing, and evaluating design variants, and is also used in construction, property administration, building administration, structural design, and cost estimation. (Coates et al., 2011).

2.1.2 Evolution of BIM

Although BIM has been around for more than twenty years, its advantages, such as more effective and efficient building design and construction, have only just become apparent. While project owners' operational efficiency has increased (Coates et al. 2011). Digital building modelling (BM) emerged in 1986, but media coverage was limited. The ISO 10303 STEP term "product model" was used until 2002, leading to alternative acronyms like building product model, or building model as shown in (Figure 2.1). As to whether BIM is an evolution of the whole construction market or only an emergence from CAD systems, BIM practitioners and thinkers have a great diversity of opinions. Certain people believe that

BIM's capacity to add data and deliver a more shared platform is the thing that makes it stand out among traditional CAD systems or that it is simply a somewhat improved extension of existing technologies with broadened functions. In the long run, how well BIM is embraced and applied by experts in the AEC sector will determine how it affects the construction industry. The debate itself shows us the weight and complexity of BIM as a tool for the construction sector´s changing. While the technology revolution continues in the built environment, there is a higher probability that as the real potential of BIM becomes clearer, the manner of project delivery will be more effective and efficient by implementing it.

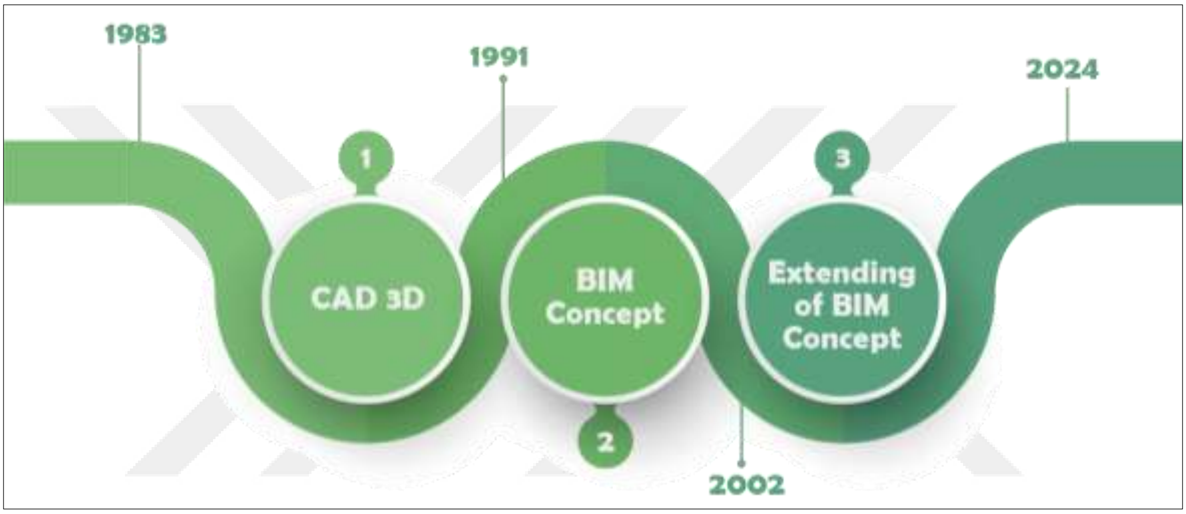

Figure 2.1: Evolution of BIM Concept (Created by Author).

Over the years, several crucial, revolutionary events in the history of BIM have been documented and have affected the purpose and scope of the field. Thanks to the development of BIM methods, procedures, and ideas, it is possible to observe how user mindsets changed from the conception of BIM to the real application of technology in construction and beyond. The two components of BIM are ideologies and information systems. As a result, BIM is a revolutionary way of thinking and doing (Borkowski, 2023). In the 1950s, project management approaches and methodologies were introduced to the industry, but there were not enough tools available for validation and verification. This led to further improvements in project management techniques, especially in the building sector (Koskela et al. 2017). Traditional communication methods like handwritten sketches and technical descriptions were outdated in the 20th century. Advancements in computers led to CAD and BIM, which challenged traditional methods. BIM has changed architecture completely and ever since 3D models are used as the primary data carrier and means for product fundamental definition (Ruemler et al. 2016). Through the years, it has been realized that teamwork between designers and tradespeople, not the learning of BIM software, which is something that is possible to learn, is the problem in this aspect (Aldiabat Albtoosh, Tarmazi Haron, and Aldiabat Albtoosh 2016).

The disciplines of research and information technology have generated the virtual and real collaborative platforms for AEC, targeting enhanced interaction with the help of wireless and cloud infrastructures. Workflow interoperability and cloud model storage are common in BIM, allowing users to share validated data and thereby preventing data re-entry. Despite national and international authorities' efforts to promote and standardize processes, various solutions will continue to develop (Miettinen and Paavola 2014).

The purpose of the BIM process is not to produce stunning 3D models that will result in fascinating, lifelike finished goods. Building information modelling (BIM) is widely recognized as a game-changer in the building industry because it provides an alternative approach based on data exchange for all 3D models, documents, and even graphics. This enables information to be efficiently gathered, stored, and managed from the beginning to the end of a project, as shown in (Figure 2.2) below. The BIM platform becomes a stimulant for decision-making and establishes a new pattern in the industry.

(Eastman 2008). To bring closure to the above subject, BIM is a vision of project design, construction, and facility management by employing digital modelling and simulation tools. It integrates data systems and thereby creates a collective of individual operators, while the life operations of the construction project are performed in a cost-effective way.

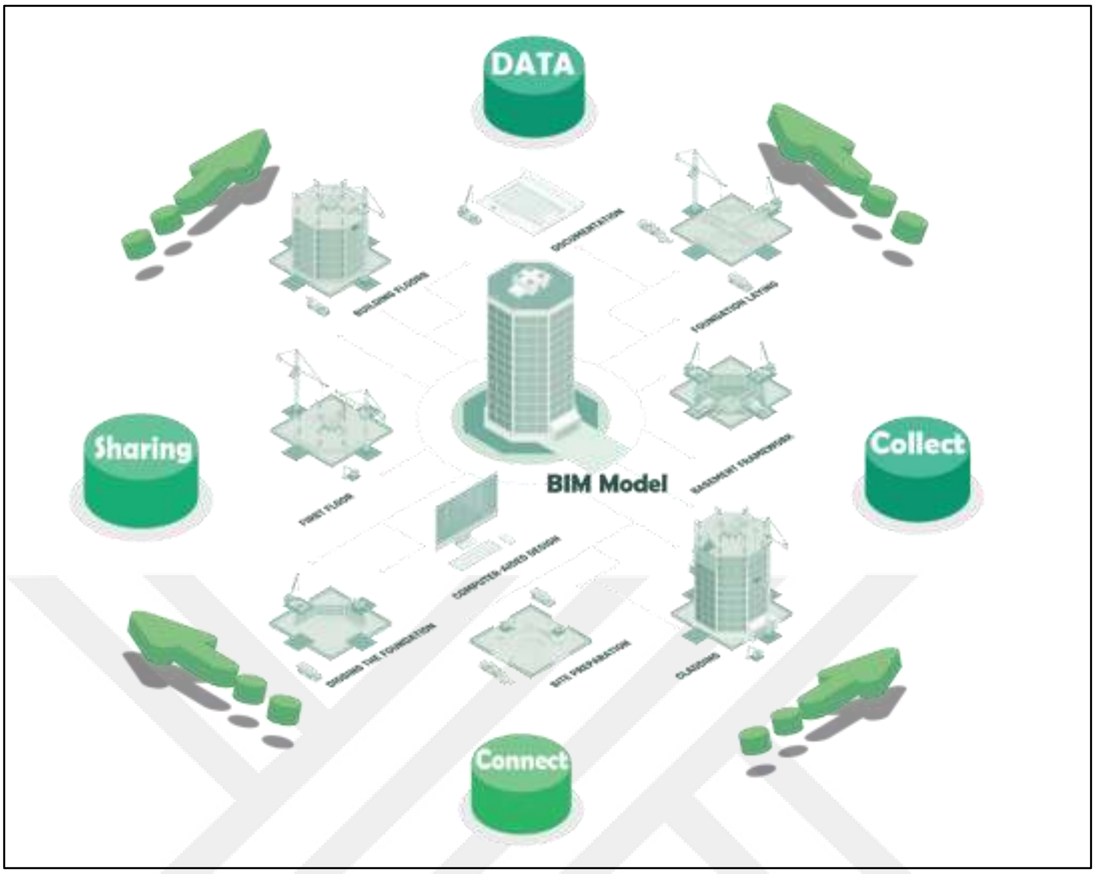

Figure 2.2: Building Information Modelling Lifecycle (Created by Author).

2.1.3 Basic Functionalities and Components

A real assessment of the BIM (Building Information Modelling) applications in AEC/FM (Facilities Management) documents shows that they empowered visualization of designs and concepts earlier and more accurately than previously, seamless teamwork between many design disciplines, and as-planned cost estimation (Raza et al. 2023). The job-site teams can also effectively coordinate and avoid clashes between systems since this reduces the rate of mistakes. Thus, through a virtual representation of the entire structure and its components, BIM is useful not only in the project management stage but also in facility management, which includes maintenance and upgrades, by making such processes easier (Chan, Olawumi,and Ho 2019). Using BIM software, a team can create 3D models automatically with no need for manual drawing, thus becoming a timesaving and accuracy enhancing tool for designers in all fields (Hei et al. 2024). This means that other design disciplines, such as the given one, can follow it successfully, thus improving control and management during the change. Moreover, such software integration with the model allows for carrying out energy analysis and makes sure that energy performance is considered in the early stages of design, thus making BIM an enabling tool towards sustainability and energy efficiency (Zhangqi 2020). Moreover, it is possible to synchronize design and construction with procurement. What is more is that the exact figure of required materials and objects in the design model copy, which is constantly adjusted to reflect any changes in construction, becomes an incredible source of information pertaining to as-built building spaces and systems (Liu 2023). This framework is implemented to the advantage of real-time monitors, natural sensors, and a distant facility control system. On the other hand, BIM software provides a platform to interconnect smart facilities, such as automation systems and sensors, and can significantly boost energy performance and operational effectiveness. Integration among different building systems, such as energy monitoring and management, on a real-time basis enhances preventive maintenance and reduces energy waste. Also, BIM is a combination of data exchange, which can be realized by building information sharing with other frameworks, such as facility management systems and asset tracking tools. Such an integration eliminates the multiple layers of control and improves communication between various systems for optimum efficiency, leading to effective cost control and better resource management. Being provided with actual-time information and analytics from BIM, facility administrators can take fast actions that will boost production and productivity over time. (Eastman 2008).

2.1.4 Benefits and Challenges of BIM

With the advent of BIM in the AEC sector, not only stakeholders in projects get facilitated, but there are also increased cost savings, better design and construction process efficiency, and project visualization advantages. There is another advantage to BIM, which is the analysis of data and simulations; thus, errors are lower and savings are achieved because of that (Miettinen and Paavola 2014). A single prepared 3D frame model was used for structure analysis, visualization, and final corrected 3D models, which greatly enhanced the supply and acquisition of produced pieces and details. About 20% less time was needed for planning, viewing, and redrawing drawings with AutoCAD errors corrected when changes happened (Migilinskas et al. 2013). Most of the work packages are organized in the same 3D model, which then makes negotiating with parties easier. As a result of a simplified procedure, suppliers and subcontractors are easier to do business with. By fixing problematic issues early on, delays were able to be avoided, coordinate the construction process, which significantly improved the workflow, and facilitate the process of handing over the building (Ruemler et al. 2016). The project manager and construction site supervisor did not leave anything unchecked in the matter of the clash detection feature in the BIM process. BIM technology is so helpful for the organization of supplies and construction procedures. The service fees related to the usage of the BIM methodology are outweighed by the savings from those chosen methods, the system's cost-effectiveness, and the materials' precise quantities by a factor of ten. For this virtual project development, a three-dimensional model was constructed to replicate the virtual work implementation management model and the construction process. Errors and project completion time were reduced as a result of the automated procedure (Eastman, 2008). Architects employing building information modeling technology should primarily profit from a reduction in the quantity and severity of challenges associated with older methods. But it will also bring about a great deal of change in the contractual arrangements and the relationships between project participants. Early cooperation between builders, architects, and other design disciplines will be necessary because expert knowledge is more beneficial at the design stage. But BIM also brings new difficulties for teamwork and collaboration, such as figuring out how to get project team members to share model information appropriately (Coates et al. 2011). For construction planning, estimating, and coordination, the contractor will need to construct the model if the architect utilizes conventional paper-based designs. After the design is finished, the project will require more money and time to create a model. But could be justified by the benefits of employing it for procurement, design change resolution, mechanical, plumbing, and other subcontractors' thorough design, as well as construction planning.

By applying BIM to the projects, they are resolving the most crucial legal issues, including who pays for, owns, and is responsible for the design, the manufacturing, the analysis, and the construction datasets. For the most part, businesses using BIM technology are required to start operating within the model of a building as a single resource that is the basis of all operational and collaborative procedures (Eastman, 2008). Despite these challenges, the construction industry's many benefits from BIM will lead to a revolution in project execution and management. It makes it possible for project stakeholders to coordinate and communicate more effectively, which reduces the possibility of errors and rework during construction.

2.2 DIGITAL TWINS AND EMERGING TECHNOLOGIES IN CONSTRUCTION

2.2.1 Definition of Digital Twin

Among the AEC-FM industries, digitization has become crucial, and it is happening consistently. Some of the technologies that are now unquestionably the most significant are sensor network data and control system automation. We’ve got one question: Are the exact images in the Digital Twin, which combine the real and virtual, a true representation of the visualization of the construction process? In short, the answer is yes. Digital Twin is a tool that is made for this, and it can help us get the exact image of the visualization of facilities and construction processes (Hosamo et al., 2022). It's possible that the AEC-FM industry may enter the fourth industrial revolution. The many goals this technology can accomplish, including modeling, decision support, and independence, make it revolutionary. Consequently, the AEC-FM The industry will inevitably transition to the fourth industrial revolution. Digitized Twin seeks to enhance project management, asset management, and asset design by combining data and information over the course of an asset's life (Zhang et al. 2020). By integrating data and information at every stage of an asset's existence, a digital twin seeks to enhance project execution, asset operation, and asset design. Currently, digital twins are being used as part of a broader continuum, ranging from simple digital prototypes with the main display method to more advanced cyber-physical systems that are based on an automated visualization approach. The digital twin convictions are effectively illustrated by the visual depiction, and the applications for construction and operation management are significant. "Digital twin" and "BIM" are phrases that are commonly used interchangeably.

While creating a 3D model of an actual object is the main purpose of BIM, imitating the object it depicts is a major goal of a digital twin. Throughout the course of a project, data and information can be shared and integrated with other Digital Twin simulators and applications. The significance of communication during the project period does not only make the digital twin an important source of decision-making but also an invaluable one (Tang et al. 2019).

Digital twins come in several varieties:

a. Digital Model: A digital model is an electronic representation of a physical object that is not capable of automatically establishing a connection with other systems. Technical specifications and blueprints are an integral part of any plan, whether it is a building design or just a collection of ideas. The fundamental difference is in the fact that the digital copy of the physical object remains unchanged regardless of alterations made to the original one. So, it provides for exchange and inclusion.

b. Digital Shadow: Digital shadows act as a one-way “transfer” between the real and the virtual world, which means that what is changing on the digital object is the outcome of the actions performed on the real-world object and not the result of changes made on the digital object.

c. Digital Twin: "Digital Twin" describes a situation in which data from both digital and physical objects is seamlessly integrated, meaning that modifications made to one will automatically impact the other as shown in (Figure 2.3) (Fuller et al. 2020). The digital twin surpasses mere 3-D modeling by providing real-time actual object data that it maps into all the time. This data helps in the evaluation, modeling, and forecasting of the targeted element's behavior, hence offering strategic insight during the duration of the project. Moreover, many digital twin simulators, as well as programs, make it possible to provide more opportunities for sharing information between the project partners and stakeholders.

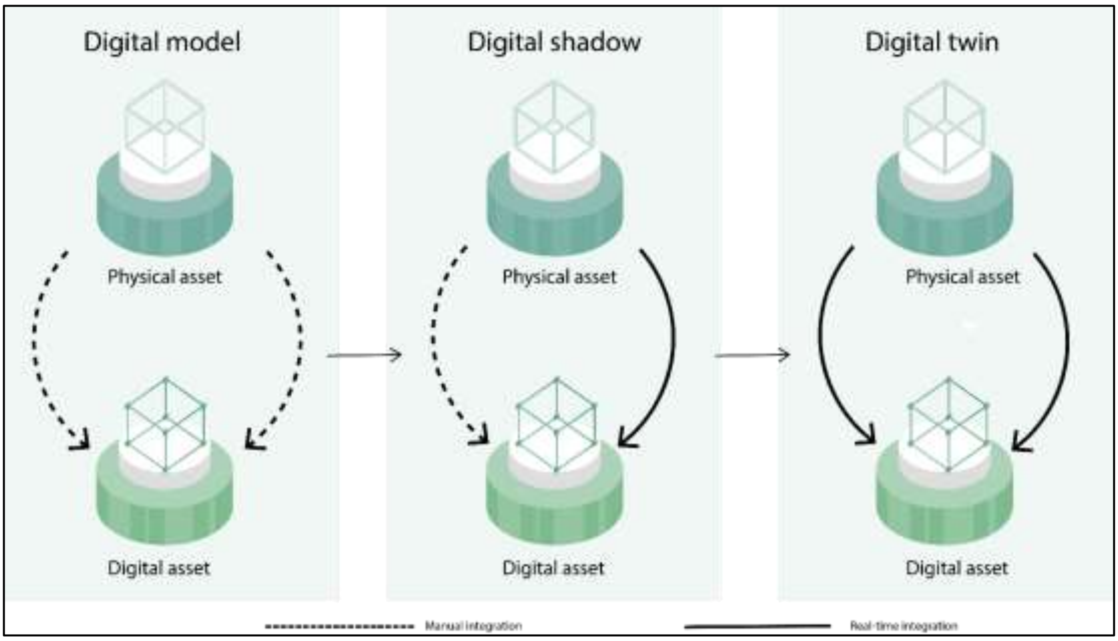

Figure 2.3: Digital Model, Digital Shadow, Digital Twin Integration (Created by Author).

2.2.2 The Importance of Digital Twin in Construction

The digital twin of the virtual model allows for the inspection and provision of management services for the physical objects, which, in turn, results in lowering operating costs and extending their lifespan and performance. It allows us to mark stored data on physical objects, giving us instant information. Digital Twin is yet to grow and expand, but it has a lot of uses in different sectors, including the building sector. However, due to industry complexity and stakeholders' tardiness, the construction sector has not fully adopted Digital Twin. The low number of research on digital twin applications in the building industry could be because of their restricted use (Palit, Datta, and Member 2017). Nevertheless, Digtial Twin in construction has not been fully embraced yet, but rather its benefits, including better project planning and coordination, more safety measures, and optimized maintenance schedules, are becoming more audible. It is expected that the number of papers and real-world implementations of digital twins in the construction business will rise as more and more industries come to understand the concept and its potential. By allowing the actual and virtual worlds to interact, data analysis and system monitoring form the basis of digital twin functions (Piromalis, 2022). The instantaneous input from a significantly quicker communication network facilitates the bridge-building process between a virtual model and a physical entity. It has been discovered that the combined power of big data analytics, cloud computing, and sensors can function with IoT as a communication platform. (Opoku et al., 2021). The data and information exchanged between the two sides is what drives the digital twin. This offers a steady flow of information on the evaluation of various physical and virtual resources during an asset's life. Like architecture, engineering, and construction, these talents are essential to AEC businesses. The implementation of digital twins in these sectors will offer the benefit of real-time tracking and analysis during the physical asset's life cycle, which will enhance project management processes and decision-making. (Ammar et al., 2022). Besides, integrating IoT technology in Digital Twins could lead to completely different approaches in building design, construction, and maintenance, thus opening different alternatives that are cheaper and environmentalist.

2.2.3 Cases Study and Examples

The state of digital twin mobilization in the construction industry is discussed in the section that follows, along with its main purposes, which include current information. Contritely, the DT of different industries like manufacturing and medicine with smart autonomous systems, the construction industry is the slowest branch of many industries to adapt to the digital twin. However, the development of efficient and smart buildings provides a solid foundation for Digital Twin use. Beyond structures with integrated automated systems, digital twins have great promise for the construction industry in terms of system synchronization, which guarantees exact coordination between real buildings and cyberworlds (cyber-physical systems). The combination of cyber-physical systems into building design and AEC industries gives up a new path toward more intricate and well-thought-out structures. (Yuan 2016). They can facilitate project coordination, resource management, and machinery utilization in construction processes that aim to improve efficiency and productivity.

Utilization of digital data for operational and life cycle management will happen in the long run. This is possible if there is enough information that has been collected by the built technology. This is the primary output of the Digital Twin, which is based on information gathered from the sensors that are incorporated into these systems. Building Information Modeling (BIM) and other features, 2D and 3D models, timetables, contracts, construction documents, operational data collected by embedded sensors, and data from artificial intelligence and machine learning are all included in digital twin (DT) features related to design and the built environment (Tang et al. 2019). Together, these interchangeable components can give operators of smart buildings the ability to monitor, manage, identify issues, and enhance the efficiency of their structures in real time. The service providers will make informed judgments that will promote energy efficiency, reduce maintenance costs, and advance occupant comfort by utilizing the data and information provided by the digitization process (Madubuike, Anumba, and Khallaf 2022).

The Frasers Tower in Singapore is one example of a built environment application of DT, offering a networked workspace. For this project, Bentley Systems and Schneider Electric worked together to gather data from 900 sensors for temperature, lighting, and air quality as well as 179 Bluetooth beacons in conference rooms as shown in (Figure 2.4). This technology has an embedded sensory system producing about 2100 measurements through it that can be linked to the cloud through Microsoft Azure to monitor the environment and therefore reduce power consumption. To this end, now the construction industry has the opportunity, due to the technology of the IoT, to survey and analyze building performance in real-time. In short, the device facilitates the services of preventive maintenance and predictive analytics. Apart from that, one of the positive aspects of this data is that it can lead to data-driven decisions on budget and space allocations, which in turn will increase workforce productivity and the satisfaction of the workers. However, while the smart nation approach is being carried out in Singapore, the adoption of digital twin solutions still lies lower than their share in other sectors of industry. But there are more people who see the advantage of virtual twins' usage in the building world, and such a system is being adopted by more organizations. A BIM detailed 3D model with all needed material specifications and information, which is a helpful tool for a facility designer, constructor, or operator, is capable of being utilized to generate the facility's digital model. Therefore, BIM makes a significant contribution that includes geometrical information, particularly for the new projects that need an exact and detailed demonstrated representation. Laser scanning or photogrammetry may be helpful in the automated data acquisition process for geometric data transfer when working with existing structures that lack digital models. (Ioannis Brilakis et al. 2019). Nowadays, Digital twins are crucial in construction, enabling real-time observation and modeling tangible assets, improving efficiency, predicting difficulties, and increasing project management efficiency by combining BIM with digital twins.

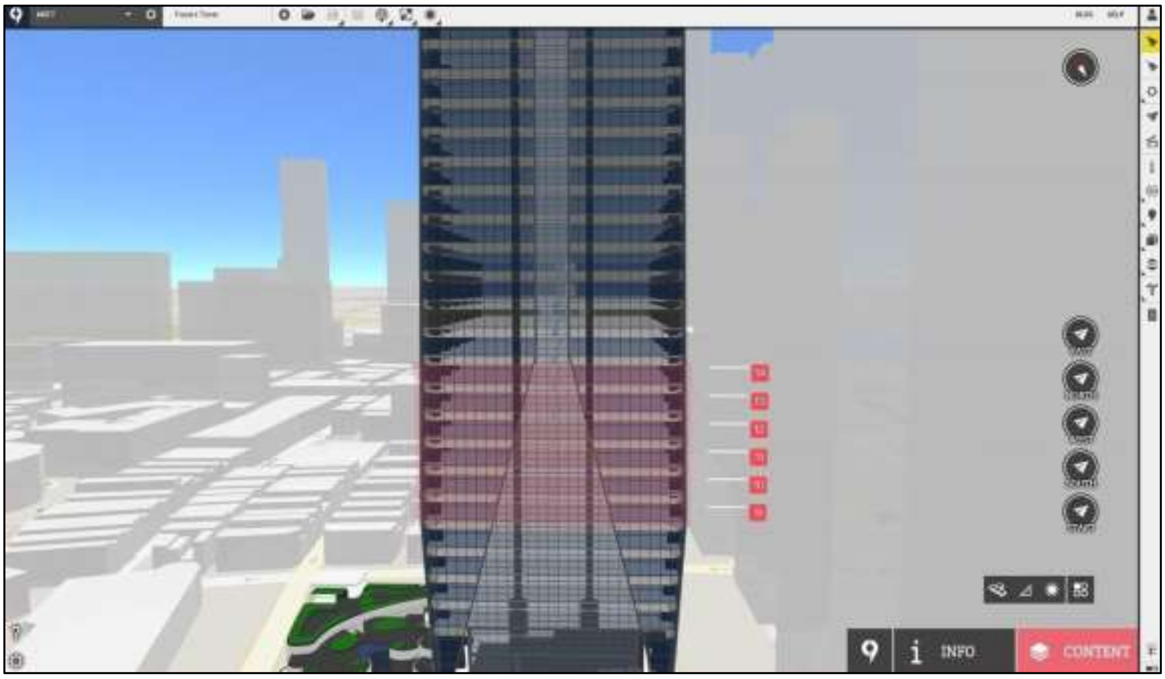

Figure 2.4: Singapore Frasers Tower, Digital Twin (Microsoft Stories Asia. 2020).

2.2.4 Challenges and Benefits of Implementing Digital twin.

A review of the relevant literature reveals that the use of digital twins in the built environment is now possible thanks to these creative technological advancements:

a. Real-time monitoring IoT technology and monitoring cameras can collect real-time data from buildings' interiors or construction sites, providing synchronous visualization on neutral platforms. Such a perspective is marked by the information advantages project managers have for better management (Deng et al., 2021).

b. Accurate predictions simulations constitute the most advanced technologies available, which take building status into consideration and evaluate the performance of buildings and construction projects (Ioannis Brilakis et al. 2019). They use complex modeling skills, as well as algorithms, to deal with behavior patterns, find solutions, make the right decisions, and discover risks as early as possible.(Yuan 2016).

c. The decision-making system real-time data and predicted outcomes are used in most studies to guide human decision-making. Modern digital twins integrate real-time information with automated processes, assisting in managing the built environment through strategy scenarios and look-ahead simulations (Hosamo et al. 2022).

d. A specific representation example of a real-world setup, including its functionality, upkeep, repair history, state of health, and additional features. It makes it possible for these organizations to gain knowledge about the performance and behavior of their real counterparts without the need for physical intervention. . Data from the physical assets can be gathered over time to update the digital twin. Following that, this data can be utilized for predictive maintenance and decision-making (Madubuike et al., 2022).

e. Sustainable Development, through a comparison of the present state to past asset conditions over time, the structure industry has proven to have undergone a lot of changes. This creates a possibility to advise investors and managers of such resources about necessary measures for prevention of their further decay and ensuring their durability (Gref, Steel, Flath, 2020; Brilakis, Ioannis et al., 2019). The structural assessment gives us a chance to identify any damage that may be there or areas that require temporary solutions. This helps us to proactively tackle the maintenance issues that need to be addressed as soon as possible.

However, while the possibility and benefits of digital twin technology may be tempting, so do the risks and vulnerabilities. Hence, using the digital twin technology can be considered twice before applying it as technology (Hosamo et al., 2022). In addition, organizations need to make sure that they have access to resources and efficiently manage technologies to make digital twins more available for practical purposes, which, unfortunately, is still full of gaps for further studies that will fill and strengthen the knowledge of this technology. Apart from the data loss that occurs during the document transfer process, there are still issues with a number of factors, such as the programs' logical compatibility and the information loss caused by external environmental disturbances (Deng et al., 2021). These impacts may result in grave consequences, including a threat to the entire system because of the corrupted file or any incomplete data transfer. Additionally, network connectivity problems can also contribute to data loss during the transfer process. Furthermore, several types of IoT sensors collect either the same or different surrounding data, and their data types may not be consistent, which might complicate information examination. The inexplicable nature of the construction industry also plays a role in the gradual adoption of digitization. The adoption of Digital Twin in the construction sector poses a challenge because of the intricacies needed in creating a model and the industry's inherent unpredictability (Ioannis Brilakis et al. 2019; Liljaniemi and Paavilainen 2020). The lack of standardization in processes and the inability of systems to cooperate to produce a single digital representation for various software systems pose additional challenges for the use of digital twin technology in the construction industry. By and large, the industry's already-inherent mentality and hesitance to embrace changes can adversely influence the realization of widespread automation in construction as well.

2.3 SENSORS IN THE BUILT ENVIRONMENT

2.3.1 Inbuilt Sensor I2dentification

When it comes to indoor air quality, thermal and visual comfort, and energy efficiency, indoor sensors play a big part in the built environment. The constructed surroundings should ideally achieve Energy-related effectiveness while ensuring high quality indoor environmental conditions since it has very big implications for occupant productivity and health conditions. Hence, an intelligent sensing network that links environmental factors (like air temperature and humidity) with building environmental control techniques (like space arrangement, window position, and air conditioning) is necessary to maintain these targets (Malekmohammadi et al., 2023). Employing indoor sensor data now, building managers can come up with the right decisions to keep energy usage at its best level and maintain the comfort of the built environment.

Non-destructive testing (NDT) is a subset of sensing systems utilized for ongoing monitoring. NDTs are generally implemented in a wide range of ways, some can be part of an on-site assessment of a framework's attributes ignoring compromising its functional usefulness, or they might be implemented under carefully monitored testing conditions (Palma and Steiger 2020). The components of building environment monitoring (BEM) and structural health monitoring (SHM) are all spelled out through a list and explanation of their sensors. (Zinno and Obrien, 2023) Ultimately, only the long-term health of the structures where high structural integrity is vital to functional value and life safety is best monitored by SHM systems. The SHM uses a data analysis system and a sensing network to evaluate the mechanical and external characteristics of a framework. Determine any damage or structural anomalies. The data acquiring system (DAS) and data acquiring equipment (DAE) are essential parts of a sensing system(Toledo et al. 2000). Sensors as well as data acquisition devices that include data collection, storage, and transfer functions are included in data acquisition equipment (DAE). More commonly, the scope of the BEM is not only confined to the systems but also the whole public domain, for the duties of maintenance, security, and user comfort of the occupants. Building environment monitoring (BEM) systems can sometimes be applied to the general environment for the purposes of maintenance, safety, and comfort of occupants, which is unlike the typical ap plication where they are only used to monitor certain systems. A building energy management system provides immediate information on the quality of the building. This significantly helps to save energy and reduce operating costs (Malekmohammadi et al., 2023). With BEM systems being capable of detecting environmental factors and structural health in a continuous way, proactive maintenance and smart resource management are both possible. Sensor Types Applied to the Built Environment. Stakeholders are pleased with the performance of sensing and communication technologies, which are crucial components of modern buildings and are well-liked by designers, owners, operators, and residents. The information delivered by these technologies remove discrepancies in energy demand forecasting and supply and hence crucial information is gained about the structure composition, performance, safety, and cost-effectiveness. Through being given the opportunity to monitor the instantaneous attributes like energy consumption, temperature fluctuation and occupants' density, all stakeholders will be able to take the relevant and well-informed decisions to make the building run in a more optimized manner and sustainability oriented as shown in (Figure 2.5). More importantly these technologies allow for localizing investment problems and discovering areas where spending can be cut down as a result generating a more pleasant and productive space.

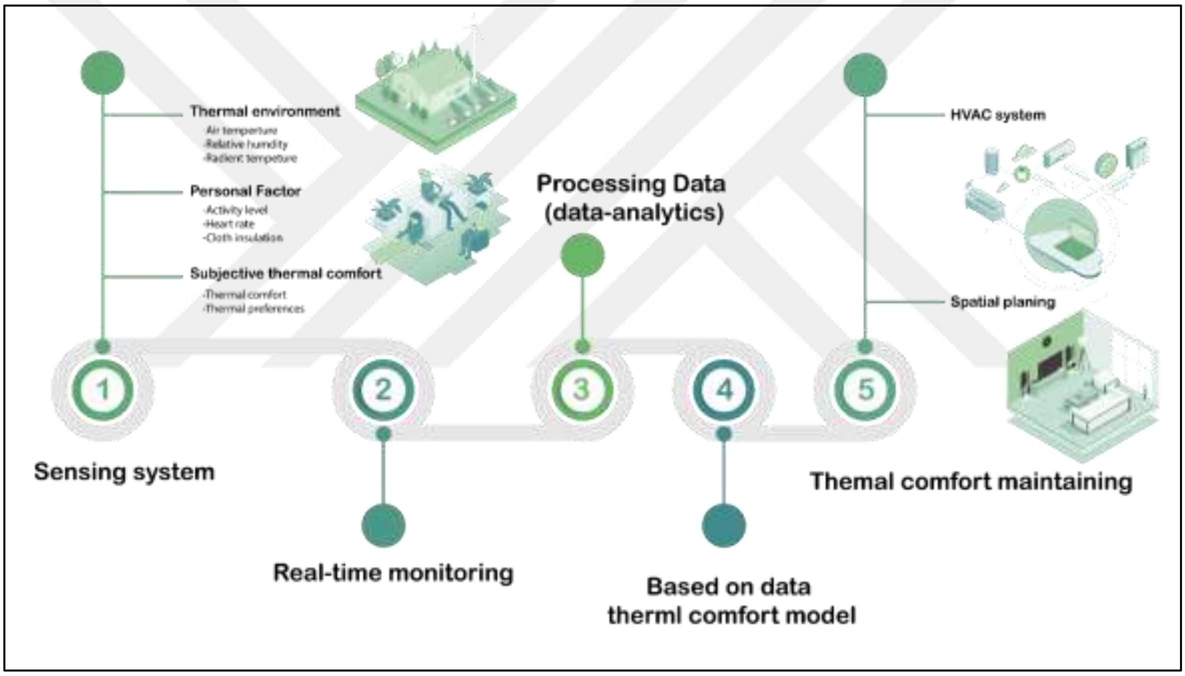

Figure 2.5: Thermal Monitoring by Sensing System for Sustainable Space Approaches**.**

2.3.2 Sensors Type and Their Applications.

Building energy consumption accounts for between thirty and forty-five percent of global energy demand. It is now crucial to reduce energy use for the sake of the environment because of the world's growing population (Dong1 et al. 2019). Such an analysis will allow all the concerned parties to have an idea of the very possible advantages and disadvantages of introducing sensor technologies into buildings that are aimed at being sustainable and energy efficient. It is of prime importance for decision-makers to remain on the cutting edge of technology in the field of sensors because it will enable them to install the latest and most effective solutions, helping to reduce energy use and negative impacts on the environment. In (Table 2.1), there is a summary view of the main attributes and competencies of the different kinds of sensor devices and communication technologies that are presently available. By using this data, stakeholders are empowered to decide on appropriate remedies based on the strengths and specific problems that they are trying to address. Finally, the combination of sensor technologies in buildings can easily generate cost- savings, improve occupants' comfort levels, and reduce carbon dioxide emissions.

Table 2.1: Sensor Types and Their Role in Built Environment.

Sensor name	Role in built environment sensing	Sensor type
Temperature sensors	Temperature sensors utilize many pieces of hardware such that they can detect the ambient temperature where these sensors have been placed. The need for temperature sensors that ensure temperature measurement in buildings is fulfilled by available products from different manufacturers. Performance varies with precision span, response time, and issues of use (Cheng and Lee 2016).	1. Thermocouples 2. Resistance temperature detectors (RTDs) 3. Thermistors 4. Semiconductor-based sensor
Air quality sensor	In addition to identifying the presence of unwanted gases, air quality sensors track the dynamics of the air quality in the surrounding area. These sensors thus have roles in creating and maintaining safe and nice cohabitation. These sensors can not only track the current air quality in real time but also send alerts and warnings to occupants and/or building managers if air quality drops to unhealthy levels. Hence, such a proactive system is useful in terms of the quick response and tackling of the possible health risks that can relate to poor air quality (Cheng and Lee 2016).	1. Oxygen 2. Carbon monoxide 3. Carbon dioxide 4. Smoke sensors
Motion sensor	The motion and occupancy sensors that do thermal detection can trace where and how	1. Passive infrared

Table 2.1: Sensor Types and Their Role in Built Environment.

Sensor name	Role in built environment sensing	Sensor type
Motion sensor	people move around a room. By generating radio waves or ultrasonic waves and timing how long it takes for the waves to return to the source, these sensors measure distance (Hayat et al. 2019).	2. Time-of-flight sensors 3. Infrared array sensors
Ultrasound	Ultrasonic sensors may detect human movement and estimate distance to establish occupancy detection. It uses the reflected ultrasonic signal to concurrently identify motions associated with location and occupancy. This technology is commonly used in smart buildings for energy efficiency and security purposes. Moreover, like ultrasonic sensors, they are also used to detect obstacles and target object positioning in robotics systems (Malekmohammadi et al. 2023).	1. drip-proof. 2. high frequency 3. open structure
Contact Sensors	The inductively powered system of two pieces is designed for magnetic field detection in the middle region to figure out if the object is in contact with another. The sensors in the building enable feasible communication. Typically, this sensor is employed as a device to detect whether a window or door has been opened. A door's sensor is installed with one piece on both within the door frame and the door itself. The magnetic field is disturbed when the door is open, and the sensor reacts by sending out a signal. Such sensors are often very functional for building monitoring and security purposes (Malekmohammadi et al. 2023).	1. Vault contact sensor 2. Metal contact sensor for roll up door. 3. Standard recessed contact sensor
Humidity sensors	Humidity sensors detect how much or what proportion of water vapor is present in the surrounding atmosphere. Furthermore, they are also usable inside a building to continually	1. Capacitive 2. Resistive

Table 2.1: Sensor Types and Their Role in Built Environment.

Sensor name	Role in built environment sensing	Sensor type
Humidity sensors	monitor the rates of water penetration, rate of evaporation, and indoor humidity (Malekmohammadi et al. 2023).	3. Thermal
Light sensors	Passive light sensors are made to convert light energy, which usually falls into one of three categories: human eye visible (430–770 THz), infrared (300–400 THz), and ultraviolet (800–300 PHz). The sensor electrode responds to light change, and the output signal is subsequently used to turn the light either on or off whenever the light becomes brighter or less bright than the pre-selected intensity. Sensors of artificial light are mostly employed in automatic lighting to conserve power and supply people with comfort. While being deployed in security systems, these sensors play their role in detecting movements and switching lights on to ward off possible trespassers (Almadani et al. 2020).	1. Photoresistor 2. Photodiode

With the advent of IoT, all types of sensors have been added to the built environment, mostly indoor climate comfort, to measure temperature, humidity, air quality, occupancy levels.

and some other parameters related to the wellbeing of the occupants and energy efficiency in real-time. These data could be used to modify the heating, cooling, and air conditioning systems to enhance comfort as well as cut down on energy costs. Additionally, by interpreting the data in this way, it becomes easier to recognize patterns and trends, which will enhance the building's overall management. Through the system of monitoring and analysing available data, building managers can make smart decisions that enhance occupant comfort and help save energy consumption.

2.3.3 Applications of Sensors in Building Management Systems

Every part of our life is impacted by sensors and other embedded technologies. Since most people spend most of their time indoors, building automation, also known as smart building, is an essential sensor technology application in people's daily lives. (Gunes, Peter, and Givargis 2015). The range of sensors used in smart buildings to gather data on the environmental level includes temperature and air pollution. Gathering information or data is a process that is used to aid in centralized decision-making when it comes to HVAC framework operation.

(Revel, Arnesano, and Pietroni 2015)The inexpensive thermal comfort monitoring apparatus is comprised of an IR scanning sensor used in an experiment and a central unit with built-in sensors that allow the measurement of air temperature, relative humidity, air velocity, and sun radiation. The main part of this system is basically made up of a dozen thermopiles mounted on the ceiling of the room that is inhabited. With this software in place, having a microcontroller (Arduino Mega Board) allows you to scan all the interior surfaces automatically, identifying the distribution of temperature. Additionally, algorithms are included to enable the estimation of temperature and comfort characteristics for many positions in the environment, including the PMV (predicted mean vote). Thanks to software developed for the Android platform, the end user can manage and operate the monitoring equipment. The system is designed to generate real-time PMV maps, which can be perfectly useful in providing prompt feedback for the controller. On Android systems for management and monitoring gear, the flexibility is higher. Through this, users can get data and analysis right away. The system utilizes recommendations for designing convenient and energy-efficient buildings as it provides temperature data and prognoses optimal environmental conditions, which can help to save energy costs, with efficiency increasing in building operations as a result. Moreover, the system can also be integrated with other smart building technologies to enhance its abilities. It will be a complete solution for building management.

It is in a different manner that sensors are placed in the construction surroundings for the aim of detecting indoor temperature comfort. To human thermal comfort (HTC) sensing, report on a single-chip integration of CMOS compatible MEMS temperature, humidity, and a highly sensitive flow sensor by (Izhar et al. 2021). The current multisensory chip (MSC) has a few advantages. First, temperature, humidity, and flow sensors are fabricated on a single chip using an inexpensive Three-mask manufacturing process. A proper packaging layer (parylene C) serves as both a humidity detecting layer and a packing layer for temperature and window sensors. To attain high sensitivity, a fully released thermosensitive calorimetric flow (TCF) sensor with two sets of detectors is constructed (Malekmohammadi et al. 2023). A built-in (speed, pressure, and temperature) sensor was evaluated in several air change situations in the sequence of speed, humidity, and temperature. As per the experimental findings, neural chips (MSCs) have the prospect of being used in applications of intelligent building systems as a solution to the problem of sensing human thermal comfort while exploiting the resources of the Internet of Things (IoT). Thus, these sensors may provide information about the internal atmosphere of a building that helps design a more sustainable energy management system and improves occupant comfort. Encouraging and sustainable building management could lead to the integration of MSCs into Internet of Things systems.

Using collected data from IoT devices based on air quality, this study proposes a smart, wireless climate sensor node with an independent operation mechanism and charging strategy (Kuncoro et al., 2022). Both thermal comfort (TC) and indoor air quality (IAQ), commonly referred to as the current indoor environmental evaluation, are necessary for occupant comfort(Krzaczek and Tejchm 2012). To monitor and analyze thermal comfort and indoor air quality, Kuncoro and his partners collected data and logged its results into the cloud via the Internet of Things protocol. The findings of the analysis will be used to regulate and manage the room's thermal comfort, which is a spatial concern for the occupants. Small form factor and low-battery function are the features that a sensor node (SHT sensor module) should have in the design stage. It is comprised of an integrated AVR microcontroller, a humidity and temperature sensor (SHT sensor module), and a wireless module that stores power in a supercapacitor. A low-power algorithm and an Internet of Things system were implemented to reduce the total energy consumption while the system was operating. Mandatory air ventilation provision is becoming more imperative. The sensor nodes are where data is collected and sent wirelessly to the central system, which is the hub that does the fine tuning in an instant when it is urgent. By continuously tracking and analyzing the interior thermal conditions, the system can fine tune energy utilization and improve occupant well-being. Therefore, for generation cycles, it is efficient in both the energy collection as well as the use of the little power. To track personal comfort levels during the experimental shift indoors, the gadget was connected using an Internet of Things monitoring system. Based on the study's outcome, temperatures were indicated to be at a median of 25–30 °C and relative humidity at 30–40%, with variation here and there.

For the detection of air quality, this sensor had to be applicable on a small scale, so as fast a sampling time as possible. On the other hand, the provision of a secure location for the comfort zone is also simple. This indicates the sensor technology that is employed in the experiment provides a measurement of the indoor thermal comfort, which is very significant, energy conservation, and comfort of the occupants. Consequently, these could pave the way for more sustainable building practices and habitat-friendly living environments. Besides, the sensor is embedded with sophisticated algorithms to achieve precise parsing of the collected data, giving out valuable information for enhancing the quality of indoor air. This green sensor as a part of the building can facilitate the decrease of energy consumption, promote the creation of a healthier lifestyle for the users, and give the stakeholders access to live data to help them have more effective control over the indoor environment and make better decisions about energy usage and the management of air quality.

Through the use of sensors, the approach to building designs for energy efficiency, controlled operation, and the comfort of the occupants gets receptive to change. Together with BIM, IOT, machine learning, and digital twin technology, smart and green buildings of the future might benefit from unlimited opportunities. By integrating these technologies, building owners and managers can streamline operations, improve efficiency, and ultimately create more comfortable and productive environments for occupants.

2.3.4 Obstacles and Barriers in the Process of Sensor Installation

To ensure the properness and authenticity of the data, technical challenges occur due to the implementation of sensor networks, and these should be considered very carefully. Challenges are primarily associated with variations in thermal comfort measurements and values, along with privacy and cost, as follows:

a. **Energy source:** Sensing systems that identify, interpret, and transmit data need to be connected to power sources so that the sensors and associated hardware can pull in the power. To be able to provide their own support, these autonomous systems need to secure a power source that is sustainable. There are diverse popular power sources, such as photovoltaic energy or rechargeable energy, that are not for repetitive use and have to be replaced on a regular basis (Malekmohammadi et al., 20223).

b. **Covering system**: The sensors need to be protected from the outside environment without affecting their functionality. Most especially when installing the sensor system in a building that will be open to the environment. A lot of sensors are made to fit inside buildings. For example, usually in the current facilities of the structures or during the construction of such structures. The casing of these sensors needs to be ruggedized for their environment so that the sensor and its surroundings are protected and not damaged (Dong et al. 2019).

c. **Environmental response:** The sensitivity of the sensing system can be influenced by the condition of the surrounding environment, like its humidity and temperature. It is imperative to make improvements in the system in which these factors should be measured and considered, which will help guarantee the accuracy of the results that may keep changing dramatically considering the variables. A small variation in environmental conditions can cause a radical change in the outcomes the sensor readings will deliver as well as the way information is shared (Al Horr et al. 2016).

d. **Thermal comfort variation**: Each person has a different level of thermal enjoyment in the built environment. Because of this, it could be challenging to ascertain the appropriate range of indoor environmental temperature to accommodate each passenger's preferred temperature. Therefore, more investigation is needed to determine the ideal temperature in real-time settings to please every occupant (Izhar et al. 2021).

e. **Safety and Privacy**: Traditional building automation systems (BAS) are being replaced by cyber-physical systems (CPS), which tightly integrate sensing, computing, communication, and control to create intelligent buildings that can sense their surroundings and detect the presence of occupants. However, most sensing systems for smart buildings are made primarily for utility, with little regard for safety and privacy (Dong et al. 2019).

Even with all those difficulties, sensors are still very important to the development of building environment systems as they provide valuable data for optimizing energy efficiency, comfort, and overall building performance. Through in-time data analysis of the condition of temperature, humidity, occupancy, and air quality, sensors will allow building managers to make intelligent decisions, which can lead to cost reduction and customer satisfaction improvement. Besides that, the rapid development in sensors forms the basis of the sophisticated image of green buildings.

2.4 EMPLOYING IOT AND BIM INTEGRATION, A DIGITAL TWIN APPROACH

2.4.1 IOT Integration with BIM for Instantaneous Data Collection

The Internet of Things (IoT) has emerged as a digital twin approach to enhance building environmental monitoring and management performance and advance energy efficiency, and the integration solution is founded on a BIM platform. Instantaneous data gathering and analysis are made possible by this method, which also makes it possible to apply predictive maintenance plans and gain insights into the operation of buildings (Desogus et al. 2021). Building managers may ensure a more sustainable built environment, improve energy use, and save operating expenses by merging BIM and IoT technologies. Real-time thermal condition tracking is achieved by connecting BIM platforms with sensor data to generate a BIM model that updates itself (Valinejadshoubi et al. 2021).

IOT sensor integration with an IOT workflow creates a BIM environment that enables the collection, compilation, and visualization of data in a fast and easy-to-understand manner. Services such as facility management, clients, or engineers can enhance their services with the real-time monitoring process of BIM, which detects and visualizes precise sensor data accurately (Villa et al., 2021). Building managers and building supervisors can go beyond normal criteria monitoring by visualizing or reviewing building thermal comfort throughout the building.

BIM models help to assess the power-saving methods of the structure implemented in the design stage. With the provided design characteristics, such as the orientation, the potential to receive information on all building elements, the material, and every component parameter, this can be done by conducting further studies and installing sensors in the structure so that real-time data can be obtained based on the actual performance (Kontothanasis, Krommyda, and Roussos 2019). This makes it possible to assess energy usage and possible design areas for the building with more accuracy. BIM level 3 is still being developed, despite level 2 being extremely clearly defined. According to BIM level 2, a building's 3D (construction parts and quantities), 4D (time), and 5D (cost) representations should all be evaluated in the model. Lifecycle management and fully integrated BIM (iBIM) are the main and most important elements as elaborated on in (Figure 2.6). It thereby implies that the model of the building would contain information including operations and maintenance in addition to the design and construction data throughout its lifetime. To improve chances for further BIM integration with other technologies for a digital twin approach, BIM Level 3 seeks to provide a smooth information flow from design to operation. In the end, BIM Level 3 lays the foundation for a additional networked and data-focused methodology to structure management and design (Goodhew 2016). Therefore, combination of a tracking framework towards BIM is necessary to take BIM to the highest level.

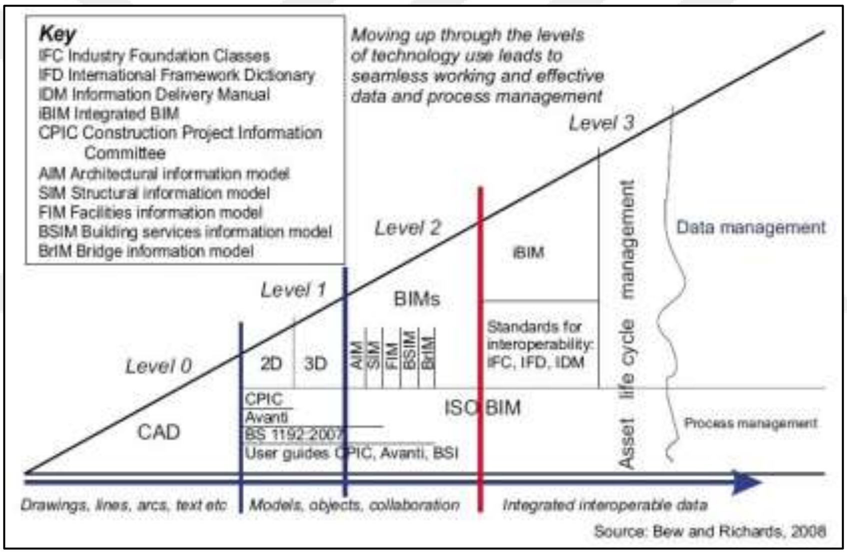

Figure 2.6: BIM Levels (Kontothanasis, Krommyda, and Roussos 2019).

The role of management tools has gone for a fresh revamp due to building sensors and IoT being introduced in the construction industry. Specifically, an important answer derived from the industrial industry has emerged: Digital twins, often referred to as cyber-physical systems (CPS) or cyber-physical models, are fast emerging as a leading-edge technological concept. Cutting-edge technology is brought together to have a computerized edition of a actual object that functions identically to the data used to create it. Through learning algorithms, data gathered in an actual environment is shared with that of the suggested virtual model. The virtual model can process data from the real building using learning independently algorithms, which allows it to reflect the realities of the corresponding building and forecast the structure components' failures, relevant insights, and state of functionality (Riaz et al. 2017).

(Asghari, Rahmani, and Javadi 2019) define as the Internet of Things is "an ecosystem that incorporates smart objects equipped with sensors, networking, and processing technologies integrating and working together to provide an environment in which smart services are taken to end-users." The Internet of Things (IoT) is a revolutionary technology that has enabled people and things to connect at a speed and scale that was unthinkable even ten years ago (Gubbi et al. 2013). It permits autonomous judgments on connected devices through algorithms and machine learning, permits innovative approaches to enhance quality of life (Mannino, Dejaco, and Re Cecconi 2021), and can appropriately inform users to make optimal decisions. As a matter of fact, the DT can be configured as a simple dashboard that shows key performance indicators (KPIs) like temperature, pressure, tilt, power, voltage, and other parameters produced by the connected devices. This Instantaneous data can be examined and used to make informed decisions, troubleshoot issues, and optimize processes. The internet of things (IoT), with the remote devices' monitoring and controlling, is greatly improving effectiveness, enhancing thermal comfort, and bringing extra convenience to the users. Overall, IoT and digital transformation will enable the ecosystem to connect devices or layers of the environment together to form a smart world. This is because sensors are installed on surroundings or system components (Zhang et al., 2021). This makes it possible for the DT to actively participate in any process or product, from the stage of design to the stage of functionality. The term "digital twin" originated in the industrial sector because of digitizing production processes and equipment and integrating sensor networks (El Saddik 2018). A design-phase simulation and a digital twin differ primarily in that the latter operates solely in a virtual environment, while the former needs a physical asset and sensor network. (Boschert and Rosen, 2016), discuss how digital twins could possibly comprise different simulation models, such as descriptions of the behavior of engineering operations, and record useful engineering and operational data. Many inspection models are being implemented by digital "twins" because they can explain behavior, solve specific problems, and create alterations that are applicable to real systems. In addition to managing the project and its elements, BIM offers a cooperative platform for managing stakeholder relationships (Riaz et al. 2017). In general, BIM improves coordination and communication amongst all stakeholders in a construction project, which increases efficiency and precision. The construction sector may leverage cutting-edge technology to optimize building design, construction, and maintenance procedures by employing both BIM and IOT for digital twin's approach.

2.4.2 Case Studies for IOT Integration with BIM

Integrating an IOT and BIM towards a digital twin approach requires merging 3D models, analyzing accurate data, conducting deep investigations on the true state of the assets to determine their conditions, and getting readings on them. Sensors on the asset send data for analysis by algorithms, followed by visualization of the data in the 3D model generating real-time data A sensor node's microcontroller simulates raw sensor input to provide humans with usable and interpretable information that is then processed further by the hardware and network components. The list of sensor nodes provides data processing to the computer connected to the system. Users are introduced to malfunction detection and cloud sensor dashboard viewing features through this platform system (Gubbi et al. 2013). Data output in IoT refers to BIM at the last stage of architecture or combined as a BIM dashboard on display. The linkage of data from IoT to BIM is responsible for a complete view of the building in one sense, and the building's functionality in another. This goes a long way in the data-driven decision-making process, where users can make informed decisions through live data and predictive analytics.

A three-dimensional (3D) model of the structure with high-precision and valuable data is mostly demanded for the modeling phase that seeks to either sense or utilize the information. Once the 3D model is obtained, the sensor location can be accurately identified and suggested through the visual items within the model, so that the sensor can be fully placed in the proper direction and orientation. The development of scenarios and interactions that resemble reality can be accelerated through visualization. The implemented sensors send their data, which is then processed by a database to extract pertinent information. Based on the measurements that are presented, the model is updated. They enable physical layout supervision and real-time virtual monitoring to detect threats when operational. Aside from helping the models determine the maintenance or rehabilitation sites where necessary, the data will be customized for a specific area. The combination of the structural model, which itself is a replication of the system, with the data processing approaches serves as a digital twin of the building's health. Therefore, it is easier to monitor and track the environmental conditions and structural health from a distant site (Malekmohammadi et al., 2023).

To increase the sustainability of a building and cut down on energy waste, the paper takes the case of a smart integrated system, which comprises BIM for the design process and IOT for the collection of real-time data through sensor technologies. Sustainable greening of smart buildings could be possible if the combination of BIM and IoT proves to be efficient, as per their findings. Studio Wio Node and the Arduino Yun Mini became very important applications to obtain for the autonomous air conditioner project as essential internet of things (IoT) devices for sensing in COZyBIM. It featured a carbon dioxide detection sensor along with the DHT22 temperature and humidity sensor. The environmental comfort data which was previously recorded was modeled and presented into a multidimensional BIM model. This blueprint allowed you to clearly understand the indoor air quality with the utmost levels of details as well as building energy efficiency. Through the Wu and Liu (2020) study, the researchers were able to do an environmental field test of their model and prove the accuracy of results. Nonetheless, Wu and Liu didn’t bring the automation into BIM synchronization to get the highest connectivity between the IOT sensors and BIM model. The advantage of this would be in achieving the update of the visualization layer without the need of using a different record-keeping system to gather and statistically evaluate the inforamtion and then subsequently feeding the results into the BIM to obtain the intended goals. Furthermore, they employed (Wehbe & Shahrour, 2019) in building information modeling (BIM) and smart monitoring to standardize and maintain indoor comfort levels. The BIM model was connected to Arduino software, which produced CSV data on a regular basis. Sensor data could be integrated into the 3D model due to interactions between the CSV file and the Dynamo Revit software. However, the lack of automation resulting from data being stored in CSV format, which does not integrate well with the BIM model, prevents the visualization from updating instantly with real-time changes.

(Natephra & Motamedi, 2019) were using the Firefly plugin for Dynamo, and real-time sensor reading transmission from Arduino Uno to BIM was made possible The most distinguishing characteristic is that the prototype system uses visual script with Unreal Engine, and this fills the application with a stream of sensor data similar to the sensor readings set in the engine. Still, there is no visualization of data in the BIM model for more effectiveness in terms of taking actions and the display of real assets. Integrated solutions using BIM sensors are outlined in (Table 2.2), along with some of their drawbacks.

Table 2.2: Comparing the Variations Between Previous Research Findings.

BIM and IOT INTEGRATED					
Authors	**Sensors**	**Tools**	**Automated integration**	**Automated Visualization**	**Limitations**
Wu & Liu, 2020)	Temperature, Humidity, CO2	Arduino, COZyBIM, Seeed Studio Wio Node	Yes	No	Lack of automated visualization
(Wehbe & Shahrour, 2019)	Temperature, Humidity, Light	Arduino, CSV file, Dynamo, Revit	Yes	No	Lack of automated visualization
(Natephra & Motamedi, 2019)	Temperature, Humidity, Light	Arduino, Revit, dynamo, Unreal engine	Yes	Yes	Lack of automated visualization and data return visit
(Chang et al., 2018,)	Temperature, Humidity	Arduino, Revit, Dynamo, Firefly	Yes	Yes	Lack of stability in the connection
(Zanchetta & Cecchini, 2018)	Temperature, Humidity, lighting	Revit, Grasshopper, ladybug, Honeybee, Galapagos	No	No	Using computational modeling and simulation with a lack of automation and gathering empirical data

Table 2.2: Comparing the Variations Between Previous Research Findings. (Table Continued)

BIM and IOT INTEGRATED					
Authors	**Sensors**	**Tools**	**Automated integration**	**Automated Visualization**	**Limitations**
(Teizer et al., 2017	Brightness	BIM, Dynamo, BLE	Yes	Yes	The integration of technologies is causing delays and errors in the automation process.
(Enrico & Grosso, 2017)	SHM sensors	Revit, Excel, Navisworks	No	No	Lack of visualization and automation
(Al-Qattan et al., 2017)	Ribbon sensors	Arduino, Dynamo, Revit, Grasshopper, Rhino	Yes	No	the automation of generating mathematical equations, but lack of automated visualization
(Smarsly & Tauscher, 2016)	SHM sensors	BIM, SHM sensors	No	No	Utilizing IFC to integrate BIM into the SHM system, but lacking automation and visualization
(Kensek, 2014)	Temperature, Humidity, CO2	Arduino, Dynamo, Revit, Grasshopper, Rhino	Yes	Yes	Transferring data between platforms automatically is error-prone process.

Despite all the obstacles present in earlier research, the integration of IOT and BIM technology will enable designers, engineers, stakeholders, and users to monitor indoor thermal comfort and obtain real-time data about the actual asset performance, ultimately leading to more efficient and sustainable building operations. In addition to this, the integration function will contribute to reducing unplanned maintenance, resulting in a more efficient use of energy and better building performance. Moreover, it will facilitate the incorporation of technological enhancements that will culminate in a comprehensive design that can easily integrate both renewables and energy efficiency to achieve a building that is sustainable and efficient overall. Also, the coordination and implementation of IOT and BIM can locate the most likely problems before they become widespread, optimizing service duration, and cutting repair costs. Thanks to the effectiveness of statistical evaluation, the owners of buildings might be aware and capable of making decisions to bring the status of their buildings to a high level and even to ensure long term sustainability. Researchers have identified several IoT-BIM benefits, which differ depending on whether the project or business investment is short-term, long-term, or upgraded. These advantages include knowledge, design management, and the long-term enhancement of the integrated data environment. At different project stages, design analysis, productivity enhancement, enhancement of security and continuous machinery tracking are also key benefits that IoT-BIM can provide. IoT-BIM integration results in improved stakeholder engagement, which in turn leads to more effective decision systems and communication (Kuncoro et al., 2022). Hence, with the adoption of the IoT into BIM systems as a tool for lowering costs and project management performance, the construction sector could even take an ultimately positive direction with the combination of these technologies.

3. RESEARCH METHODOLOGY AND EXPERIMENTAL DESIGN

3.1 PROTOTYPING AND SIMULATION METHODOLOGY

In this study, prototype and simulation are the methodologies that will be applied. Prototyping, in turn, is a process that helps to look at the functionality and design of the product or system (Yin and Mckay, 2018). Simulation, on the contrary, is a technique of a virtual model that allows researchers to predict all possible outcomes of the situation (Yin and Mckay, 2018). Building a prototype of a real or supposed system (may be symbolically standing for a design idea), followed by experimentation with the model with the aim to study how the system performs operating under different factors, and designing and assessing potential management strategies are referred to as prototyping and simulation processes (Abar et al., 2017).

Exploiting prototyping and simulation will act as a powerful manipulation instrument in the hands of the developer and the designers, thus shortening development and increasing the probability of success. The main procedure and framework that has been used during research was prototyping and simulating, which involved troubleshooting and final evaluation, as shown in (Figure 3.1). This process may show how the system or product performance and efficacy will be if it is implemented as scaled production. An iterative manner of early modifications is enabled by this approach, which is likely to generate more viable and productive results. Another advantage of this methodology is that it may start the process of identifying possible obstacles and clearing them up, taking care of the situation before incurring any other costs. The early stages of design development can be supported and simulated in the form of prototyping and show the designers the right informed decisions, which can result in better solutions in the long run.

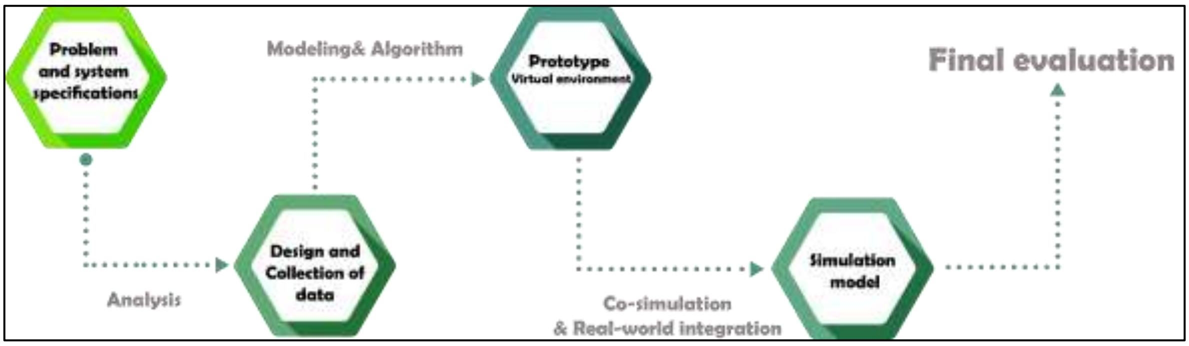

Figure 3.1: Prototyping and Simulation Framework (Created by Author).

3.2 PROTOTYPE PIPELINE PROPOSAL

The experiment basically uses Revit, one of the most popular BIM tools, to build up a digital model of a real room with actual dimensions, material ranges, and the storage of all data for each component. With this model, the highest precision for the calorific load calculation was achieved successfully. The digital model that has been created allows for accurate simulations of the temperature and humidity levels in the room, providing the information required to adjust thermal comfort, including moisture balance. This method is used to cut off multiple steps and bring all predefined data to one centralized platform, where it will be used to design and develop the experiment. Next, a DHT11 temperature and humidity sensor connects with an Arduino board to control the data transmission in real time. The sensors being connected to an Excel spreadsheet with the Data Streaming Add-in (DSA) are used so that the heat management system will operate in real time to adjust the thermal comfort in the room in compliance with the set standards. Therefore, the data gathered can be simply translated into Revit with the assistance of Dynamo for analysis and subsequent display in Revit using visualization tools, which will, in the end, enable locations of the room to be optimally affected with the aim of creating a comfortable environment.

The fact that the simulator is directly linked to other devices that use micro-controller boards, such as Arduino, and presents the data in real-time to the user makes the whole process of handling the digital model very engaging. The system will be equipped with a digital measurement device for both temperature and humidity to be measured in real time, which will improve the performance and precision of the endeavor. The Revit Dynamo script, which is the one to link temperature and humidity data directly and return an instant update in real time, will execute to do this automatically. Such integration is appropriate so that the required loop for observation and response is created, thus always leading to maximum efficiency. Connectedness serves the purpose of tracking historical data trends and can facilitate the determination of patterns for making decisions about prospective enhancements as well.

The visual programming tool Dynamo in Revit helps address the emerging need for parametric modelling and automation in Revit. It executes parametric operations, consults, and updates components and data, and brings real-time information to life by means of the Revit API (Opoku et al., 2021). The last layer of visualization is the one that provides the entire idea and is quite easy to be perceived by everyone to get adequate information to make the right decision.

IOT-based real-time data were visualized and integrated into BIM for a digital twin prototype, as shown in (Figure 3.2), by the integration of BIM modelling with all the details included in the 3D model and having the temperature and humidity values stored and analyzed using Dynamo. It is a process that is overall divided into two main processes, which are further classified as prototyping processes and simulating processes. The steps in the prototyping process comprise producing a digital model of the system, and users can simulate various scenarios using this model and conduct analysis of the results prior to implementation. Coming together like this, apparatuses make a complex system of real-time data visualization by combining IOT and BIM technology to get a digital twin prototype.

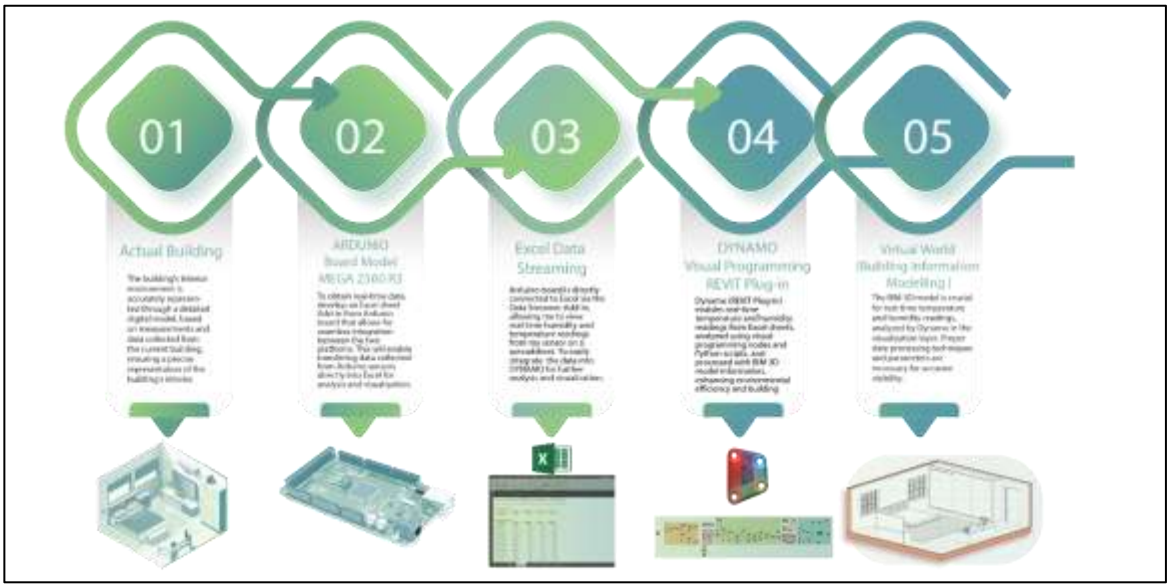

Figure 3.2: Visualization and Automation Framework (Created by Author).

Classified as the prototyping phase and simulation phase, the project consists of five crucial steps, which are as follows:

a. Having the building, which is a physical space where the test will be conducted and where the accurate thermal comfort real-time readings will be collected.

b. The real-time data can be received and processed by collecting all the data in an Excel sheet using the add-in for data streaming.

c. This allows for data that is created in the instant and directly linked to Dynamo Revit for the real-time condition monitoring of rooms with an updated BIM model visualization layer that works alongside a precise colour scheme.

d. The connection points from the add-in for data streaming to one Excel sheet will be automatic connections to a Dynamo script that will pull the immediate and real-time readings automatically from the Arduino microcontroller and integrate them into the BIM model in real-time updates.

e. The PMV (predicted mean vote) values will be automatically calculated from the real-time data that has been transferred in real-time from the Excel sheet into Dynamo to be visualized in an effective and consistent way through the visualization layer in the BIM model by integrating Dynamo visual programming nodes and Python script nodes. The interface can interact with the Arduino COM and the Excel sheet through direct communication between both due to the fact that they can all exchange information in real-time. This means that the information visualization layer is accurate and up to date.

f. The use of Python scripts to automate PMV (predicted mean vote) computing facilitates the decision-making process since it eases data analysis and evaluation.

g. All the analysis is done in real time and is reflected just in the visualization layer of the BIM model, which uses a specific colour system to display actual indoor conditions

3.3 DATA COLLECTION PROCESS

The Arduino Mega 2560 R3 microcontroller board was utilized in this paper, and it was linked to (DHT-11) monitoring the interior space's temperature and humidity, as shown in (Figure 3.3). DHT11is is a simple, inexpensive digital sensor for temperature and humidity.

Utilizing a capacitive to measure the air quality, a humidity sensor and a thermistor are used. A digital signal output is produced on the data pin; analogy input connections are not required. Although it is reasonably easy to operate, data detection requires precise timing. This sensor's only restriction is that it can only provide fresh data every two seconds. Temperature and Humidity Sensor Specifications as follow (Shafiril et al., 2016):

a. Supply Voltage: 3.5 to 5.5V
b. Operating Range and Accuracy (Humidity): 20-80% RH; +/-5% RH
c. Operating Range and Accuracy (Temperature): 0 to 50 C; +/-2% C
d. Average sending period: 2 seconds.

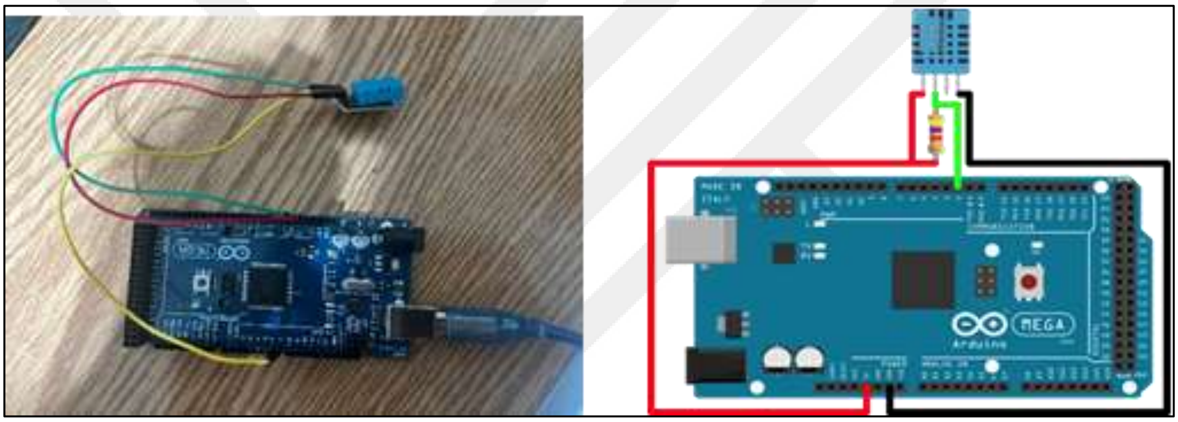

Figure 3.3: Arduino Microcontroller Connected to DHT11 Sensor (Created by Author).

Spreadsheets, especially Excel, have gained popularity as tools for data analysis and engineering calculations(Chehab & Artail, 2004). Visual Basic for Applications (VBA) is a macro language included in Excel spreadsheets that enables programmers to create add-ins that enhance the functionality of spreadsheets. Real-time data visualization and analysis can be accomplished with Microsoft Excel by using the Data Streamer add-in (Aliane, 2010). It enables users to update the spreadsheet in real-time by connecting Excel to other data sources, like Arduino. By using this add-in, users can easily track and monitor the environmental comfort of their indoor spaces, such as temperature and humidity levels, without the need for manual data entry as shown in (Figure 3.4).

In this research paper, a data streamer add-in has been used to collect real-time data related to temperature and humidity readings that are then displayed on a user-friendly interface. As soon as the Arduino board is connected as a data source, readings are gathered and shown in real time to give precise and current data for analysis and decision-making. The gathered temperature and humidity data are displayed in an Excel spreadsheet along with the exact time and date, making each measurement clear in terms of time and precise seconds. This is highly helpful for the analysis that will take place in the dynamo nodes and for making precise forecasts of future trends and monitoring the indoor thermal comfort. By monitoring change over time, it becomes possible to discover to what extent the indoor atmosphere and factors influencing the temperatures and humidity levels can be understood. Providing this data readily in simple tabulations enables the connections made in real time to scripts of Dynamo and allows for automation processes for providing a clear and effective way to reflect the thermal comfort index of the room's indoors through visualization in the BIM model, which ensures optimal performance and comfort for building occupants. Subsequently, it was simpler to establish an automatic link between the Dynamo script and the Excel spreadsheet so that certain nodes and parameters could provide instantly updated data.

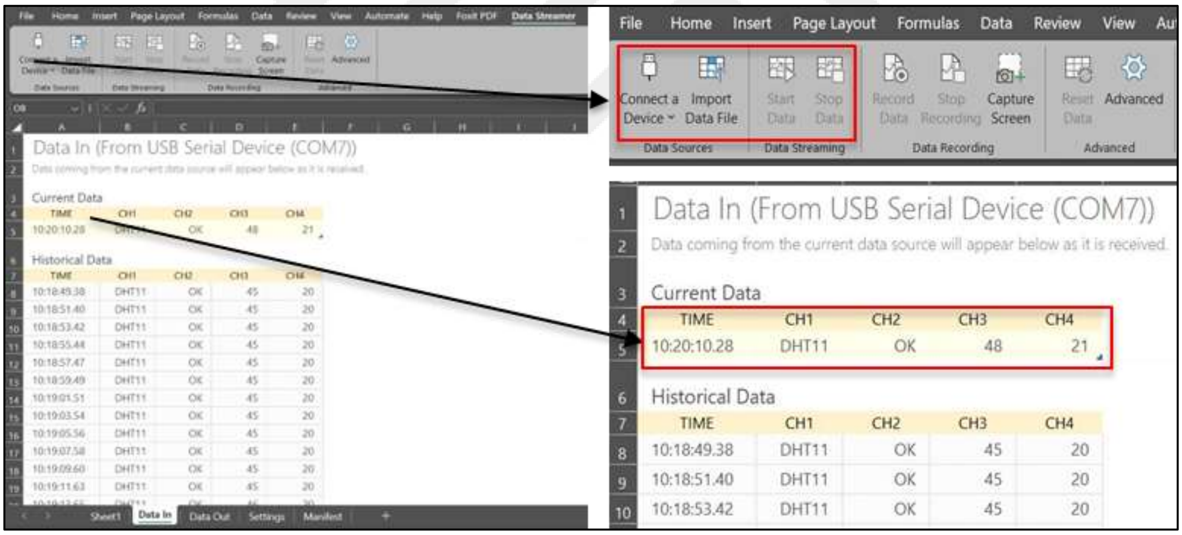

Figure 3.4: Data Streamer Add-in in Excel Spreadsheet (Created by Author).

3.4 BIM MODEL PREPARATION

Building Information Modelling (BIM) is a project management approach that integrates people, procedures, technology, and regulations. It permits the construction of a digital image of the building or some infrastructure project, allowing stakeholders, engineers, and designers to collaborate more effectively and make well informed decisions due to the comprehensive and readily apparent information and details presented in the digital modals of the building and projects. The BIM model has been modified and customized to the actual conditions of the project, which is named LOD (Level of Detail). The terms Level of Detailing (LOD) and its six levels (LOD 100, 200, 300,350, 400, and 500) are used in project design documentation. From conceptual to as built and facility management, every level of LOD addresses a different phase of the project depending on the specifications and information stored on every model component(Latiffi et al., 2015) The levels of LOD are equivalent to the different project phases, and they guarantee that the model displays the project at its present development stage. It thus takes care of the smooth interaction and cooperation amongst all project participants.

The conceptual foundation of the model for LOD, identifying LOD100 as the starting category, is the first rank. One of the main tasks of the Positioning System is evaluating such factors as volume, position, area, height, and orientation. In the other group, the model which consist of LOD200, LOD300, and LOD350 is called system-oriented modelling. The documentation of LOD200 which in away includes rough sites and approximate sizes of both the system and individual components. The detailed design, represented in LOD300, is where object components are modelled to correspond non-graphically with most accurate dimensions, shape, quantity, placement, and orientation. LOD350 contains lexical and visual (with both graphic and non-visual) displays that show how a specific part works with other components of the system. Modelling towards the element and coupled LOD400 and LOD500 makes the last group. LOD400 has its prime applications in assembling and fabrication. The model consists of different parts, and these are dismantled into assembling units, the processes of fabrication, assembly, and installation as well are described. Preceded by errors, the measurements indicate amounts, forms, positions, and orientations. Every item of non-graphical information is interconnected with all. At the as-built section, employ LOD500. It provides verified data on the production and workflow of parts and components such as date, brand, and marked product. It is very commonly used in facility management, operations, and maintenance sections (Ur Rehman, Kim, and Choi 2023). The BIM maturity indicates on the way BIM users in project management applying spectrum of LOD level in the BIM. The ability to exchange data uniformly, which guarantees consistency across all databases, is what makes the LOD application on BIM modelling so revolutionary(Latiffi et al. 2016)

Through the application of BIM, which clarifies the models and their parameters, the study will be able to develop accurate and efficient 3D modelling. Autodesk Revit has been used in the process aimed at obtaining a 3D model of the space. That process starts with acquiring the real asset's dimensions and information about materials from the actual scheme. As a result, the coordinates and parameters are transferred into the Revit model by modelling tools and making the components, as well as materials correlated with actual parts and room attributes, for the thermal comfort accuracy measurement. This required input data is already supplied. Different building materials of the construction, for instance, walls, doors, and windows, are used in the computational part, which shows the heat transfer and energy consumption in the room.

All the functions could be assigned in this energy model, after which they could be analysed to optimize energy efficiency and thermal comfort in space by receiving the readings of Arduino sensors, which are then processed and analysed using the dynamo nodes and the visual programming. This demands orientation changes in the building's design and materials; hence, the achieved thermally comforting state becomes an energy efficient one.

After the data collection process, where real-time data updates are available, the room is then virtually recreated on a Revit platform, showing the specifics of the spatial layout, material selections, and furniture arrangement. Window acted as the key mediator in handling the actual humidity and temperature data in the room in real-time to achieve high-precision simulation, and hence this is the most critical moment in this research to assure that its parameters, analytical properties, and material specifications are correct. The standards and norms referring to walls and floors. have precise and adequate quantities so that they can be appropriately accounted for in the simulation. On top of that, the lighting conditions were carefully designed to have the digital output mimic the level of incoming light into the room, since this can significantly influence how effective the simulation is.

These inputs must be accurate, because if they are not, the results cannot be expected to be a reliable result or a space that has been properly rendered to be accurate. (Figure 3.5) represents comprehensively this method, leading to a more precise demonstration of internal thermal comfort and a realistic and detailed simulation of a site by contemplating all related elements for producing a very reliable analysis to integrate it into the Dynamo script competently. Aside from that, introducing variables like material properties and occupant behaviour makes the model able to dig deeper into this matter and understand it much better. This comprehensive approach gives us a clearer view of the actual state; therefore, the virtual environment matches reality as closely as possible, and as a result, the decision-making process becomes more adequate.

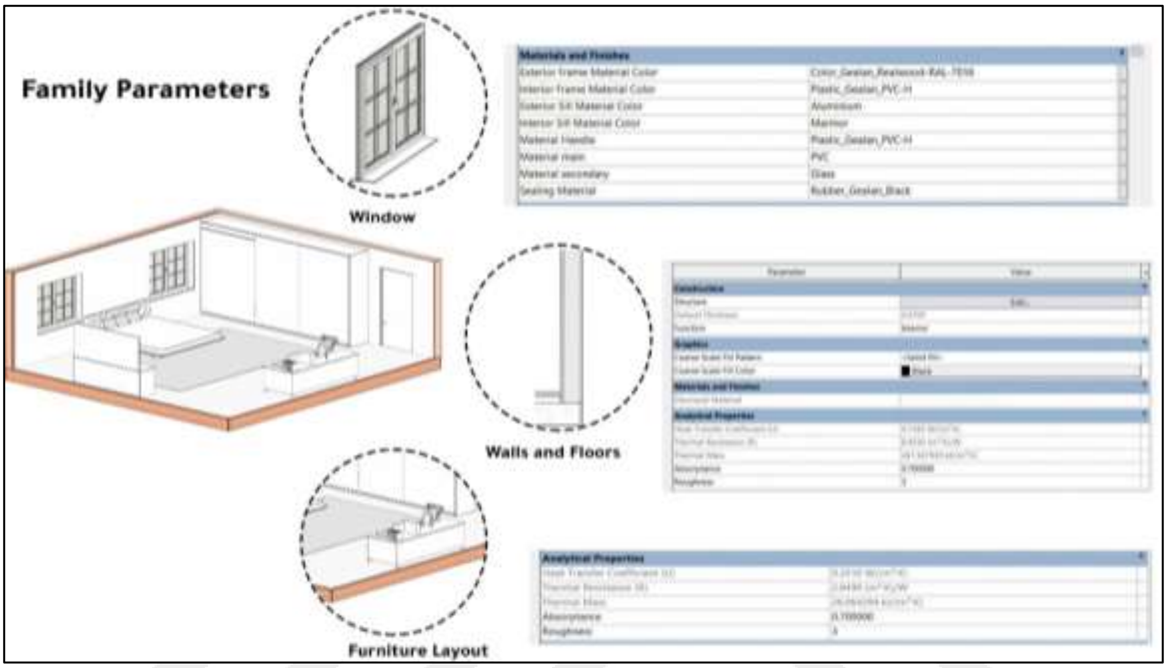

Figure 3.5: Family Parameterized BIM Model (Created by Author).

3.5 DYNAMO AUTOMATION PLATFORM

The technology has had a positive influence on the AEC business through the fact that computer programming has so far developed several BIM systems, which have in turn been used to digitize projects (Collao et al. 2021). These tools have nevertheless tackled the simplest BIM application like modelling, drawing, and visualization processes that have been developed and improved for decades (Yang and Liao 2016). Although some BIM application options related to (1) parametric design, (2) creating analysis graphs, and (3) emission estimation are still not addressed in a more effective way, keep in mind that those options are highly beneficial and should be used during the construction process. For building the bridge across this gap, the AECO industry initially created an object programming for line coding method, which was later integrated into the BIM software. By providing command lines as directives, such programming programs were able to generate algorithms that arranged the process sequence. Nevertheless, industry professionals in the

AEO industry have concerns about the fact that many of these programs have repetitive interfaces and programming levels (JAY et al. 2009). In response to these deficiencies, BIM software development firms have developed visualization tools as a solution. The tools themselves select the process sequence instead of showing the user the list of algorithms based on visual input expressions. Consequently, the codes are shown in a regular shape, described as process charts, as compared to traditional programming, which showed them as lines. Dynamo is the most widely used software in the AECO sector of project functioning. Its implementation area is the fastest growing in the industry and it is integrated with Autodesk Revit software. Visual programming made through the open-source Dynamo add-in is one of the factors that allows Revit to be fully automated by its workflow and customized (Seghier et al. 2017). By doing this, the developers of the software create the possibility for custom scripts and automate the tasks performed within the Revit environment (Shishina & Sergeev, 2019). In addition, Dynamo coordinates with Revit via its APIs to exchange information and data with the Revit model and variables, thus ensuring the correct operation of the software. Dynamo's having APIs for Revit facilitates its capacity with access to the software abilities directly. Therefore, it becomes a very effective tool to drive operations through workflow streamlining and increasing productivity. Its intuitive interface and wide array of nodes provide users with effective and flexible tools for the optimization of Revit projects, including mostly architects, engineers, and construction managers. Thus, Dynamo enables users to automate time consuming ones, create complicated geometries, and generate their own design algorithms inside the Revit environment. It therefore brings about more efficiency and speed, which eventually results in time savings and better project outcomes.

(Figure 3.6) displays data transmission between the sensor generation and the visualization of the BIM model interface. The first step is to link the data from the Excel sheet to Dynamo, and then add the real-time data from the Excel sheet to Dynamo for the automation of the processes and analysis. Due to this reason, PMV calculations would be used for a node in Python that will process the occurrence of all the real-time humidity and temperature data and put them into the BIM model as parameters (Valinejadshoubi et al., 2021). In the next step, the plane is divided into grids, and the parameters of objects and families are assigned to each grid cell. The section that follows describes how you observe and assess the value: After the combination of the BIM parameters and APIs, the model is now ready for visualization and examination. Finally, by interpolating all computed and PMV analysis data, zones can be plotted where all the values of indoor thermal performance can be seen. It is going to be accomplished by applying the colour scheme, which was derived from the values that were investigated, and embedding it in the visualization layer to produce a comprehensible and informative visual representation of the thermal performance data.

That layer will be used to provide a visual representation of the room's overall thermal performance, highlighting any inefficiencies and potential improvements in layout. Hence, a comprehensive picture of the thermal performance of the room and its areas for improvement will be received. Using this tool for visualization, the owners of buildings and designers can now be able to make informed decisions, which will positively impact energy utilization and occupant comfort.

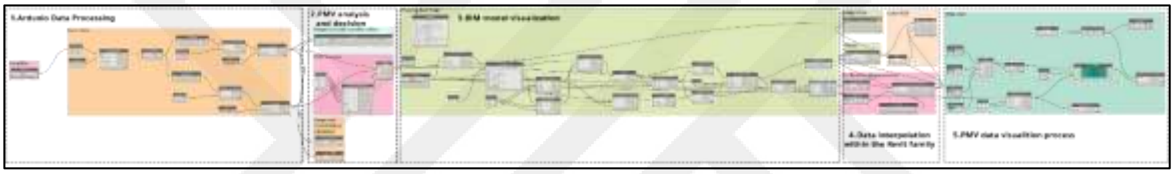

Figure 3.6: Process of Data Visualization Using Nodes and Dynamo Script (Created by Author).

After the Excel spreadsheet and Dynamo script are plugged in, data collection can be handled automatically, data on temperature and humidity can be viewed in real-time, and the data can be immediately updated. The nodes of the Dynamo scripting process the spreadsheet cells to pull out all current temperature and humidity values that are updated through the Arduino micro-controller to the nodes right away for analysis and a visual display. It enables continuous tracking and analysis of environmental parameters in real-time, facilitating evidence-based decision-making improvement and efficiency.

It is depicted in (Figure 3.7) that when the script starts, the Microsoft Excel file and the data streamer button are opened beside each other. The data streamer button provides for the direct transfer of the microcontroller's real time temperature and humidity values onto the spreadsheet in an instant. The integration of software and hardware provides rather precise and fast information for knowledge-based decisions. At the same time, these real-time temperature and humidity readings are generated and go through analysis and visualization by the Dynamo nodes, which automate such processes, reducing human error and increasing productivity. To add on that, the usage of live data streaming deprives the need for manual data entry and therefore conserves time and leads to data accuracy.

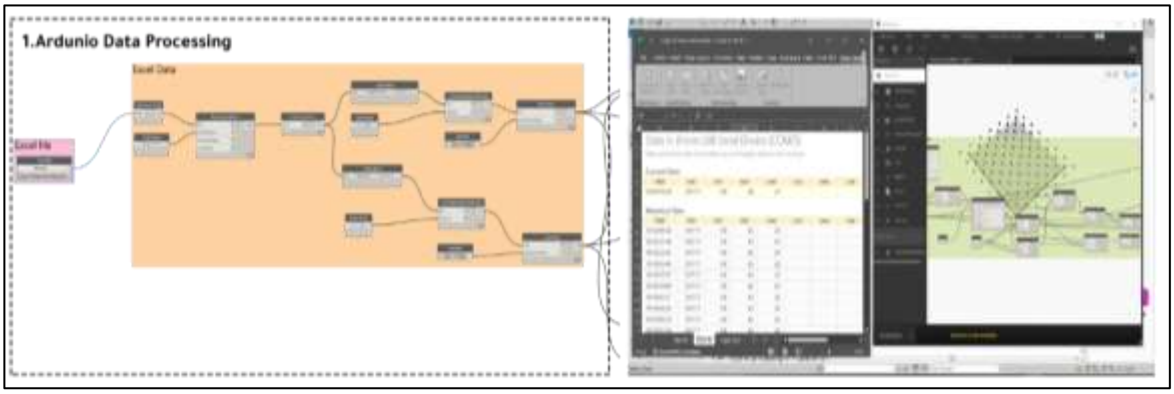

Figure 3.7: Excel Spreadsheet Processing for Arduino Data Inside of Dynamo Script (Created by Author).

3.6 THE PMV FORMULA AND ANALYSIS

The integration of Excel spreadsheets with Dynamo can be considered a milestone by saving data collection time since it automatically performs the PMV (predicted mean vote) calculations. The PMV model is a device employed to calculate the average sensation of thermal comfort of the individuals in a particular setting (Wei et al., 2024) describe variables as follows: clothing insulation, metabolic rate, relative air velocity, mean radiant temperature, humidity, and temperature.

The mean radiant temperature in Celsius = 25.0 that is known as the temperature aggregate of these surfaces is the average temperature of all the surfaces that are very close to people like walls, floors, and objects. But obviously the individual plays a decisive role in that pursuit of a thermal comfort.

The air velocity in m/s = 0.1 shows how fast the air moves in relation to the human body. In the simulations, the air velocity was 0.12 m/s in the case study room.

The resting metabolic rate in met (W/m2) is the amount of energy a body uses when it is still or is moving at a low pace. At a metabolic rate of 1.2, the conditions for thermal comfort correspond to light activity levels.

Clothing Insulation= 0.5 since the study was conducted in the winter, when temperatures are lower, and people thus need more warmth provided by their clothes.

Here I would mention that the PMV scale goes from -3 to +3, with negative numbers corresponding to feeling cold and positive numbers to feeling hot. Neutral thermal feeling is represented by a value of 0. To get the optimum people's thermal comfort, PMV model is usually used in both fields of the building designing and HVAC (Heating, Ventilation, and Air Conditioning) systems (Malet-Damour et al., 2021).The Python script performed the calculations of the PMV values by collecting the live temperature and humidity values and combining them into a single list as shown in (Figure 3.8), which indicates the average thermal comfort indices. The data acquired could be used for thermal comfort evaluation, which will later be used as input to create BIM models for visualization and extra analyses. An equation that assesses the occupants' perceived comfort leaning was used to determine the experiment's PMV (Wu & Liu, 2020) (1). The PMV evaluation outcomes give the heat factors inside, which then will be the clues in the changes in the operations to offer better comfort to the occupants. Predicting heat balance during the design and operation of a building facility will now be more accurate thanks to the use of real-time data and advanced modelling techniques.

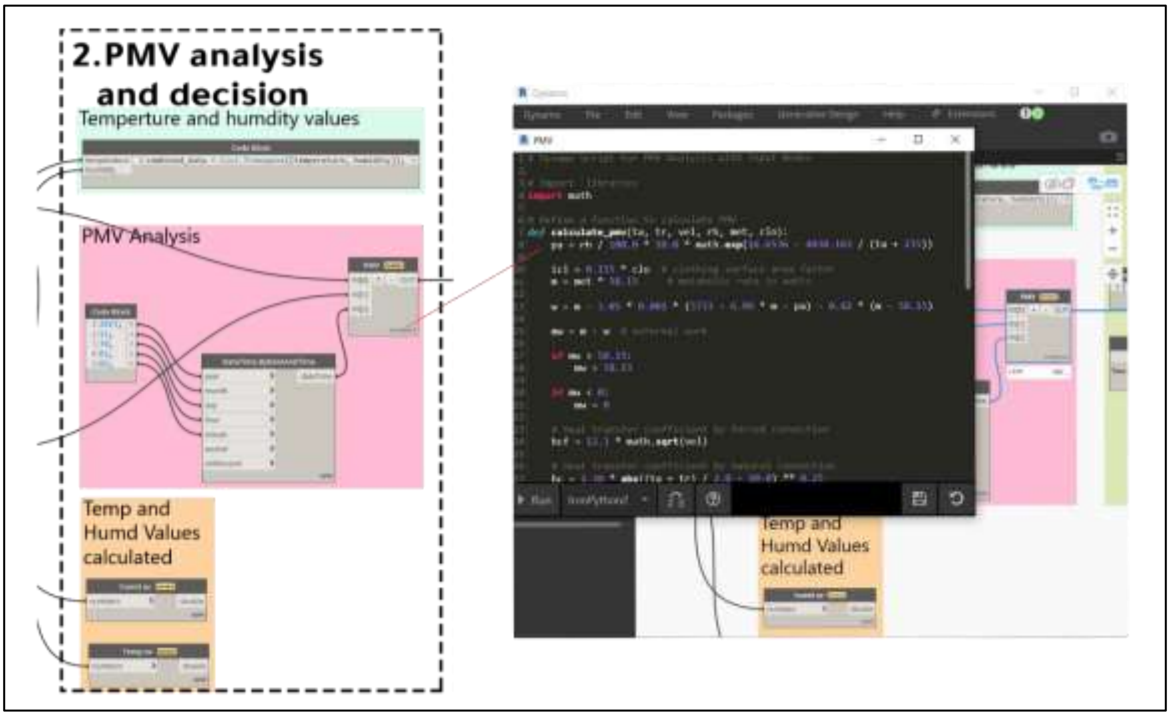

Figure 3.8: PMV Analysis Python Script (Created by Author).

3.7 INTERPOLATION PROCESS

In the 3D modelling system, Revit uses three key groups of entities: model-parameters, Family-components, and geometrical instances. 3D modeling informatics represents a perspective that includes the use of geometrical relationships, component parameters, component geometry, geographic information systems of buildings, and other engineering quantities besides the key features of model elements data structure and mapping. The kinds of elements, commonly referred to as families in several building structure product frameworks, fall into the suitable categories of building components (Li, Li, and Ma 2019). In fact, every model component is a real three-dimensional element, also known as a complete model of objects, managed, and defined by their family (Ma, Azari, and Elnimeiri 2024). 3D elements with specific parameters and characteristics can create various inputs that allow us to insert certain instances into the family components to carry out different analyses and configurations within the BIM model. The model can be efficiently utilized in engineering information systems by classifying its properties. From this point the adaptive family building components will be used to facilitate the thermal comfort prototype model in this experiment, and it will be easy to develop and analyze the model thermal comfort based on the collected and calculated real time temperature and humidity data from the real room and the PMV analysis that has been done by the Python node, which shall then be entered into the family instance for further analysis by the Dynamo nodes. The process is implemented by developing the REVIT family adaptive components, which contain temperature and humidity instants for collecting all the PMV analysis data, and then integrating them into the Revit model in which all the analysis is depicted. Besides, the PMV calculated values will be integrated into the family component instance to represent the values, and then directly translated into the visualization layer in the Revit model of the room for visualizing the thermal comfort index according to the specific color scheme shown in (Figure 3.9). It means the acquisition of a more comprehensive picture of the room's indoor thermal comfort. Furthermore, the visualization level can find spots in the environment that might need to be adjusted to provide the desired thermal comfort. The use of this data will serve as the basis for the Revit to guide the process of making the right decisions to provide better comfort and efficiency in the building.

Figure 3.9: Creating Revit Family Containing Temperature and Humidity Parameters (Created by Author).

After inserting the plane that will act as a visualization layer into the Revit model, dividing it with the Dynamo script, making test grids to position the adaptive family components that have been done and its temperature and humidity instances within the grids to translate all the real-time temperature and humidity values and calculated PMV values as shown in (Figure 3.10). Then, interpolating the PMV-analysed data into it to prepare it for visualization and analysis ensures that the adaptive components are accurately placed and have the right thermal comfort instances for further analysis within it and the ability to interpolate the real-time thermal comfort readings. Making the Revit model ready for running simulations to validate the accuracy of real-time temperature and humidity data readings, the PMV calculations that have been interpolated to family adaptive components, and the performance of the adaptive components in response to changing temperature and humidity levels.

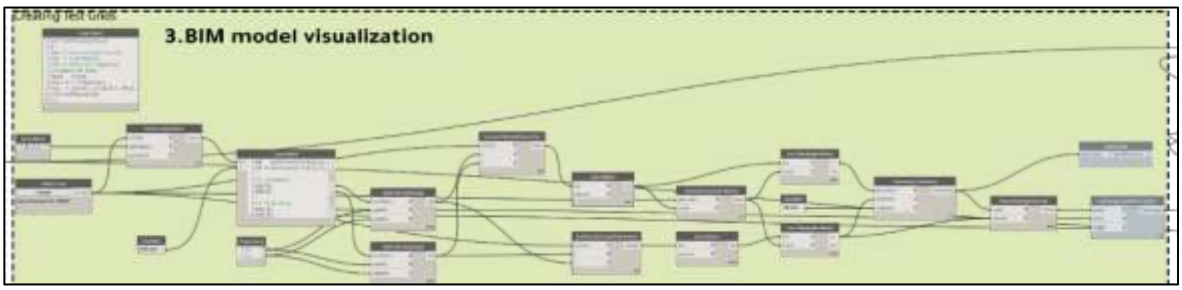

Figure 3.10: Dynamo Script Dividing Visualization Layer into Grids to Load Revit Family into it (Created by Author).

As demonstrated in (Figure 3.11), the plane of visualization is divided into grids, and family parameters are filled in the grids to make the analysis. Through each grid, a specific value of parameters is laid out. Thus, it becomes possible to analyse the multidimensional categorization of the data set within various value interactions.

The visualization enables one to see thermal comfort in different parts of the space that are not visually identified when looking at the overall data. Then, to have a valid measurement of the thermal comfort in the room, it was raised to 90 centimetres above the ground. Therefore, having a real image from the desk level will give you a better idea of the thermal conditions perceived by the occupants at their stations.

By using such an approach, thorough grid data analysis can be used to computationally modify the indoor grids for project-specific improvements to achieve the most comfortable and spatially planned design for indoor thermal comfort. Through this method, additional functions can be modified or improved to boost comfort levels in the room based on the collected data, including thermal grid analysis within the room to achieve indoor planning and furniture layout enhancement.

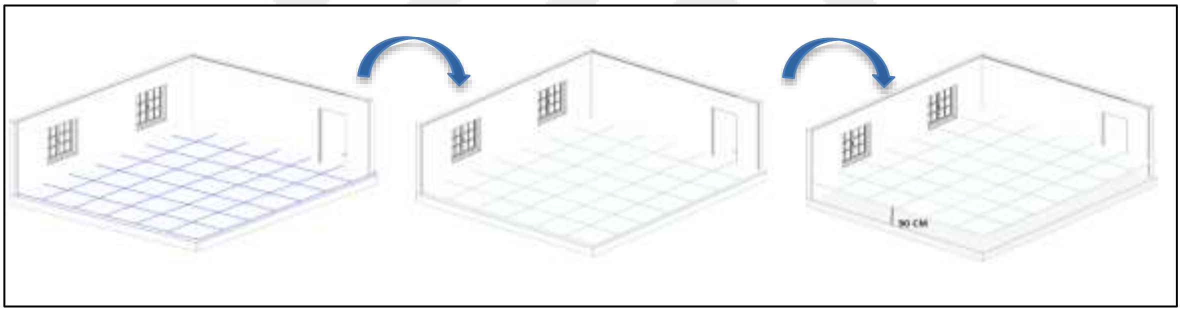

Figure 3.11: Visualization Layer Dividing Process for the Data Interpolation Process (Created by Author).

Following (Figure 3.12), the adaptive components family was put together with the real-time temperature and humidity in addition to the computed values of PMV. Consequently, the Python node of interpolation was used to connect these components to be functioning in real time. The process hence started, and the values were inserted via automation interpolation and saved in the Revit model for visualization.

The simulation of real-time temperature and humidity through sensors gives you real-time readings that can adjust the systems adaptively based on the noted conditions, thereby enhancing both operational performance and user experience. Such an automation is the one that, above all, simplifies work procedures and allows the Revit model to correctly reflect the updating of the thermal comfort conditions within the room in real time.

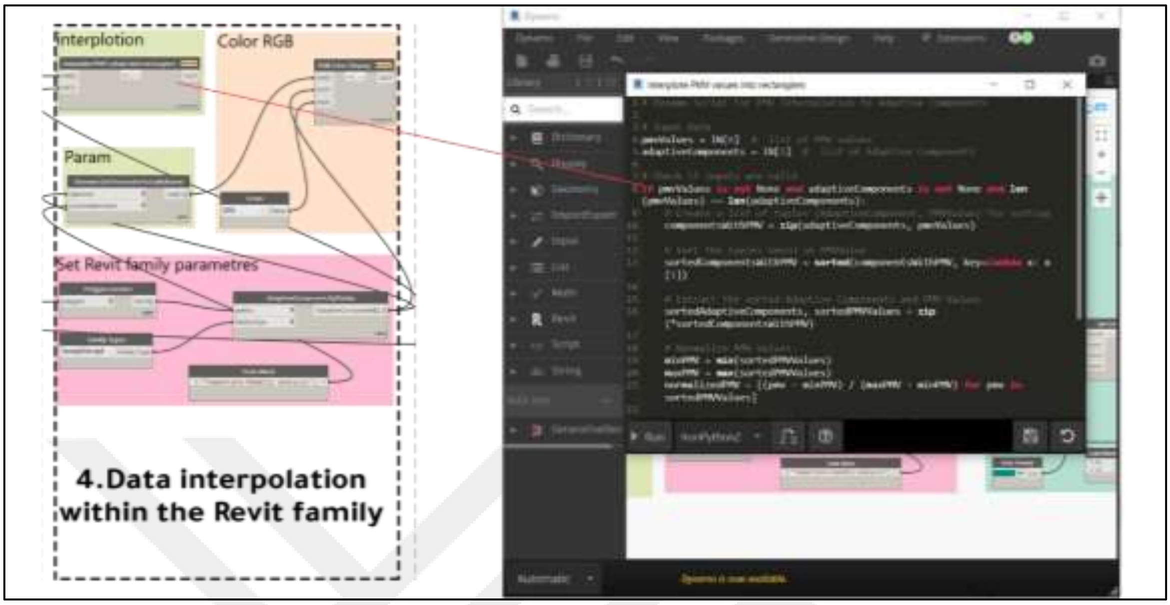

Figure 3.12: PMV Calculated Values Interpolation into Family Parameters by Python Node (Created by Author).

3.8 SIMULATION PROCESS

The next section will provide a practical demonstration of how the proposed integration of the Internet of Things (IoT) and building information modelling (BIM) can work to produce a digital twin prototype, which will give insight into the usage of this innovative technique in improving the design and construction of buildings and their maintenance. The significance of using IoT and BIM together to create digital twins for a master bedroom will be demonstrated through this simulation part of the experiment. It will focus on the potential benefits and the resulting efficiency. This part discusses the way the claimed IoT platform is used for visualization and contains the actual case study of the use of an Arduino and a temperature and humidity sensor. In return, the platform displays the analysis in a visual manner, which makes it easy to monitor efficiency across the entire space and to determine areas that require additional green building interventions for the comfort of occupants. (Figure 3.13) shows how to use this visualization layer as a colour scheme based on the PMV values that measure the different comfort levels of space. This coloured scheme, which gives quick and clear meanings to the data users, likewise helps in the process of informing people about the findings while at the same time enabling favourable decisions in the layout and operation of buildings. Besides that, the colour scheme can be personalized, just like how the users have their preferences considered or the colour patterns governing their own industry, which, in a way, makes the user experience even better. Such display becomes a tool, especially in comparing data across time to document the same trend or to notice the changes in the internal conditions of a building.

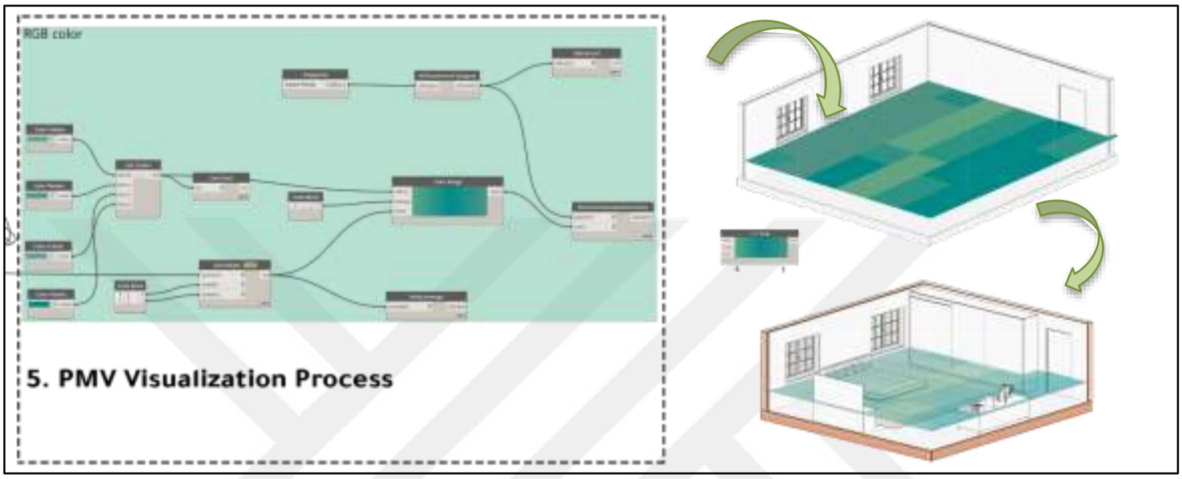

Figure 3.13: Dynamo Script for Visualization Layer Process (Created by Author).

In the following text, an example is given for the possible use of PMV comfort ratings to reconfigure spatial layout. For this project the utilization of a Revit model, an Arduino microcontroller, a Dynamo, a spreadsheet, and temperature and humidity sensors were adopted. The project was implemented in one of the rooms in a residential building and the merging of IoT and BIM technologies successfully recreated and visualized the prototype digital twin. With such a visual, the user could redesign the room arrangement by utilizing actual data from the sensors which would, in turn, show the smart buildings capability to leverage the data for optimization.

(Fig 3.14) shows the spatial arrangement of the room corresponding to the PMV comfort ratings, the furniture in different arrangements and temperature/humidity levels is demonstrated in it. By employing the combination of IoT and BIM technologies, the project provides a glimpse of the future potential of producing efficient and comfortable apartments using digital twin prototypes. For illustration of how some factors will affect comfort levels, daily temperature and humidity data was collected during a week, started on December 30, 2023, different hour of the day. Two distinct demonstrations were made, demonstrating the impact on warmth and air flow with the windows closed or open for an hour. This innovative way of delivering data enables the users to interact with it and make accurate decisions on controlling their indoor setup for enhanced comfort. By analysing this data, individuals can modify their living spaces to enhance comfort levels.

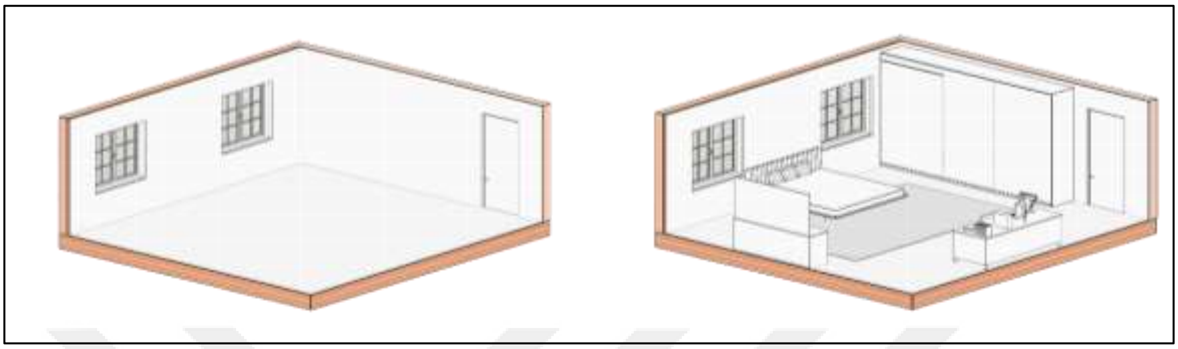

Figure 3.14: Room Spatial Planning and Furniture Layout (Created by Author).

(Figure 3.15) illustrates the condition calculations of PMV, including the difference in thermal comfort levels in two separate scenarios, which are with windows closed and open on two different days. The visualizations importantly feature a remarkable disparity in thermal comfort range between the two situations, with PMV values indicating a room that is relatively more comfortable when windows are open, due to improved ventilation and air flow. With this in mind, the role of normal ventilation in indoor atmospheres becomes clear in order to attain the most effective thermal comfort for occupants. This experiment has been conducted in Egypt in December, when winter officially begins. There will be a slight, but significant, difference in the humidity and readings of temperature between night and morning because it is the beginning of the winter, which also causes precipitation. This shows the reason why the (Figure 3.15) values of temperature and humidity drop down to different values successively during two days as the weather conditions vary from night to morning. To make a correct evaluation of indoor comfort levels and to adjust accordingly, it would be reasonable to know the change rates of these fluctuations. With these acknowledgments, inhabitants of a building can adapt well to the conditions of the environment and maintain a comfortable level irrespective of the time. Furthermore, guidelines to manage the level of indoor air quality and temperature may play a major role in providing a stable level of comfort, excluding the fluctuation of external conditions.

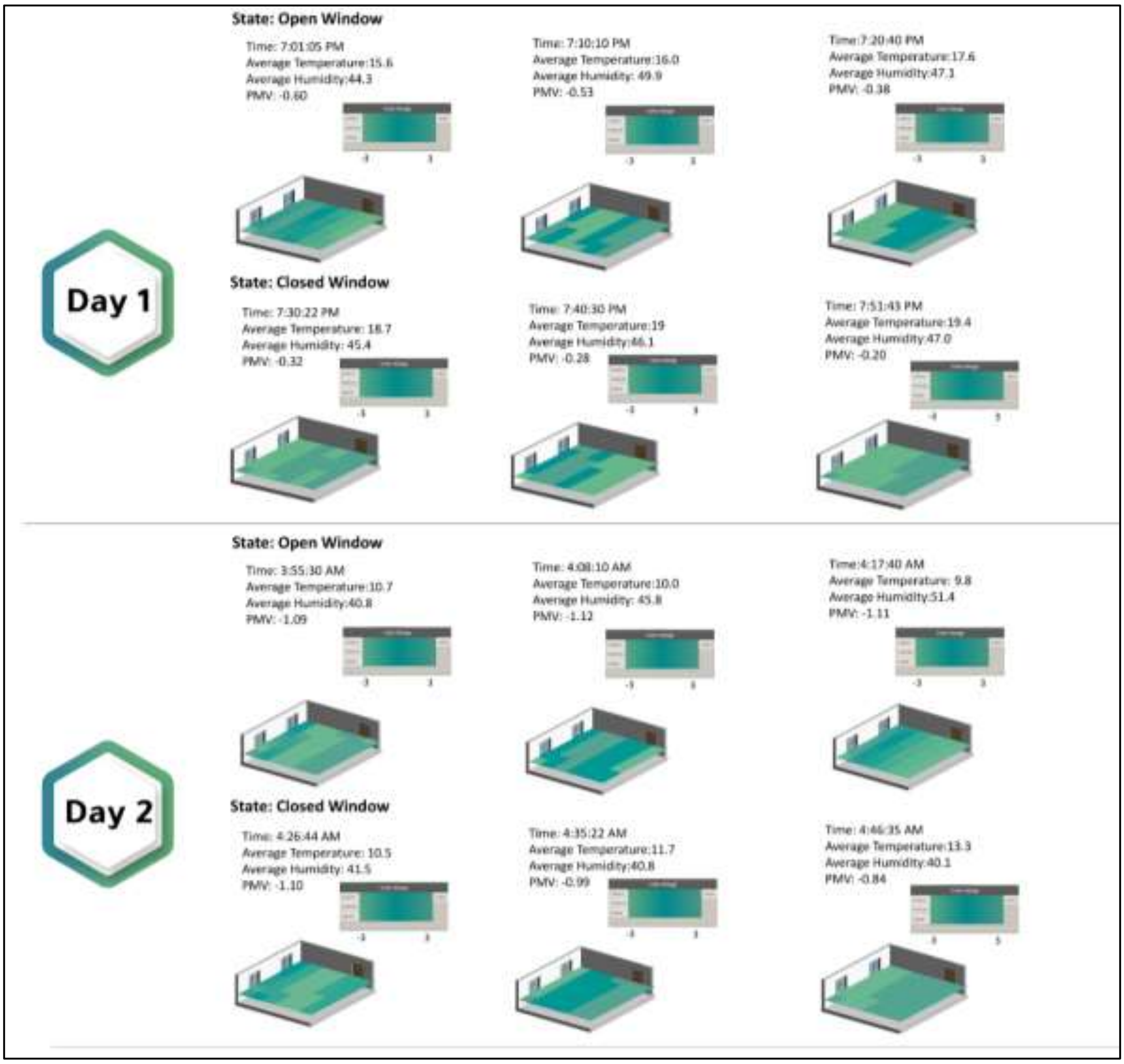

Figure 3.15: PMV Visualization Results for Open Window and Closed Window Scenario For Day 1 and Day 2 (Created by Author).

As (Figure 3.16) shows, there is a noticeable difference in the temperature and humidity levels between the nighttime and the adjacent environment when compared to days one and three. This difference could possibly be because of the weather patterns or the environmental conditions explaining how this is done over the three days. Furthermore, one should take into consideration how these highs and lows may lead to some fluctuations in the different activities of life.

Nevertheless, the atmosphere here is very different and fluctuates throughout the hours of the day due to the desert atmosphere. This diversity in the climate situation is general and anticipated based on the characteristics of the area. To be able to handle and be ready for all the effects that a change in daily activities could have on a regular routine and the indoor environment, it is essential to observe these fluctuations. Realizing the types of fluctuations in humidity levels can provide the users of the space with strategies that are suitable for regulating indoor conditions and planning the furniture layout according to window placement and thermal comfort visualization result.

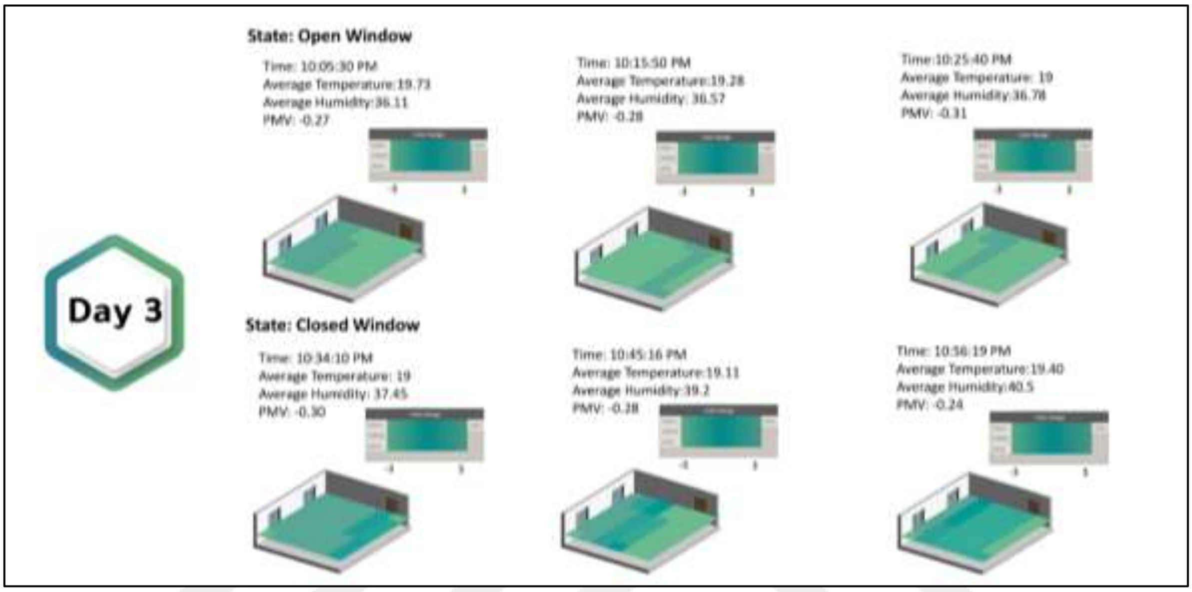

Figure 3.16: PMV Visualization Results for Open Window and Closed Window Scenario for Day 3 (Created by Author).

(Figure 3.17) shows the visualization for PMV values on days four and five for the room building at different times: day four in the evening and day five in the early morning. PMV frequencies indicate a comfortable thermal climate in the room during the evening of day No. four, while demonstrating a slightly lower temperature in the early morning of day No. five. While the case in Egypt is that the country had an instantaneous drop in the ambient temperature at night, this caused a minor difference in the PMV value.

The calculated PMV value shows that thermal comfort in the room is maintained during the day and at night. The PMV value was between 0.13 and 0.2 on the fourth day of the experiment and between -0.15 and -0.17 on the fifth day of the research. Those results have been conducted through two different scenarios, which are the closed and opened windows.

Besides, the room was able to sustain a natural and comfortable atmosphere despite the fluctuations in temperature and humidity on the outside.

It shows that the building is decently insulated, and the window design, integrated with the space scheme, fulfils the thermal demands of occupants as well as managing the heating loss while closing windows, which makes it easier to keep a warm interior without the need for heating systems in winter.

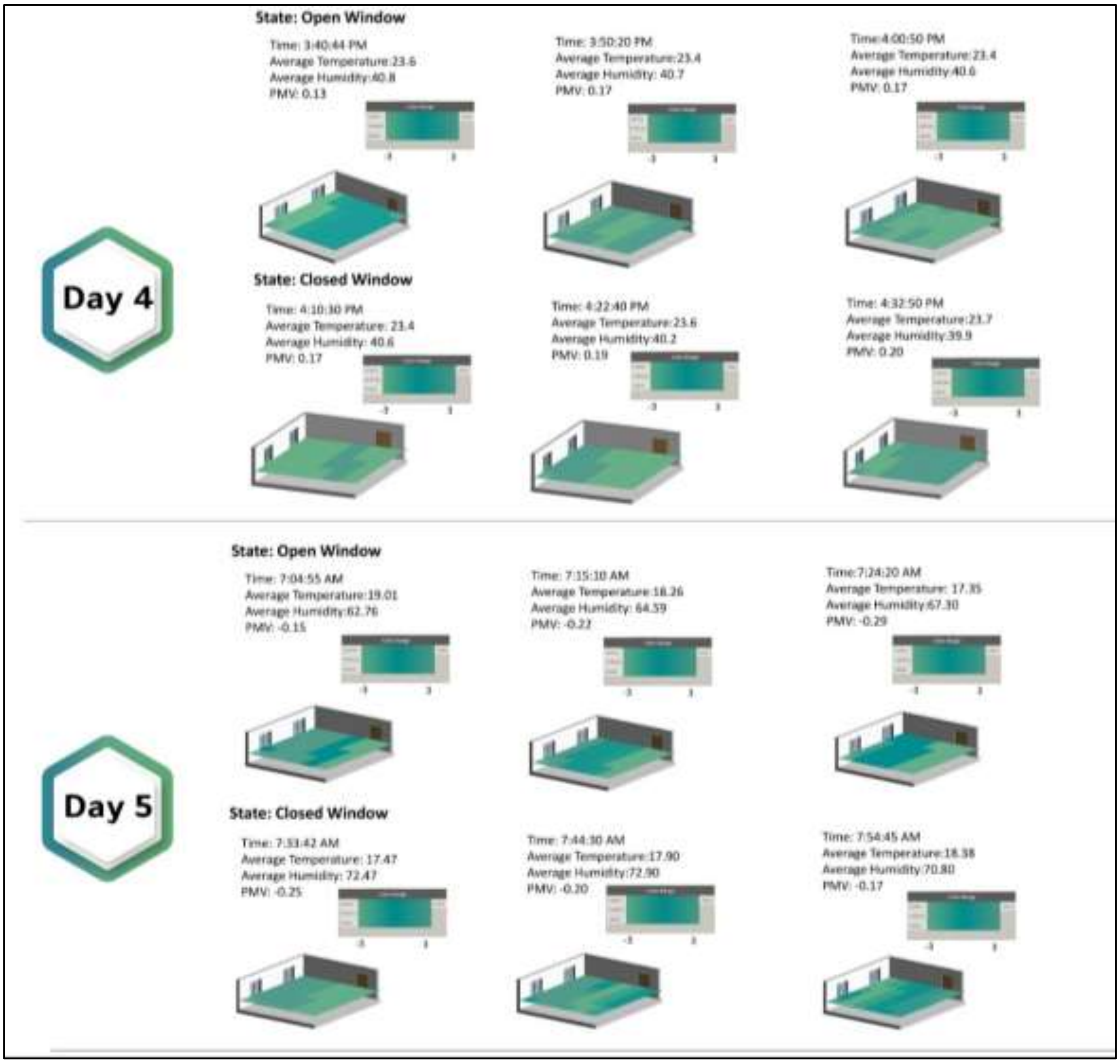

Figure 3.17: PMV Visualization Results for Open Window and Closed Window Scenario For Day 4 And Day 5 (Created by Author).

The illustration of the PMV's visualization from days six and seven of the experiment is shown in (Figure 3.18) underneath. Different from the other days of the study, days six and seven have proximity in time, and both are evening performances. The statistic that both days were close in time may help us make a more direct comparison between those PMV values. Then a better understanding will be able to be obtained of the level of thermal comfort during the evening hours. (Figure 3.18) demonstrates the fact that only a few hours apart represent a tremendous difference in terms of both temperature and humidity, irrespective of the time interval. These variants are caused by external factors, particularly weather, which is very much a logic given that the desert is a dry climate and can manifest in many ways. The PMV values at the beginning are at 0.43, which is neutral, and after day six, they end up at -0.70 when an open window situation occurs, which is slightly cold. This illustrates that on some days there was a noticeable shift from comfortable conditions due to the changed weather conditions inside the building. All in all, the above findings reveal the fact that external factors are to be identified to understand the levels of heat in every place. These external factors should be considered when looking through the numbers to realize the effect they have on thermal comfort levels. By considering all that, users can interpret the data precisely and make wise decisions on how to maintain an excellent indoor air environment.

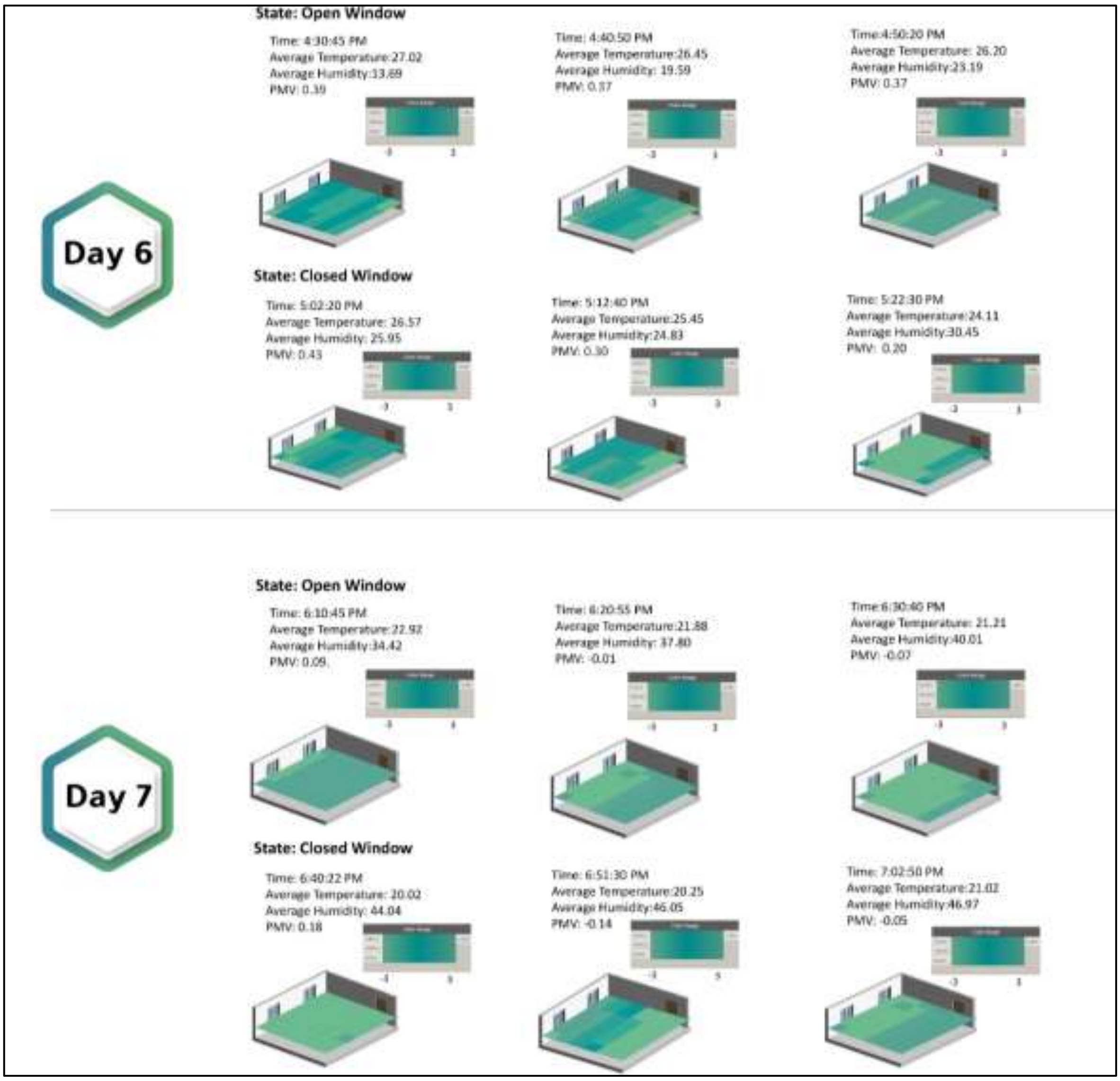

Figure 3.18: PMV Visualization Results for Open Window and Closed Window Scenario For Day 6 And Day 7 (Created by Author).

4. RESULTS AND ANALYSIS

The study explores the boundary between BIM and IoT by developing a digital twin that is monitored in real time, and an evaluation of the indoor thermal comfort is carried out. The experiment showed what is referred to as live streaming and monitoring for real-time visualization, an opportunity to view sensor in the room, and options for setting up optimal conditions according to the data.

4.1 FINDINGS AND BENEFITS OF THE PROTOTYPING AND SIMULATION

This system quickly visualizes heating, cooling, and ventilation modulations based on the data being collected from Arduino microcontroller sensors, mostly for temperature and humidity. As a result of these upgrades, the building became more energy-efficient, and occupant satisfaction increased. Through BIM modelling, it is possible to get more accurate figures of the building’s physical traits, which resulted in better predictions of air quality inside and thermal comfort. Moreover, issue prevention rather than waiting for something to happen is also provided through simulation using the BIM model, which allows forecast analysis of problematic comfort occurrences, hence saving time and costs. Specifically, the wide range of building maintenance services allows the inhabitants to possess a connection to their living environment and enjoy a higher quality of life. Through this unique and eco-friendly method of designing interior areas, the spaces will be environmentally sensible and, at the same time, user-friendly. As a result, individuals began to adapt and perceive their surroundings differently. Employing a data-driven strategy and using technology will allow building managers to carry out continuous monitoring and optimization of the indoor climate, creating a healthier and more productive place to work. Moreover, real time data can be used to detect trends and patterns in occupant behaviours that will provide a chance for modifying the interior environment dynamically and individually. The result is emphasizing technology and sustainable principles integration for a comprehensive and efficient approach towards building management.

The implementation of prototyping and simulation of building indoor thermal comfort through automated visualization can further enhance the understanding of indoor environment dynamics and inform decision-making processes for optimal building performance as shown in (Figure 4.1), in contrast to just seeing charts and graphs of data, as shown in (Oh & Song, 2021). This technology can serve the managers of the buildings in an excellent manner by providing important data points that further work on reducing energy usage and guaranteeing occupant comfort. This may result in a great saving in the cost and green operation of the building.

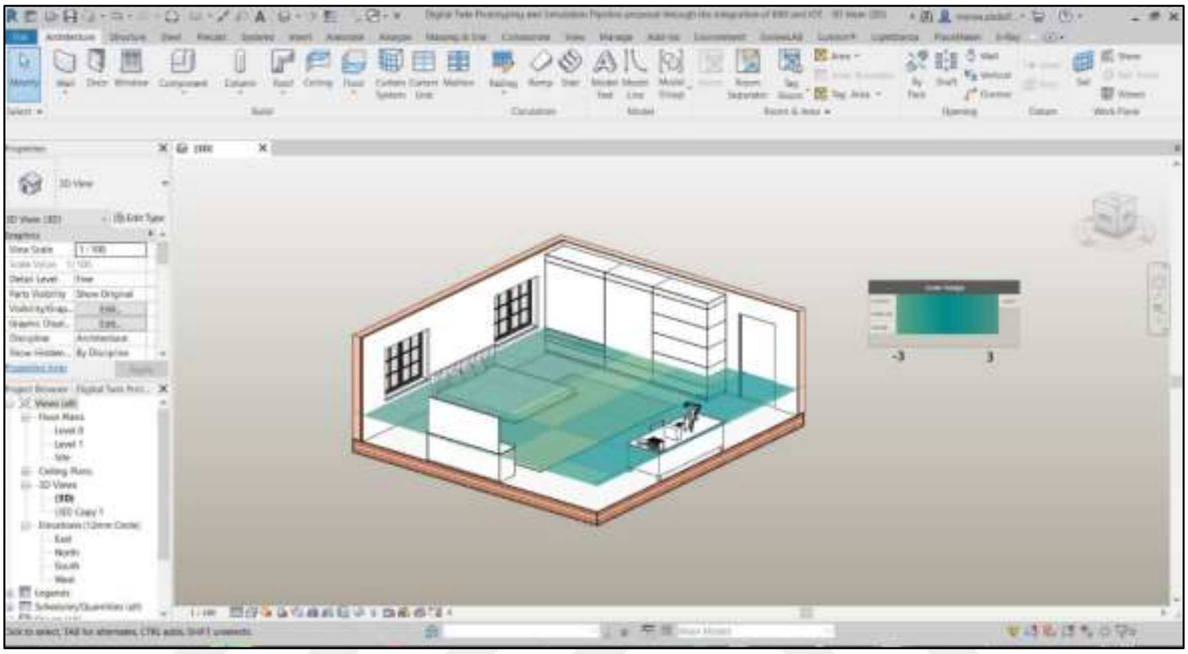

Figure 4.1: Automated Visualization for Building Indoor Thermal Comfort Prototyping and Simulation (Created by Author).

4.2 VISUAL PROGRAMMING AND PARAMETRIC DESIGN

With temperature and humidity controls as well as the use of recognition technology with smart sensors. They will link the energy consumption and the parametric control incorporated for more efficient decisions with visualization modules. This will, in turn, help activate the autonomous mechanisms to improve comfort due to temperature variations and humidity. As well as, having prototyping and simulation digital twin experiment which are produced through the integration of BIM platform's visual programming and parametric design.

Using visual programming (Dynamo), the data can be collected by identifying pertinent files and data sets, configuring view modes, and maintaining real-time communication with the BIM work environment. By relying on the features of parametric design, it visualizes the data for easier comprehension by extending the physical structure with sensor-based extension and generating a digital twin (BIM model) by adding a virtual space in 3D and placing the sensors that are identified with the IoT platform. Digital Twin is auto updated by associating the rules that govern the custom nodes created within the context of visual programming with the decision goals fitted for different contexts.

4.3 PROTOTYPING AND SIMULATION EXPERIMENT ANALYSIS

By using a digital twin to replicate a master bedroom is the main objective of the case study. At first, the room had sensors connected to an Arduino microcontroller that tracked different characteristics of its current state. This study made use of primary sensors. A temperature sensor as well as a humidity sensor. Real-time integration into the BIM model is made possible by the Excel spreadsheet data streamer, which automatically gathers the data after it has been acquired. The subsequent stage entails the instantaneous display of sensor data within the BIM model, facilitated by Dynamo. Dynamo was used to compute the PMV values and thermal comfort of the room to view and monitor them in real time.

The Revit Platform is then actually directly accessed by a certain API, and, through a display, the actual data from it is then directly sent into the Digital Twin in a BIM environment. This data collection, in real-time, allows a detailed look at the indoor environment. Additionally, it turns into a tool to assist with design choices, enabling the necessary adjustments. to be made instantly in response to needs and the prompt and useful observation of these decisions' outcomes. Integration of these technologies will be used to observe and monitor building functioning and maintenance, which will in turn make construction sustainable and effective. Along these lines, the digital replica will aid preventive maintenance and boost the productive use of the buildings.

4.4 SIMULATION AND PROTOTYPING DEVELOPMENTS

More specifically, additional research and recommendations should be done for the most suitable ways to overcome the diverse industries’ demands and challenges, and there are several points associated with IOT and BIM merging for the generation of digital twins that should be discussed in possible future research. The unique effects would include the realization of their potential usage, improvement of benefits, and impact on AEC industries, possibilities to enhance operational and decision-making processes due to the effectiveness and efficiency of digital twin application across AEC industries. There are more opportunities and definitely numerous emerging technologies that can be implemented along with IOT and BIM technologies to develop AEC sectors and achieve the maximum possible gains and benefits of digital twins. Analyzing these options and benefits should give companies a chance to refuse to stay ahead of change and continue competing within the evolving area of technology-based building projects.

Generative design is one of those ideas; it is an iterative method that employs machine learning to generate several design possibilities that follow preset rules. If a project is being developed, it might select the best choice and maximize complexity. It can be utilized in BIM environments with the help of applications like Revit and Dynamo (Filippo et al., 2021). Revit is used for BIM modeling, while Dynamo is used for visual programming with customized graphs and nodes, including Python scripts. A beta version of Autodesk software called Refinery is used for generative design and simulating BIM environments. It employs a genetic algorithm known as NSGA-II optimization, which serves as a stand-in for multi-objective optimization (Editors et al., 2014). With a computational system and the current data available to us because of the Dynamo script, refinery in Dynamo can be used to create a massive design space of likely solutions. Selecting inputs and limitations forms the basis of generative design. There is no reason to believe that the engineer's and/or architect’s duties have been weakened. Instead of attempting to construct new strategies, they can be further refined over time, and the strategies created may be improved over time. This is since that system can ultimately make better-conceived products. Generative construction can also expand living comfort (temperature, air quality, acoustics, etc.) and overall well-being, to meet the needs of the stakeholders. To achieve this, a new set of criteria for the automated assessment of end-user satisfaction in certain regions can be outlined, and the technique can be extended to include the assessment phase of generative design for architectural space planning (Villaggi et al. 2018).

5. DISCUSSION

The novel services offered by newer companies like Google and Amazon would partly fall into the data analytics area, which includes data visualization systems. These services, although capable of collecting data and creating graphs and alarms, cannot be called adaptable and enable automated integrations with the design model of the built environment, especially when working in indoor environments where a BMS (building management system) is complicated to have and adapt. An original automated thermal comfort monitoring system was presented in this study. A system comprised of Internet of Things and BIM technologies was built to assess thermal comfort level in master bedroom automatically and remotely.

Large buildings typically utilize BMS (building management systems) to control their sustainability. BMS can only be operated by a skilled operator and is not completely interactive. where the BMS might not be utilized in small to medium-sized interior spaces or in structures whose sole goal is to thermal comfort and effectiveness component (like temperature and relative humidity) of the area rather than to regulate the mechanical and electrical parts.

The solution connected the virtual and actual worlds by using sensor data and an Internet of Things system to measure the room's temperature and humidity readings which were instantly transferred through excel spreadsheet and analysed using the Revit Dynamo plug-in to the Digital Twin in the BIM system automatically in a real-time updates, allowing the measured environmental index of the room to be seen in BIM as seen in (Figure 5.1), the thermal comfort readings the data gathered in the experiment were examined as well as evaluated in real-time.

The automated visualization discussed in that experiment will serve as a substitute for a potent system for asset management based on data to offer intelligent method for reducing power and electricity use and fostering a convenient and efficient work environment, particularly in habitual situations. A cheap tool was used to extract the temperature and humidity sensor data. microcontroller, smartboard, and sent to an Excel sheet in the system that was constructed. The advantages of sending all thermal comfort data via the IoT system are lowering the installation and improving flexibility by passing them over the wire. To read and sort data, a novel workflow was created, utilizing specifically developed components for the Dynamo visual programming tool. Include them in the BIM model, then refresh the BIM model autonomously at each segment of period. BIM's incorporation into thermal comfort by supporting the facility managers, tracking would enhance the building's regular upkeep schedule. Thus, for any causes of heat discomfort, such as HVAC malfunctions or heat loss from fractures in rich BIM model data, including building envelopes, would assist facilities managers in finding an appropriate and quickest resolution, offering a successful maintenance schedule. Additionally advantageous would be moving relevant building space measurements and information from the BIM model to the facility. This information would include room placements, usage counts, temperature index, required steps, HVAC system types and placements, and building surrounding characteristics. It is easy and effective for the managers to supervise physical workplace conditions, even though they are not present. With the help of this data from environmental sensors, they can use their desktop and analyse it at anytime from anywhere. In the framework of this tool, the management can make the most pragmatic decisions. This classification also has a similar effect on the operators' selection of which ones should get priority in the repair processes or system maintenance planning. considers a wide range of aspects, including the percentage of occupants and the significance of the areas.

The current study aims to bridge the gaps in literature. For example, the absence of automation, the absence of a mechanism for retrieving data and the application and verification of computers in the thermal monitoring comfort. In this experiment, a multifunctional BIM-based automated system with some of the previously mentioned features such as programming executions, automation, and record recoveries was introduced for building environmental satisfaction tracking.

However, there are a few drawbacks to this project, including the following:

a. Even though this study shows that distant sensing and making choices considering the management of environmental convenience in room, the project has several limitations of the area under observation. It will take further research to carry out a thorough analysis and examine how it integrates with the establishment supervisors and other relevant parties to evaluate the framework for its dependability, consistency, durability, and user-friendliness.

b. A restricted set of sensors was used to evaluate the system that was built. The apparatus is capable of being expanded to employ various sensors for additional applications, such as indoor air quality sensors, particle dust sensors and oxide gas sensors. in addition to sensors for building management like resident, movement, and illumination sensors. The created system must be examined more thoroughly using more and different kinds of sensors.

In this way, the most comprehensive assessment of the system's effectiveness in operating in various scenarios and environmental situations will be obtained. Furthermore, the information gathered from stakeholders and end users will be essential to creating a flawless system that offers the optimum user experience.

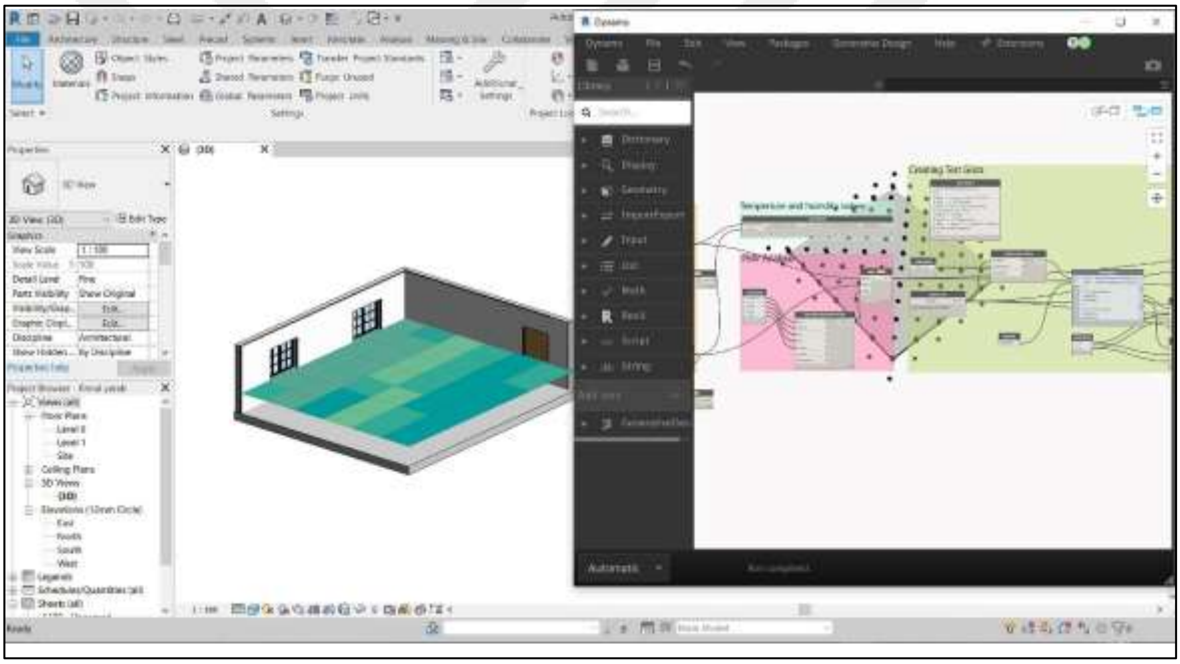

Figure 5.1: BIM and Dynamo Automation and Visualization Platform (Created by Author).

6. CONCLUSION AND SUMMARY

The aim of this thesis was to investigate the possibilities of combining BIM with IoT to create a digital twin prototype. The experiment hypothesis stated that data received from IoT sensors in real-time could be incorporated into the BIM model, increasing its capacity to see real-time conditions and, consequently, improving administrative and operational decision-making activities for building management and maintenance. This integration intends to contribute to the improvement of such an absence in traditional BIM models that, despite being detailed and information intensive, do not have real-time data and dynamic updates. The experiment addresses a master bedroom setting based on the control of temperature and humidity through sensors Arduino and DHT11, with subsequent data analysis in the environment of the BIM model by Dynamo and Python scripts accessible from the Unity interface.

BIM stands for Building Information Modelling, and this is a revolution in the AEC industry. It is an organization of digital information related to a building's geometry and function that is used as a reference throughout the building's life cycle by all parties involved. The advantages of BIM include visualization improvement, collaborative improvement, coordination improvement, and lifecycle dimensioning, which result in the enhancement of projects and decreased costs.

However, due to its static environment, BIM becomes immobile in presenting the actual conditions of the built environment. This is where integration with the Internet of Things comes into play. The IoT possibility allows for constant monitoring of the data collected from numerous sensors that may be installed in the building, including the real-time status of environmental variables, including temperature and humidity. The integration of BIM with IoT also allows one to construct a vital digital twin of the building that shows the model in real time, making the use of BIM more effective and efficient in terms of decision making and monitoring.

The use of BIM and IoT to develop a digital twin is one of those strategies that is rather valuable within the AEC field. This experiment demonstrates several key benefits:

a. Enhanced Decision-Making: Real-time data makes it possible to make decisions right within the BIM model, which is rather beneficial for building managers and their partners.

For example, to enhance energy efficiency and achieve comfort, knowing the present temperature and humidity of various zones in a building is necessary for optimizing HVAC systems.

b. Improved Maintenance: The use of real time tracking enables prognostic maintenance because early signs of a problem may be detected before it worsens into a major problem. Such an approach is preventative in nature, which makes it more effective in lowering the frequency of system breakdowns and increasing the useful life of building structures.

c. Sustainability and Energy Efficiency: By means of the digital twin, constant control over the environmental conditions is suddenly provided, which in turn helps adopt all the effective energy-saving measures and sustainability measures. Real-time data can detect energy waste areas, and ways of optimizing an organization's energy intake and carbon emissions can be developed.

d. Occupant Comfort: Information on the changing environmental conditions can be managed to improve indoor conditions, hence the health of the users of the building. This is especially relevant to residential utility applications where comfort is a primary element influencing the user's living conditions.

e. Data-Driven Insights: Due to integration, one gets the ability to gather and analyse a large quantity of data over time to determine the performance and use of a building. These are the knowledge that, if pursued well and incorporated into the future work of designing and constructing buildings, can help in the creation of intelligent buildings.

The use of BIM as well as IoT was further effectively explained in terms of their synergistic working for obtaining a digital twin in a master bedroom context. This experiment focused on gathering temperature and humidity data via Arduino and DHT11 sensors, entering this data into an Excel document, and then transferring the data into a BIM model through Dynamo with some Python commands added into the experiment to enhance the method. Information was incorporated into the BIM model in order to obtain information on the current conditions of the environment and also to permit dynamic updating, in order to obtain the following factors within the experiment:

a. Successful Integration: The experiment proved that IoT sensors' real-time data could be incorporated into BIM to develop an updated and accurate digital twin reflecting the environment.

b. Accurate Visualization: A layer created in the BIM model regulates the visualization, where temperature and humidity real-time readings can be immediately identified by the stakeholders.

c. Enhanced Functionality: The integration of real-time data into the use of the BM model improved decision making, maintenance, and sustainability aspects as offered by this digital twin.

d. Effective Use of Prototyping and Simulation: The approach of prototyping and simulation helped to check whether the actual integration was difficult in a virtual model.

While the experiment demonstrated the feasibility and benefits of integrating BIM and IoT, there are several areas for future research and development:

a. Scalability: To resolve the above limitation, future work should investigate the possibility of applying this integration to even larger and more complicated buildings. Namely, it requires installing additional sensors and creating new methods to process and analyze data in cases of higher amounts.

b. Interoperability: There will also be importance in coordinating between the BIM software applications and the IoT gadgets to allow data compatibility and integration.

c. Advanced Analytics: While the basic concept of a digital twin focuses on real-time data acquisition and the use of real-time data exploration, adding data analytics and deep learning tool sets can enhance the decision-making precision of the digital twin.

d. User Interface: Enhancing the graphical user interface on the data presentation front end will make the digital twin more friendly to end users, analysts, and program managers alike.

e. Broader Applications: Building on the initiative of using digital twins in monitoring the environment of a facility can be extended to such other uses as structural health, security, and space allocation to make a complete solution for the management of building facilities.

Overall, this experiment proved that BIM and IoT can be combined to develop a digital twin and stressed the innovation of this technology in managing and maintaining buildings through the integration of real-time data. The implications present in these findings for the AEC industry are that these technologies can be used synergistically in order to improve decision-making, sustainability, and occupants' comfort. The findings of this research open the door for further enhancement in the application of digital twin technology in construction with better and more efficient results.

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