MODUL-AR.JOURNAL

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Digital Twin Prototyping and Simulation Process Proposal in Architecture Through the Integration of BIM and IOT

Mimaride Dijital İkiz Prototipleme ve Simülasyon Süreci İçin
YBM ve IoT Entegrasyonu ile İş Akışı Önerisi

Marwa ABDELFATTAH[1*], Can UZUN[2]

Received: 21.11.2024 - Accepted: 27.10.2025

Abstract

Building Information Modelling (BIM) integrated with real-time Internet of Things (IoT) data streams is emerging as a foundational approach in the development of architectural digital twins. This study proposes a structured and replicable process to achieve an architectural digital twin by integrating BIM and IoT technologies. In the proposed framework, real-time environmental data from a 35 m² indoor room was collected using Arduino-based sensors and processed through Excel and Dynamo to synchronize with a Revit-based BIM model. The results demonstrate successful and continuous real-time synchronization of environmental data with the BIM environment, offering valuable insights for optimizing building performance and comfort conditions. However, limitations such as scalability to larger spaces and response time delays require further research. The study presents a novel pipeline for smart building management by integrating real-time monitoring and digital visualization. Future studies should focus on improving automation workflows, minimizing latency, and extending applicability to complex, multi-room settings. This research contributes to the growing field of digital twins by enabling data-driven, real-time environmental monitoring and enhanced decision-making for architects and facility managers.

Keywords: Digital twin, Building information modelling (BIM), Internet of Things (IOT), Automated Visualization, Environmental sensors.

Özet

Bina Bilgi Modellemesi (BIM) ile gerçek zamanlı Nesnelerin İnterneti (IoT) veri akışlarının entegrasyonu, mimari dijital ikizlerin geliştirilmesinde temel bir yaklaşım olarak ortaya çıkmaktadır. Bu çalışma, BIM ve IoT teknolojilerinin entegrasyonuyla mimari bir dijital ikizin elde edilmesine yönelik yapılandırılmış ve tekrarlanabilir bir süreç önermektedir. Önerilen çerçevede, 35 m²'lik kapalı bir odadan Arduino tabanlı sensörler kullanılarak gerçek zamanlı çevresel veriler toplanmış ve bu veriler Excel ve Dynamo aracılığıyla işlenerek Revit tabanlı BIM modeline senkronize edilmiştir. Sonuçlar, çevresel verilerin BIM ortamı ile başarılı ve kesintisiz bir şekilde gerçek zamanlı olarak senkronize edildiğini göstermekte ve bina performansı ile konfor koşullarının optimize edilmesi için değerli içgörüler sunmaktadır. Ancak, daha büyük alanlara ölçeklenebilirlik ve yanıt süresi gecikmeleri gibi bazı sınırlamalar daha fazla araştırma gerektirmektedir. Bu çalışma, gerçek zamanlı izleme ve dijital görselleştirme entegrasyonu ile akıllı bina yönetimi için yenilikçi bir süreç önerisi sunmaktadır. Gelecekteki çalışmaların, otomasyon iş akışlarını iyileştirmeye, gecikmeleri azaltmaya ve daha karmaşık çok odalı ortamlara uygulanabilirliği genişletmeye odaklanması önerilmektedir. Bu araştırma, mimarlar ve tesis yöneticileri için veri odaklı, gerçek zamanlı çevresel izleme ve gelişmiş karar verme süreçlerini mümkün kılarak dijital ikizler alanına önemli bir katkı sağlamaktadır.

Anahtar Kelimeler: Dijital ikiz, Yapı Bilgi Modelleme (YBM), Nesnelerin interneti (IOT), Otomatik görselleştirme, Çevresel sensörler.

Citation: Abdelfattah, M. & Uzun, C. (2025). Digital twin prototyping and simulation process proposal in architecture through the integration of BIM and IOT. *Modular Journal*, *8*(2), 427-447.

[1] Altınbaş University, Institute of Postgraduate Education, Architecture Programme, Istanbul, Türkiye. 223725777@ogr.altinbas.edu.tr
[2] Istanbul Technical University, Faculty of Architecture, Department of Architecture, Istanbul, Türkiye. uzunc@itu.edu.tr
[*] Corresponding Author

MODUL-AR.JOURNAL

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Extended Abstract

Introduction: The Architecture, Engineering, and Construction (AEC) industry is undergoing a paradigm shift through digitalization, primarily driven by the integration of Building Information Modelling (BIM) and the Internet of Things (IoT). BIM offers a comprehensive digital representation of buildings, facilitating enhanced coordination across design, construction, and operation phases. In parallel, IoT technology enables real-time data collection through sensor networks, yielding dynamic insights into building performance. The convergence of these technologies forms the foundation for digital twin systems—virtual replicas of physical environments that can monitor, simulate, and optimize real-world performance. Digital twins are emerging as vital tools in the AEC domain for improving energy efficiency, sustainability, and occupant comfort. Despite significant potential, their real-world implementation is often hindered by the absence of automated data synchronization workflows, limited scalability, and fragmented software interoperability. This study addresses these challenges by presenting a novel, automated framework that integrates BIM and IoT using Revit APIs, Dynamo scripting, Arduino sensors, and Microsoft Excel's Data Streamer add-in to create a real-time, dynamic digital twin prototype.

Purpose: This research aims to establish a replicable and scalable digital twin framework that automates the synchronization of real-time IoT sensor data with BIM environments to enable continuous visualization of indoor environmental conditions. Key objectives include: (1) Developing an automated workflow that links Arduino-based environmental sensors to BIM via Revit, Excel, and Dynamo. (2) Enhancing indoor environmental monitoring through real-time thermal comfort data visualization and PMV (Predicted Mean Vote) analysis. (3) Addressing current limitations in scalability, manual intervention, and data latency seen in prior studies. (4) Demonstrating the applicability of the proposed system through a 35 m² indoor experimental setup, evaluating thermal conditions under varying ventilation scenarios. This study contributes a novel integration method that is adaptable, user-friendly, and conducive to improved facility management and design decision-making.

Method: The research employs a prototyping and simulation-based methodology. A BIM model (LOD 500) of a 35 m² indoor space was developed using Autodesk Revit. Environmental data, including temperature and humidity, was collected using DHT11 sensors connected to an Arduino Mega 2560 board. Data was streamed in real time to Microsoft Excel via the Data Streamer add-in, which served as an intermediary data management platform. Dynamo scripting automated the extraction and transfer of this data from Excel into the Revit model. A custom Python script within Dynamo calculated PMV values, which were interpolated across the room using parameterized Revit families and visualized through a color-coded BIM layer. This enabled real-time thermal comfort analysis and visual feedback within the digital twin. The framework was tested under varying window conditions to evaluate its responsiveness and practical utility.

Findings: The prototype demonstrated full-cycle automation from sensor data collection to real-time visualization within the BIM environment. Key findings include: (1) Automation: Real-time integration significantly outperformed previous manual or CSV-based methods, with seamless updates and no user intervention required. (2) Visualization: The system enabled dynamic BIM visualizations that responded instantly to environmental changes, with clearly interpretable thermal zones aiding decision-making. (3) Accuracy: PMV values were calculated and visualized automatically, improving the reliability of indoor comfort assessments. (4) Spatial Optimization: The digital twin highlighted areas of thermal discomfort, guiding iterative rearrangement of furniture to achieve more uniform comfort distribution. (5) Energy Optimization: The framework enabled proactive adjustments based on real-time insights, reducing reliance on HVAC systems and enhancing energy efficiency. (6) Scalability: Although demonstrated in a small-scale environment, the system architecture is designed for scalability, with potential applicability to larger spaces or facilities. Comparative analysis with previous studies underscored the novelty of this research. Unlike prior efforts that relied on manual data inputs or lacked visualization automation, this study delivered a fully integrated and automated solution, minimizing human error and enhancing operational responsiveness.

Conclusion: This study presents a fully automated digital twin framework that leverages BIM and IoT integration to enable real-time monitoring, analysis, and optimization of indoor environmental conditions. By streamlining the flow of environmental sensor data into a BIM model using tools like Revit, Dynamo, Excel, and Arduino, the system allows for continuous, hands-free updates and visualizations. The findings reveal the practical value of real-time digital twins in smart building management—improving occupant comfort, reducing energy consumption, and enabling data-driven spatial planning. Furthermore, the system's success in guiding layout modifications based on PMV data validates its potential for use in both design and operational phases. Despite the success of this prototype, limitations such as the small sample size and lack of broader user feedback were noted. Future research should explore larger-scale applications and integrate machine learning models for predictive analytics. Additionally, coupling the current workflow with generative design tools like Autodesk Refinery could enable more advanced, automated design iteration based on environmental feedback. This research highlights the transformative potential of BIM-IoT integration for smart building systems, offering a scalable, replicable, and efficient solution for achieving real-time environmental control and performance optimization in built environments.

Keywords: Digital twin, Building information modelling (BIM), Internet of things (IOT), Automated Visualization, Environmental sensors.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry is undergoing a digital transformation, driven by advancements in Building Information Modelling (BIM) and the Internet of Things (IoT). BIM provides a comprehensive digital representation of buildings, enabling stakeholders to manage design, construction, and operations with greater efficiency and accuracy (Doukari et al., 2023; Park, 2008). Meanwhile, IoT facilitates real-time data collection from physical environments through interconnected sensors and actuators, offering dynamic insights into building performance (Gubbi et al., 2013; Lu et al., 2020). When combined, these technologies lay the groundwork for developing digital twins—virtual replicas of physical spaces that support real-time monitoring and data-driven control of building systems.

Digital twins have gained significant attention in recent years due to their potential to enhance building sustainability, energy efficiency, and occupant comfort. By integrating IoT data with BIM models, digital twins provide a dynamic, real-time representation of physical assets, enabling proactive decision-making and predictive maintenance (Chang et al., 2018; Wu & Liu, 2020). However, despite their potential, the practical implementation of digital twins in the AEC industry faces several challenges, including limitations in automation, scalability, and real-time data synchronization (Wehbe & Shahrour, 2019). Most prior research lacks a fully automated and scalable workflow that can continuously update BIM models using live IoT data streams.

To address this gap, this study proposes a digital twin prototyping framework that integrates BIM and IoT technologies through an automated pipeline using Revit, Dynamo, Excel Data Streamer, and Arduino-based environmental sensors. The research focuses on improving real-time synchronization, automation, and visualization within BIM environments and contributes to the development of scalable smart building systems.

Research Problem

Research demonstrates the advantages of merging IoT data with BIM systems, but lacks automation methods to synchronize data in real-time within BIM models. Most prior efforts depend on manual or CSV-based data inputs, resulting in delays, reduced responsiveness, and an absence of real-time updates within BIM environments. Traditional data input through CSV files characterizes most past efforts, creating delays along with reduced automation while blocking instant building parameter updates. The existing research fails to properly elaborate on scalability, automation, and data management solutions, particularly in dynamic indoor spaces where continuous real-time adjustments remain critical for occupant comfort and energy system optimization.

To overcome these limitations, this study implements a fully automated system that integrates IoT sensor data into BIM models via Revit APIs and Dynamo scripting, leveraging Excel Data Streamer as a live data conduit. The proposed framework revolutionizes environmental data synchronization by delivering immediate information updates so that real-time monitoring and automated control systems operate without human operators. This automation approach contributes a practical, adaptable methodology to the field of smart buildings and highlights how such integration can be both accessible and effective.

Aim of the Research

This research aims to establish a replicable and scalable digital twin framework that automates the synchronization of real-time IoT sensor data with BIM environments to enable continuous visualization of indoor environmental conditions. The study addresses critical gaps in current digital twin implementations by providing a comprehensive solution that combines automation, real-time data processing, and visualization capabilities. Key objectives include:

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

- Developing an automated workflow that links Arduino-based environmental sensors to BIM via Revit, Excel, and Dynamo.
- Enhancing indoor environmental monitoring through real-time thermal comfort data visualization and PMV (Predicted Mean Vote) analysis.
- Addressing current limitations in scalability, manual intervention, and data latency seen in prior studies.
- Demonstrating the applicability of the proposed system through a 35 m² indoor experimental setup, evaluating thermal conditions under varying ventilation scenarios.

Research Questions

The integration of IoT data with BIM models significantly enriches the capability for presenting the real-time status of a building's thermal comfort and functionalities. The research questions of this study explore how the introduced IoT-BIM integration framework addresses architectural applications by providing enhanced automated digital twin processes. This study introduces Microsoft Excel as an intermediary platform that allows real-time IoT sensor data transfer through Dynamo scripting into the BIM model visualization layer. The benefits of using Excel for data management and easy tool integration, combined with its flexible automatic capabilities, pave the way for real-time decision systems.

1. How can IoT data be seamlessly integrated into BIM models to achieve real-time visualization and analysis with enhanced automation capabilities?
2. What are the practical challenges and limitations associated with implementing the proposed digital twin process in indoor environments using IoT and BIM technologies?
3. How can the proposed digital twin process contribute to enhancing indoor thermal comfort through real-time data-driven decision-making?
4. In what ways does the proposed framework improve upon existing IoT-BIM integration methodologies in terms of automation, accuracy, and practical applicability?

Scope of the Research

The study entails the development and implementation of a digital twin prototype in a controlled environment of a 35 m² indoor space, using Arduino and other environmental sensors to update and transfer data in real time. The proposed framework explores real-time integration of IoT into BIM by utilizing a structured workflow with tools such as Arduino, environmental sensors, and BIM software, specifically Revit and Dynamo platforms, to facilitate automated data processing and visualization.

BACKGROUND

Building Information Modelling (BIM) is a computer-aided design technology that facilitates decision-making across the entire lifecycle of built assets, integrating time, cost, 3D modelling, and information management (Doukari et al., 2023). It enhances collaboration among stakeholders (Park, 2008), supports clash detection, and ensures efficient coordination during construction. The Industry Foundation Classes (IFC) standard enables interoperability between BIM software, improving data sharing and sustainability analysis (Lin et al., 2013; Ruemler et al., 2016). Additionally, BIM serves as a knowledge resource for data storage, allowing in-depth thermal efficiency analysis (Ku & Taiebat, 2011; Miettinen & Paavola, 2014; Chan et al., 2019).

A detailed BIM model supports designers, constructors, and operators by providing accurate geometric and material specifications. For existing structures lacking digital models, laser scanning and photogrammetry aid in geometric data acquisition (Brilakis et al., 2019). Recent research emphasizes the integration of BIM with Digital Twin frameworks to enable real-time monitoring, predictive analytics, and performance-based control

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

of built environments. This integration significantly improves project efficiency and facility management (Gubbi et al., 2013; Lu et al., 2020). IoT sensors further enhance BIM's real-time capabilities, with plug-ins like Dynamo facilitating automation and data exchange (Chang et al., 2018).

The combination of BIM and IoT technologies holds considerable promise for smart building operations, particularly in optimizing energy use, improving air quality, and enhancing indoor comfort conditions. Systems such as COZyBIM leverage IoT sensors for air quality monitoring within BIM models (Wu & Liu, 2020). However, limitations in automation continue to hinder the fully seamless and scalable integration of real-time IoT data into BIM visualizations. Efforts like Firefly for Dynamo and Unreal Engine scripting have demonstrated real-time connections, but these methods often require manual configurations and lack comprehensive, automated data handling workflows (Wehbe & Shahrour, 2019; Natephra & Motamedi, 2019). This highlights the need for an accessible, automated framework that ensures continuous synchronization and visualization of sensor data within BIM environments. Table 1 illustrates the variations between previous research findings on BIM and IoT technologies.

Table 1. Comparing the variations between previous research findings

Authors	Sensors	Tools Used	Automated Integration	Automated Visualization	Limitations
(Wu & Liu, 2020)	Temperature, Humidity, CO_2	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, Firefly, Revit.	Yes	Yes	Lack of stability in the connection.
(Zanchetta & Cecchini, 2018)	Temperature, Humidity, Lighting	Grasshopper, Ladybug, Honeybee, Galapagos.	No	No	Modelling and simulation without. automation, no empirical data gathering.
(Teizer et al., 2017)	Brightness	BIM, BLE, Dynamo, Revit.	Yes	Yes	Integration causing delays and errors in the automation process.
(Del Grosso etl al., 2017)	SHM Sensors	Revit, Excel, Naviswork.	No	No	Lack of automation and visualization.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Authors	Sensors	Tools Used	Automated Integration	Automated Visualization	Limitations
(AL-Qattan et al., 2017)	Ribbon Sensors	Arduino, Revit, Dynamo, Grasshopper, Rhino.	Yes	No	The automation od generating matmatical equation, but lack of automation visualization.
(Smarsly & Tauscher, 2016)	SHM Sensors	BIM, SHM sensors.	No	No	Utilizing IFC to integrate BIM into the SHM system, but lacking automation and visualiztion.
(Kensek, 2014)	Temperature, Humditiy, CO2	Arduino, Revit, Dynamo, Grasshopper, Rhino.	Yes	Yes	Transfering data between platforms automatically is error-prone process.

METHOD

Prototyping and simulation will be the methodologies employed in this study. Prototyping is the process of creating an early version of a product or system to test its functionality and design, whereas simulation is the process of creating a computer model to predict how the system would perform in various circumstances (Yin & Mckay, 2018). Building a model of an actual or anticipated system, such as a design concept, and then running experiments with the model to ascertain how the system performs under various operating conditions and assess alternative management strategies and decision-making processes are the processes of prototyping and simulation (Abar et al., 2017). Prototyping and simulation together can expedite development and raise the chance that systems or products will succeed. The research paper's prototyping and simulation method, which started with problem-solving and went through final evaluation and findings, can provide crucial insights into the potential performance of a system or product before devoting resources to full-scale production. Early modifications are possible with this iterative approach, producing more effective and efficient outcomes.

The Research Model

This research proposes a digital twin framework that supports real-time decision-making for interior spaces, integrating IoT and BIM. The proposed automation framework consists of five crucial steps (Figure 1). As-built BIM model development, data acquisition, real-time data processing and analysis, automated data integration, visualization, and reporting constructs not only provide the theoretical backbone of the study, but also constitute the research model itself. The proposed model in question not only defines the steps of the research but also presents the proposed digital twin logic at the conceptual level, with the data flow and the interrelations between the model's components. Hence, the research model defines its theoretical and methodological models together. The validity and applicability of the proposed framework will be tested through simulation and prototyping processes.

MODUL-AR.JOURNAL
RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

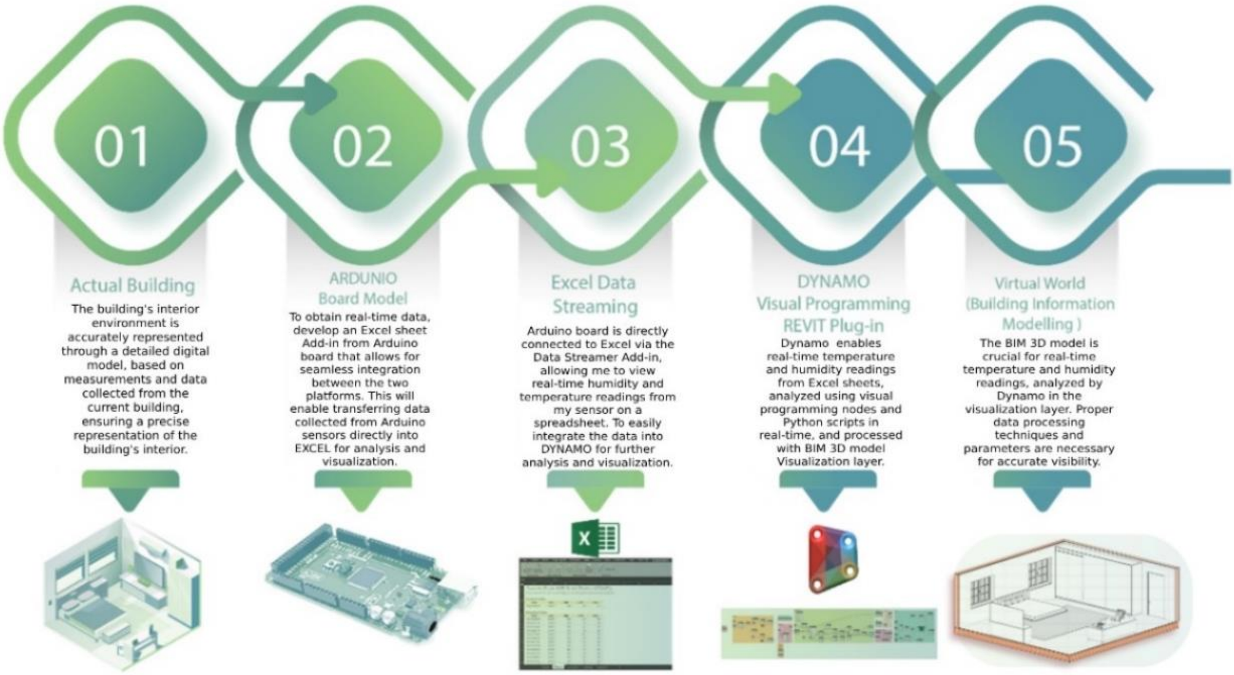

Figure 1. Visualization and automation framework

1. As-Built BIM Model Development (Actual Building)

Building Information Modelling (BIM) integrates people, processes, technology, and regulations to create a digital representation of buildings and infrastructure, enhancing stakeholder collaboration. The Level of Development (LOD) framework (LOD 100–500) ensures models accurately reflect project stages, from conceptual design to as-built documentation and facility management (Latiffi et al., 2015).

This study focuses on refining BIM models using Revit after data collection, ensuring precise 3D representations. Real-time data, including humidity and temperature, is integrated into the model, with a focus on windows for accurate simulation. Walls, floors, and lighting conditions are also carefully considered to enhance visualization and thermal comfort analysis. The refined model is then effectively integrated into a Dynamo script for detailed simulation and analysis (Figure 2).

Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

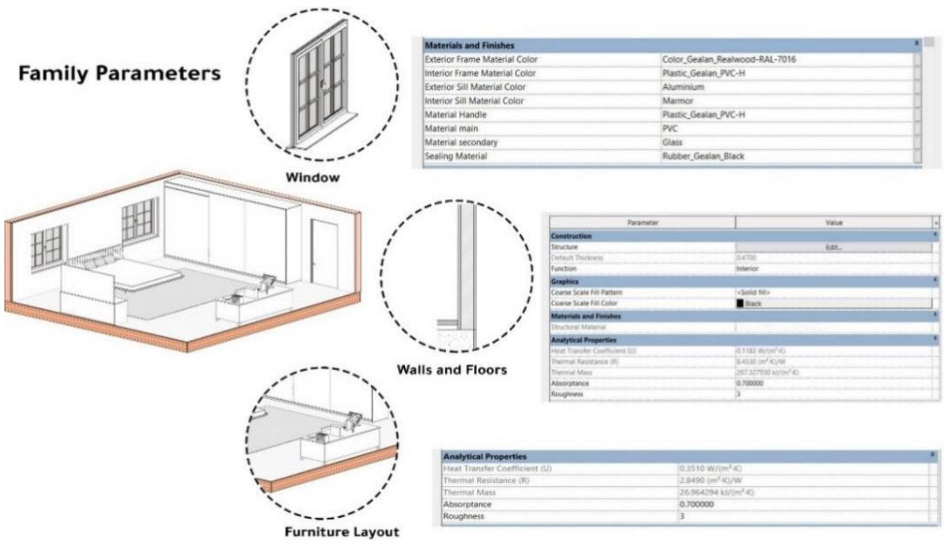

Figure 2. Family-parameterized BIM model

2. Data Acquisition (Ardunio)

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). DHT11 Temperature and Humidity Sensor Specifications as follows (Shafiril et al., 2016):

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

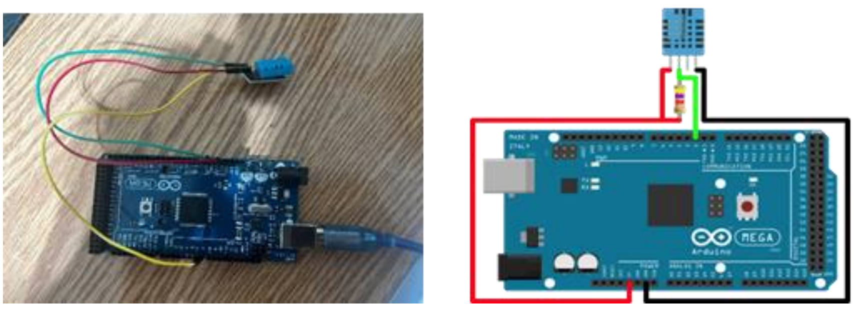

Figure 3. Arduino microcontroller connected to DHT11 sensor

3. Real-time Data Processing and Analysis (Excel Data Streaming)

Excel is widely used for data analysis and engineering calculations, with VBA enabling enhanced functionality through add-ins (Chehab & Artail, 2004). The Data Streamer add-in allows real-time data visualization by connecting Excel to external sources like Arduino (Aliane, 2010). This facilitates continuous monitoring of environmental conditions, such as temperature and humidity, without manual input (Figure 4). In this study, Data Streamer is used to automate real-time data collection and integration into the BIM model. A user-

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

friendly interface improves readability and accessibility for stakeholders, ensuring accurate data synchronization. The workflow establishes an automated link between Arduino, Excel, and Dynamo, enabling instant updates to the BIM model's visualization layer with high precision and minimal latency.

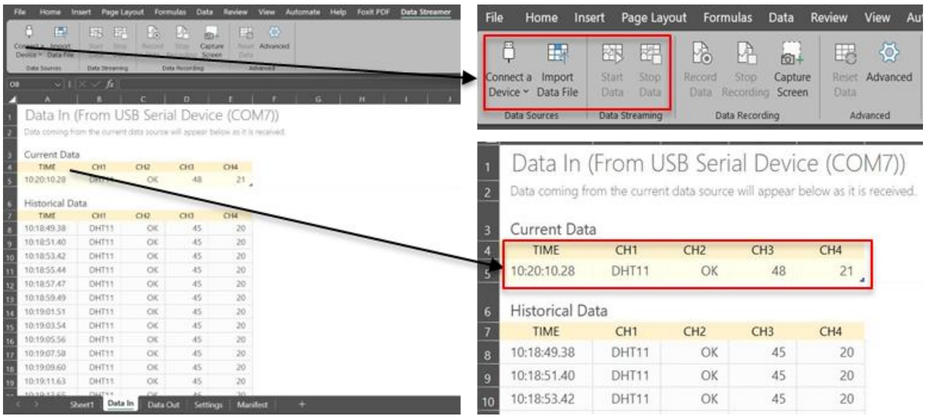

Figure 4. Data streamer add-in in Excel spreadsheet

4. Automated Data Integration (Dynamo)

Revit workflow automation and customization are made possible by the open-source Dynamo add-in, which facilitates visual programming. This allows the creation of custom scripts and automates various tasks within the Revit environment (Shishina & Sergeev, 2019). Additionally, Dynamo uses Revit APIs to interact with the Revit model and data, enabling the seamless and efficient manipulation of elements and parameters within the software. This study utilizes the automated real-time data integration process via Dynamo. The dynamo script is divided into several key phases, each handling specific data processing and visualization tasks to achieve automated building performance monitoring and analysis as follows: Arduino data processing, PMV analysis/ decision, BIM model visualization, data interpolation within the Revit family, and PMV data visualization process.

5. Data Acquisition from Excel

The workflow starts by importing real-time sensor data from an Excel file, which serves as an intermediary platform for storing and managing data collected from IoT sensors, which are temperature and humidity values from Arduino. The Excel sheet is automatically connected to the Dynamo script and nested within the nodes, ensuring that once the script is opened, the Excel sheet is simultaneously launched, facilitating the automatic collection and transfer of real-time temperature and humidity values into the script as shown in Figure 5. An automated connection between the Excel file and the Dynamo script ensures seamless data updates without manual intervention. The script reads real-time values using the 'Read from File' node, ensuring continuous synchronization of temperature and humidity values. Data from specific Excel cells is parsed and prepared for further analysis.

To address previous research limitations:

1. Enhanced clarity of data input structure by specifying the Excel sheet layout and linking mechanisms for better reproducibility.

2. The workflow now ensures real-time updates without data loss or delay.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

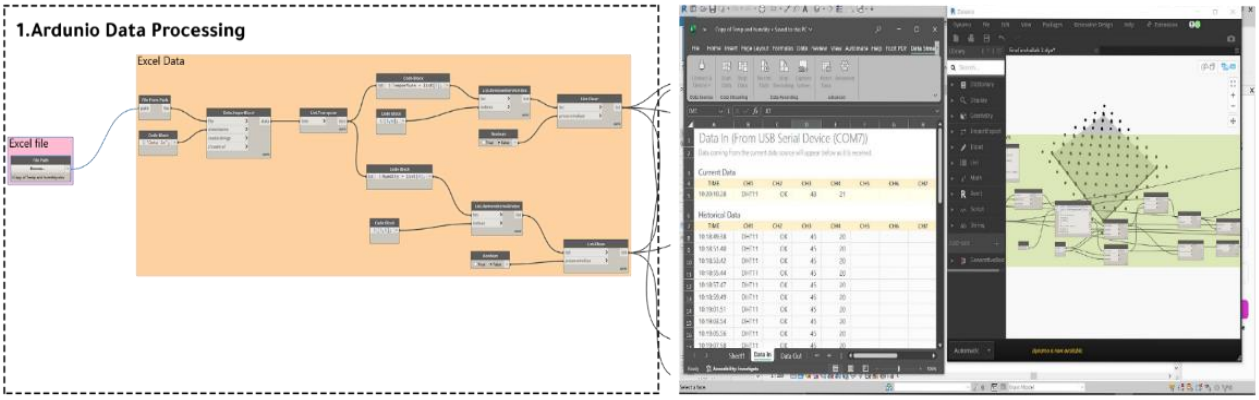

Figure 5. Excel spreadsheet processing for Arduino data inside of Dynamo script

The PMV formula and analysis

The automatic integration of Excel spreadsheets with Dynamo streamlines PMV (Predicted Mean Vote) calculations, simplifying data collection and analysis. The PMV model estimates thermal comfort by considering key environmental factors, as described by Wei et al. (2024). A Python script was developed to automate PMV calculations dynamically, combining real-time sensor data from Excel and Arduino. This automated workflow, shown in Figure 6, ensures seamless data transfer and calculations without manual intervention, enhancing efficiency and accuracy. Thermal comfort is continuously monitored and analysed, with results automatically interpolated and visualized within the BIM model for decision-making. This real-time integration enables immediate updates, fostering a more adaptive and responsive approach to indoor environmental control. The PMV was computed using the formula of Wu & Liu (2020).

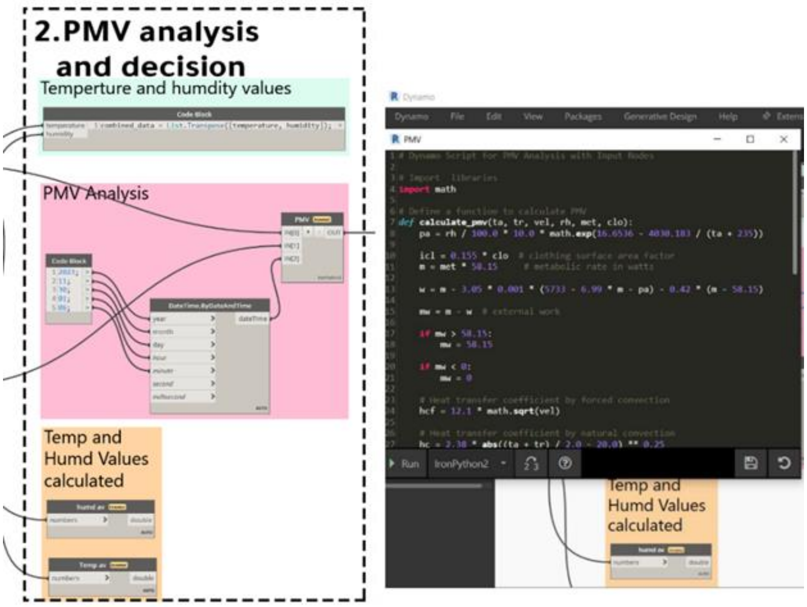

Figure 6. PMV analysis Python script node

MODUL-AR.JOURNAL

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Interpolation process:

After the automated execution of the PMV analysis using the Python script node, it is important to interpret the results to facilitate real-time decision-making and optimize indoor environmental conditions. The interpretation is systematically carried out by creating a Revit family with defined parameters for temperature and humidity readings, ensuring a structured approach to data organization and retrieval. The PMV analysis data is dynamically linked and structured within the Revit environment, allowing for seamless visualization and analysis. Subsequently, the data is automatically integrated into the visualization layer within the BIM model, providing instant feedback and improved usability for facility management. This process, as shown in Figure 7, enhances the accuracy and efficiency of monitoring thermal comfort conditions in the building by offering a clear and comprehensive representation of indoor environmental performance.

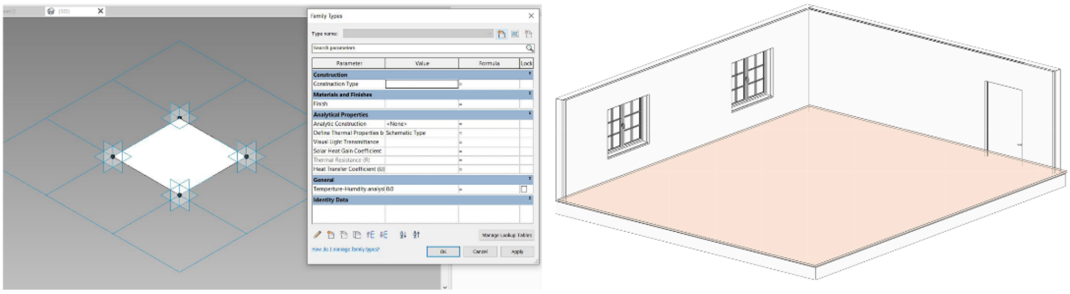

Figure 7. Creating a Revit family containing temperature and humidity parameters

After inserting the plane into the Revit model, dividing it with the Dynamo script, making test grids to position the family and its parameters within the grids, to interpolate the PMV-analyzed data into it to prepare it for visualization.

6. Visualization and Reporting (Virtual World):

As shown in Figure 8, the visualization plane has been divided into grids, and the family parameters are loaded into the grids. Then, to precisely measure the thermal comfort of the area, it was elevated 90 cm above the floor so that the PMV analysis and visualization could be seen at desk level.

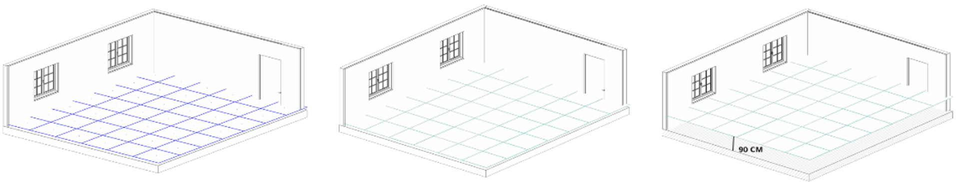

Figure 8. Visualization layer dividing process for the data interpolation process

Subsequently, the interpolation Python node was employed to merge the adaptive components family with real-time temperature and humidity, as well as all PMV computed values. This initiated the automation interpolation procedure to store its values in the Revit model for visualization. After the creation of layer components in BIM at the predetermined elevation, collect employing sensor data to determine each grid's context view index (PMV) within the layer interpolation, then assign the corresponding colour for each grid based on the predefined scheme of colors. This step's outcome produces an image resembling thermography and enables the distribution of the intended context view index value for the space in BIM to be seen visually by the user.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Simulated Study Area

The proposed automation framework for integrating IoT and BIM in real-time for decision-making processes simulates a simple 35 m² room, including furniture, two windows, and an interior door, as a real-world problem. The rationale behind selecting and simulating a single room is to easily handle a small-scale space for the complex framework proposal problem. The primary objective of the study is not to simulate an actual room, but to propose and test the automation framework, which is the study's hypothesis.

Testing the Framework

Most important measures for estimating the validity of applicability and scalability of the proposed framework are the real data usage rather than synthetic generated samples, automation and data integration speed, interpretability of the results, and the ease of reproducibility of the prototype.

To validate its effectiveness, the workflow was tested in a residential setting, incorporating a Revit model, Arduino microcontroller, Dynamo script, Excel spreadsheet, and environmental sensors. The integration successfully recreated a prototype digital twin, automating data flow and synchronization. This advancement eliminates manual data entry, improving consistency and response time compared to previous approaches, ultimately allowing users to optimize room arrangements for better comfort and energy efficiency. Figure 9 shows the PMV visualization process.

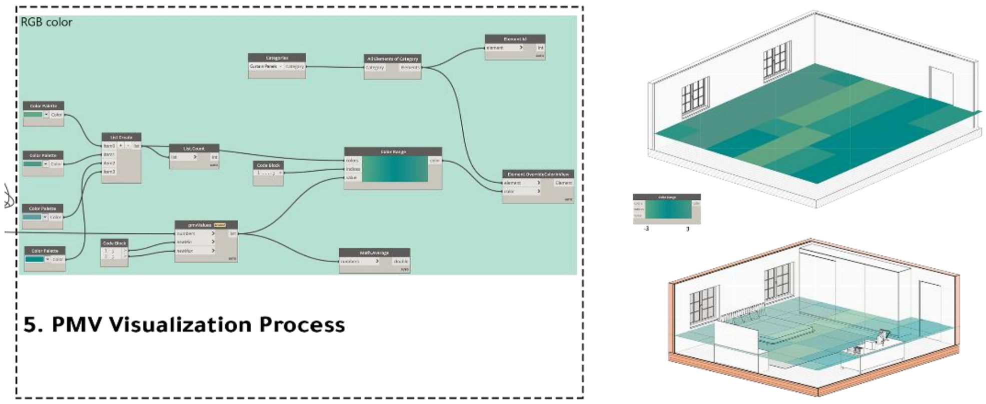

Figure 9. Dynamo script for the Visualization layer process

To assess indoor comfort levels, daily temperature and humidity data were collected over a week starting December 30, 2023, at different times of the day.

Two scenarios—windows closed and open—were analysed to evaluate their effect on temperature and airflow. This interactive approach allows users to dynamically analyse scenarios and make informed decisions to optimize thermal comfort.

Unlike manual methods, the automated workflow delivers real-time insights, enabling proactive adjustments with minimal effort. Figure 10 showcases two-day snapshots of thermal comfort visualization, highlighting PMV variations between the closed and open window scenarios. A notable difference in temperature and humidity was observed between night and morning, reflecting seasonal fluctuations in Egypt's winter. There was a temperature decline overnight, followed by a gradual increase in the morning, emphasizing the need for continuous monitoring to capture real-time environmental changes. Additionally, the findings demonstrate the system’s capability to assess occupant thermal comfort under varying conditions, offering a foundation for optimizing passive design strategies to enhance energy efficiency and occupant well-being.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

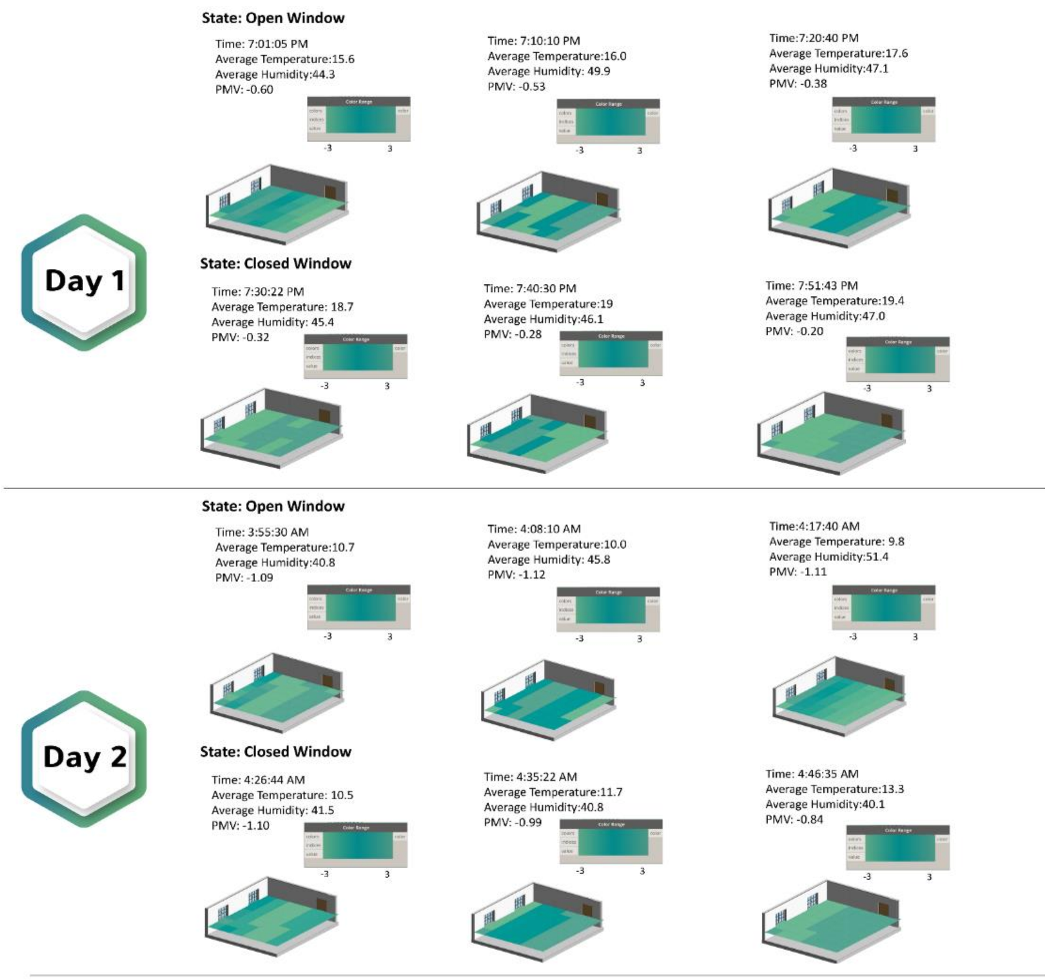

Figure 10. PMV visualization results for the open window and closed window scenarios

Even though it is nighttime and close to each other, there is a discernible difference in the humidity and temperature measurements between day one and day three, as shown in Figure 11. Location's atmosphere fluctuates greatly from day to day, particularly as winter approaches in this region; the prevalence of variations in climate is a typical and anticipated occurrence due to the location. It is crucial to monitor these changes closely to maintain a comfortable and healthy indoor environment.

Understanding the patterns of humidity fluctuations can help in determining the most effective strategies for regulating indoor conditions.

Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

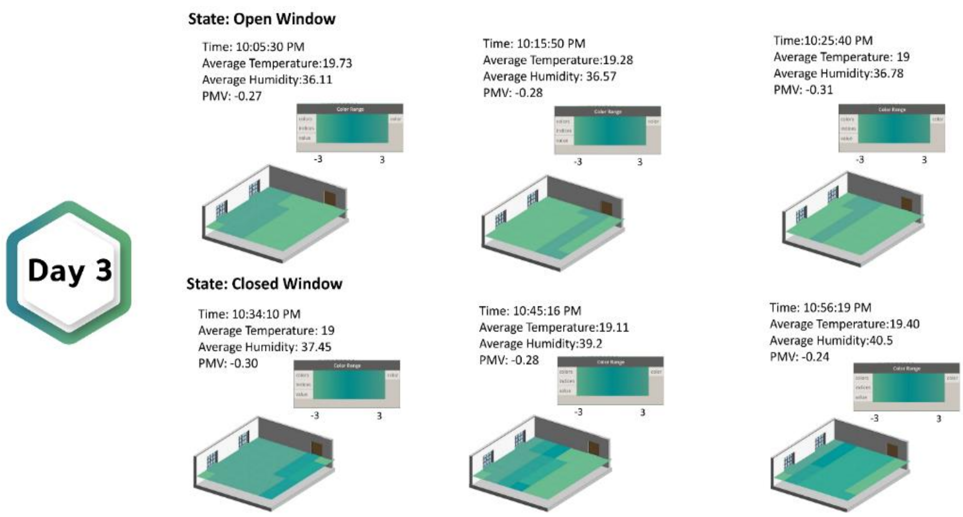

Figure 11. PMV visualization results for the open window and closed window scenarios

RESULTS

This section presents a real-world case study demonstrating the practical application of the proposed IoT-BIM integration workflow for digital twin visualization in indoor environmental monitoring. The workflow integrates an Arduino microcontroller, temperature and humidity sensors, Revit API, Dynamo, and Excel to automate real-time data acquisition and visualization. Unlike previous studies, the proposed method enhances automation, reduces manual interventions, and improves interoperability between IoT data sources and BIM models.

The developed platform enables real-time assessment of thermal comfort levels, helping stakeholders identify areas needing adjustments for optimal conditions. As shown in Figure 13, this visual representation enhances accuracy and supports data-driven decision-making regarding building layout and operations

By integrating BIM modelling, the study improved predictions of indoor air quality and thermal comfort, allowing for proactive rather than reactive adjustments. This approach reduced operational costs and enhanced building sustainability (Miettinen & Paavola, 2014). Additionally, IoT-enabled BIM simulations provided automated alerts for potential comfort issues, contributing to a more responsive and efficient building management system (Ku & Taiebat, 2011).

The digital twin prototype facilitated real-time thermal comfort visualization within the BIM environment, offering actionable insights for spatial planning. Initially, sensor data revealed thermal inconsistencies, such as heat accumulation near seating areas and poor airflow in workspaces. These insights guided iterative furniture rearrangement to optimize occupant comfort, ensuring a more uniform thermal distribution through real-time PMV (Predicted Mean Vote) values, as shown in Figure 12.

Key strategic decisions based on window placement and airflow analysis included:

1. Relocating workstations to areas with improved airflow for better ventilation efficiency.

2. Adjusting furniture placement to prevent direct exposure to temperature fluctuations from windows.

3. This process demonstrated the practical application of digital twin technology for optimizing indoor environments through data-driven design modifications.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

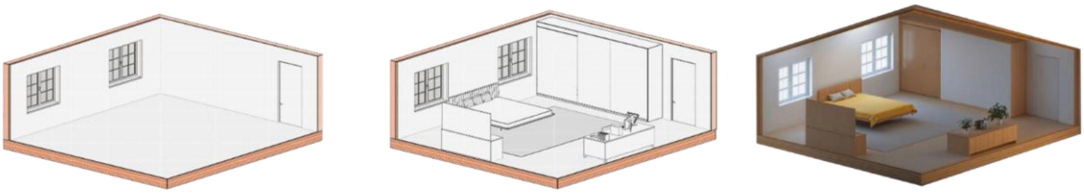

Figure 12. Improve spatial planning according to thermal zones

Each adjustment was validated by re-running the simulation and observing the updated visualization layer within the BIM model. The results demonstrated a measurable improvement in overall thermal comfort, leading to a more uniform distribution of comfort across the space.

By continuously leveraging the visualization data, the system allowed for an evidence-based approach to furniture placement, ensuring that spatial planning decisions were no longer based on intuition but rather on real-time environmental insights.

To assess the impact on user satisfaction, a structured self-evaluation was conducted based on various parameters, including comfort levels, ease of use, and monitoring efficiency. The results indicated a reduction in manual interventions and a notable improvement in thermal comfort stability. The system's automation capabilities provided a seamless user experience, ensuring consistent environmental conditions with minimal user input.

Despite being based on a single-user evaluation, the findings suggest significant improvements in user satisfaction and operational efficiency. Future research will aim to validate these findings through broader user studies and different building environments to provide more comprehensive insights into the system's effectiveness.

Table 2 highlights the most developed aspects of this research compared to previous studies, addressing their limitations and emphasizing the novel contributions introduced in this study (Wu & Liu, 2020; Wehbe & Shahrour, 2019; Natephra & Motamedi, 2019).

Table 2. Key Contributions: Differentiation from Previous Research

Aspect	Previous Research Limitations	Proposed Study Improvements
Data Integration Approach	Manual CSV-based data transfer leads to delays and potential data loss. This approach required periodic manual uploads and lacked real-time synchronization (Wehbe & Shahrour, 2019.	Automated real-time data updates using the Excel Data Streamer add-in, ensuring continuous data flow from Arduino sensors to the BIM model without the need for manual intervention.
Visualization Capability	Static 2D and 3D visualizations required manual updates, leading to outdated representations and time-consuming processes for facility managers. (Wu & Liu, 2020).	Real-time visualization via automated Dynamo scripting, dynamically updating the BIM model to reflect current environmental conditions with minimal latency.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Aspect	Previous Research Limitations	Proposed Study Improvements
Scalability	Limited scalability in previous studies, as data processing and visualization were constrained by manual processes and hardware limitations. (Natephra & Motamedi, 2019).	A scalable and adaptable framework tested within a 35 m² indoor space, with potential for expansion to larger building environments through optimized data processing techniques.
Automation Level	Partial automation, where manual interventions were required to trigger data imports and visualization updates, resulting in inefficiencies. (Wu & Liu, 2020).	Fully automated workflow from sensor to visualization without manual input, reducing human error and ensuring continuous monitoring.
Revit and Dynamo Integration	Limited and fragmented integration with third-party platforms (PanStamp), requires additional steps for data processing and interpretation. (Wehbe & Shahrour, 2019).	Seamless integration of IoT sensor data into Revit models via Dynamo scripting, enhancing interoperability and allowing direct manipulation within the BIM environment.
Decision-Making Support	Lack of actionable insights and real-time analytics makes it difficult for facility managers to make informed decisions quickly (Chan et al., 2019).	Provides comprehensive real-time analytics and insights to optimize building operations, improve energy efficiency, and enhance occupant comfort with actionable data visualization.

CONCLUSION AND DISCUSSION

This research successfully integrates Building Information Modelling (BIM) with the Internet of Things (IoT) to create a digital twin prototype, enabling automated real-time monitoring and control of indoor thermal comfort. By incorporating Arduino sensors, Excel Data Streamer, Revit, Dynamo, and Python, the proposed system automates data collection, processing, and visualization within a BIM environment, significantly reducing manual interventions and improving efficiency, as illustrated in Figure 13.

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

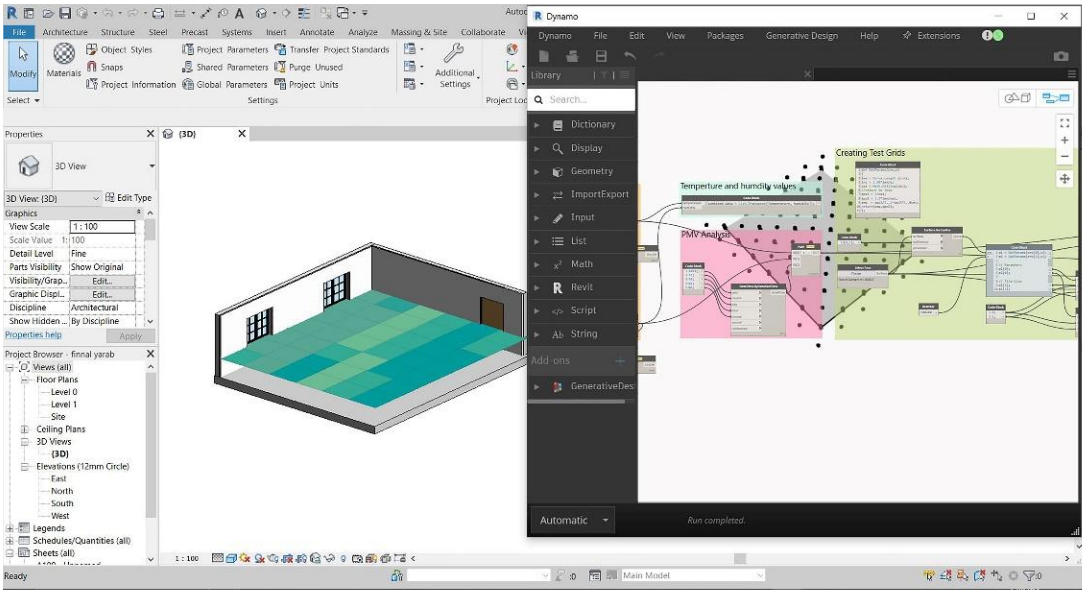

Figure 13. BIM and Dynamo automation and visualization platform

Key Contributions and Implications

The study demonstrates that real-time monitoring and BIM integration offer tangible benefits in enhancing indoor environmental quality, optimizing thermal comfort, and improving energy efficiency. The system provides actionable insights into building performance and maintenance, allowing stakeholders to make data-driven decisions to improve occupant comfort and operational efficiency. Additionally, the digital twin prototype supports predictive maintenance, enabling proactive adjustments based on environmental data trends rather than reactive responses.

The findings highlight the effectiveness of the automated workflow in overcoming traditional challenges associated with data synchronization and real-time visualization. Unlike prior manual or semi-automated efforts, the proposed system establishes a continuous data exchange loop between IoT sensors and BIM platforms. Compared to previous manual methods, the system enhances interoperability between IoT data sources and BIM models, ensuring seamless data flow and improved decision-making. Moreover, by integrating PMV (Predicted Mean Vote) calculations, the study presents a robust approach to assessing thermal comfort levels dynamically, which aids architects and facility managers in optimizing spatial planning, HVAC control, and adaptive building responses.

Limitations and Future Directions

While the proposed workflow significantly improves automation, several limitations remain that affect its broader scalability and industry-specific adaptation. The system's current implementation focuses on a single residential setting, and expanding it to large-scale commercial or industrial applications requires further refinements, including advanced machine learning algorithms to predict indoor environmental patterns more accurately. The current framework also depends on local data processing; shifting toward real-time, cloud-based data integration could improve remote access, scalability, and multi-user functionality.

Future research should explore the potential of generative design in refining building configurations based on thermal comfort data. By leveraging tools such as Autodesk Refinery, Revit, and Dynamo, designers can explore multiple design alternatives and optimize spatial layouts through iterative computational analysis. (Embedding generative design within the BIM-IoT framework could enable dynamic adaptation of

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

architectural solutions in response to real-time comfort feedback, improving energy efficiency and space usability.

This study provides a comprehensive framework for integrating BIM and IoT to create a real-time, data-driven digital twin for indoor environmental monitoring. The findings demonstrate that automation and real-time data processing enhance the efficiency and responsiveness of building management systems. The proposed system reduces reliance on manual data input, increases accuracy, and enables continuous environmental tracking and control—all essential for smart building deployment. By eliminating manual interventions, improving data accuracy, and supporting proactive environmental control, the proposed workflow contributes to the broader adoption of smart building technologies.

As the construction industry shifts toward data-driven decision-making, this research highlights the transformative potential of BIM-IoT integration in improving occupant well-being, energy efficiency, and operational sustainability. With continued advancements in machine learning, generative design, and cloud computing, the digital twin paradigm is expected to evolve into an adaptive, intelligent infrastructure tool with wide-reaching implications for architectural practice and facility management.

Author Contribution Statement

Order	Name Surname	ORCID	Contribution to Writing*
1	Marwa ABDELFATTAH	0009-0007-3920-6144	1, 2, 3, 4, 5
2	Can UZUN	0000-0002-4373-9732	1, 3, 5
* Write the number(s) corresponding to the relevant explanation in the contribution section.			
1. Designing the study 2. Collecting the data 3. Analysis and interpretation of the data 4. Writing the article 5. Critical revision			

Author's Note

This article was produced from the master's thesis titled 'Digital Twin Prototyping and Simulation Pipeline Proposal Through the Integration of BIM and IoT,' completed in 2024 under the supervision of Asst. Prof. Dr. Can Uzun at the Institute of Graduate Studies, Master of Architecture Program, Altınbaş University.

Conflict of Interest Statement

There is no personal and/or financial conflict of interest within the scope of the study.

REFERENCES

Abar, S., Theodoropoulos, G. K., Lemarinier, P., & O'Hare, G. M. P. (2017). Agent based modelling and simulation tools: A review of the state-of-art software. *Computer Science Review, 24, 13–33*. https://doi.org/10.1016/j.cosrev.2017.03.001

Aliane, N. (2010). Data acquisition and real-time control using spreadsheets: interfacing Excel with external hardware. *ISA transactions*, *49*(3), 264–269. https://doi.org/10.1016/j.isatra.2010.03.009

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Al-Qattan, E., Yan, W., & Galanter, P. (2017). Establishing parametric relationships for design objects through tangible interaction. In P. Janssen, P. Loh, A. Raonic, & M. A. Schnabel (Eds.), *Protocols, flows and glitches: Proceedings of the 22nd International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2017)* (pp. 147–156). The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). https://doi.org/10.52842/conf.caadria.2017.147

Chan, D. W. M., Olawumi, T. O., & Ho, A. M. L. (2019). Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: The case of Hong Kong. *Journal of Building Engineering, 25*. https://doi.org/10.1016/j.jobe.2019.100764

Chang, K. M., Dzeng, R. J., & Wu, Y. J. (2018a). An automated IoT visualization BIM platform for decision support in facilities management. *Applied Sciences, 8*(7). https://doi.org/10.3390/app8071086

Chehab, A., & Artail, H. (2004). Spreadsheet applications in electrical engineering: A review. *International Journal of Engineering Education*, *20*(6), 902–908.

Doukari, O., Kassem, M., & Greenwood, D. (2023). Building Information Modelling. In T. Lynn & P. Rosati (Eds.), *Palgrave studies in digital business and enabling technologies* (pp. 39–51). Palgrave Macmillan. https://doi.org/10.1007/978-3-031-32309-6_3

Del Grosso, A., Basso, P., Ruffini, L., Figini, F., & Cademartori, M. (2017). Infrastructure management integrating SHM and BIM procedures. In M. Motavalli, A. Ilki, B. Havranek, & P. Inci (Eds.), *Proceedings of the 4th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017)*. Empa.

Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems, 29*(7), 1645–1660. https://doi.org/10.1016/j.future.2013.01.010

Kensek, K. M. (2014). Integration of environmental sensors with BIM: Case studies using Arduino, Dynamo, and the Revit API. *Informes de La Construccion, 66*(536). https://doi.org/10.3989/ic.13.151

Ku, K., & Taiebat, M. (2011). BIM experiences and expectations: The constructors' perspective. *International Journal of Construction Education and Research, 7*(3), 175–197. https://doi.org/10.1080/15578771.2010.544155

Latiffi, A. A., Brahim, J., Mohd, S., & Fathi, M. S. (2015). Building information modeling (BIM): exploring level of development (LOD) in construction projects. *Applied mechanics and materials*, *773*, 933-937. https://doi.org/10.4028/www.scientific.net/amm.773-774.933

Lin, Y. H., Liu, Y. S., Gao, G., Han, X. G., Lai, C. Y., & Gu, M. (2013). *The IFC-based path planning for 3D indoor spaces*. *Advanced Engineering Informatics, 27*(2), 189–205. https://doi.org/10.1016/j.aei.2012.10.001

Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J., & Schooling, J. (2020). Developing a digital twin at building and city levels: Case Study of West Cambridge Campus. *Journal of Management in Engineering*, *36*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000763

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modelling. *Automation in Construction, 43, 84–91*. https://doi.org/10.1016/j.autcon.2014.03.009

Natephra, W., & Motamedi, A. (2019). Live data visualization of IoT sensors using augmented reality (AR) and BIM. In M. Al-Hussein (Ed.), *Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC 2019)* (pp. 632–638). IAARC. https://doi.org/10.22260/isarc2019/0084

Oh, S., & Song, S. (2021). Detailed analysis of thermal comfort and indoor air quality using real-time multiple environmental monitoring data for a childcare center. *Energies, 14*(3). https://doi.org/10.3390/en14030643

Park, H. J. (2008). Evolution+ BIM: The utilization of building information modelling at an early design stage. *CAADRIA 2008*, 552–559.

Ruemler, S. P., Zimmerman, K. E., Hartman, N. W., Hedberg, T., & Feeney, A. B. (2016). Promoting model-based definition to establish a complete product definition. In *Proceedings of the ASME 2016 11th International Manufacturing Science and Engineering Conference: Vol. 2. Materials; biomanufacturing; properties, applications and systems; sustainable manufacturing* (Paper No. MSEC2016-8702). American Society of Mechanical Engineers. https://doi.org/10.1115/MSEC2016-8702

Shafiril, S., Yusoff, A., & Yusoff, N. C. (2016). The development of an automated system in detecting environmental data for the monitoring of forest activity. *International Journal of Environmental Science and Development, 7*(7), 532–536. https://doi.org/10.18178/ijesd.2016.7.7.834

Shishina, D., & Sergeev, P. (2019). Revit dynamo: Designing objects of complex forms. Toolkit and process automation features. *Architecture and Engineering, 4*(3), 30–38. https://doi.org/10.23968/2500-0055-2019-4-3-30-38

Smarsly, K., & Tauscher, E. (2016). Monitoring information modelling for semantic mapping of structural health monitoring systems. In N. Yabuki & K. Makanae (Eds.), *Proceedings of the 16th International Conference on Computing in Civil and Building Engineering (ICCCBE 2016)*. Osaka University. http://www.see.eng.osaka-u.ac.jp/seeit/icccbe2016/Proceedings/Full_Papers/001-004.pdf

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modelling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction, 101*, 127–139. https://doi.org/10.1016/j.autcon.2019.01.020

Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Propach, M., Neges, M., & König, M. (2017). *Internet of Things (IoT) for integrating environmental and localization data in building ınformation modelling (BIM). ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction,* 603–609*.* https://doi.org/10.22260/isarc2017/0084

Valinejadshoubi, M., Moselhi, O., Bagchi, A., & Salem, A. (2021). Development of an IoT and BIM-based automated alert system for thermal comfort monitoring in buildings. *Sustainable Cities and Society, 66*. https://doi.org/10.1016/j.scs.2020.102602

RESEARCH ARTICLE
Vol. 8, No. 2, 2025, 427-447
DOI: 10.59389/modular.1589036

Wehbe, R., & Shahrour, I. (2019). Use of BIM and smart monitoring for buildings' indoor comfort control. *MATEC Web of Conferences, 295*, Article 02010. https://doi.org/10.1051/matecconf/201929502010

Wei, Z., Calautit, J., Wei, S., & Tien, P. W. (2024). Real-time clothing insulation level classification based on model transfer learning and computer vision for PMV-based heating system optimization through piecewise linearization. *Building and Environment*, 111277. https://doi.org/10.1016/j.buildenv.2024.111277

Wu, I. C., & Liu, C. C. (2020). A visual and persuasive energy conservation system based on BIM and IoT technology. *Sensors, 20*(1). https://doi.org/10.3390/s20010139

Yin, C., & McKay, A. (2018). Introduction to modelling and simulation techniques. In *Proceedings of the 8th International Symposium on Computational Intelligence and Industrial Applications (ISCIIA 2018)* and the 12th China–Japan International Workshop on Information Technology and Control Applications (ITCA 2018), Tengzhou, Shandong, China, 2–6 November 2018.

Zanchetta, C., Cecchini, C., & Bellotto, C. (2018). BIM-based multi-objective optimization process for energy and comfort simulation: Existing tools analysis and workflow proposal on a case study. *Journal of Building Sustainability*, *1*(1), 11–26.

AUTHOR BIOGRAPHY

Marwa ABDELFATTAH

Marwa Abdelfattah holds a Bachelor's degree in Architecture from the University of Malaya (2021) and a Master's degree in Architecture from Altınbaş University (2024), where her thesis was titled 'Digital Twin Prototyping and Simulation Pipeline through the Integration of BIM and IoT.' Her research focuses on the integration of Building Information Modeling (BIM) and the Internet of Things (IoT).

Can UZUN

Can Uzun holds a Bachelor's degree in Architecture from ITU (2012), a Master's in Architectural Design (Thesis) (2021), and a PhD in Architectural Design Computing (2021), all from ITU. His PhD dissertation focused on architectural plan generation using GAN. His research interests include architecture, AI, machine learning, and data. He is currently an Assistant Professor Doctor at ITU.