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DOCTORAL THESIS:

The Use of BIM and Advanced Digital Technologies for Energy-Efficient Building Renovation Projects: A Path Towards Digital Building Twins

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A mi abuela

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After five years, today I can finally say that this is the last page I write of this thesis. During this time, I have combined my full-time work as a researcher with the development of this doctoral thesis. This has allowed me to be part of very interesting research projects, some closely related to the topic of this thesis and others less so, but all of them have contributed to my knowledge.

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Abstract

Most of the buildings in the European Union (EU) were constructed before 1990, making them energy inefficient and resulting in poor indoor thermal and acoustic comfort. Given that buildings account for 40% of EU's energy consumption and 36% of greenhouse gas (GHG) emissions, their renovation is crucial to achieve sustainability goals. Consequently, deep renovation projects are becoming increasingly prevalent, driven by European regulations aimed at improving energy performance and reducing environmental impacts to achieve climate neutrality by 2050. In line with the *European Commission's Recommendation (EU) 2019/786*, Member States are required to develop renovation strategies incorporating a cost-benefit analysis tailored to building types and climatic zones. Developing effective strategies also requires technicians to understand the building's current condition to propose targeted thermal or acoustic improvements. However, conducting thermal diagnostics or assessing indoor acoustic comfort often requires lengthy and complex calculations, which are prone to errors when performed manually, highlighting the need for innovative and automated approaches.

Key aspects defined in the *European Renovation Wave Strategy,* as part of the *European Green Deal,* include enhancing energy efficiency, reducing carbon emissions, and integrating digital tools such as Building Information Modelling (BIM) and Digital Twins (DTs) into renovation processes to ensure sustainability and promote circularity in the building sector. Nevertheless, despite the growing adoption of BIM for creating digital models of buildings and its potential to automate renovation processes by leveraging extensive data, significant challenges persist. These include interoperability issues between BIM models and tools for energy and acoustic performance evaluation, as well as the frequent exclusion of the digitisation of the building monitoring systems from such models.

This thesis addresses these challenges by developing methodologies for integrating advanced digital technologies into the renovation process, with BIM serving as the central framework, to improve energy efficiency while advancing towards the integration of Digital Building Twins (DBTs). The research is structured around two key phases: (i) renovation design and (ii) digitisation of the existing building data. The proposed approaches focus on improving decision-making processes for building renovation projects, specifically in energy diagnostics and acoustic assessment, and on enhancing the digitisation of building status. The digitisation of the existing data is addressed by updating BIM models with data from the existing monitoring network.

Firstly, for energy diagnostics, a Machine Learning (ML) approach based on a decision tree algorithm has been employed to analyse As-Built BIM models, diagnose critical areas, and propose targeted Energy Conservation Measures (ECMs). Secondly, for acoustic assessments, an innovative Extract, Transform, and Load (ETL) solution has been developed to automate the retrieval and processing of geometric and acoustic data from BIM models, significantly enhancing the accuracy and efficiency of acoustic comfort assessments. Finally, the integration of Building Automation and Control Networks (BACN) with BIM has been achieved by automatically updating the Industry Foundation Classes (IFC) file of the building to include devices from an existing monitoring system. This integration addresses interoperability challenges and bridges the connection between Internet of Things (IoT) devices and IFC data, simplifying the process for building owners and technical users to create and manage monitoring networks directly within BIM. The connection between static (BIM-based) and dynamic data supports the transition from static BIM models to dynamic DBTs.

These methodologies have been validated in various case studies, demonstrating significant reductions in processing time and increased accuracy compared to traditional manual methods. By integrating advanced digital technologies with BIM, this thesis addresses key challenges in building renovation, including data interoperability, facilitated by the IFC standard, workflow automation, improved decision-making, and the integration of building monitoring systems. These improvements contribute to more efficient and sustainable renovation practices.

This thesis is presented by compendium of scientific publications in high-impact journals in pursuit of the degree of Doctor of Architecture (PhD) by the University of Valladolid.

Resumen

El uso de BIM y tecnologías digitales avanzadas para la renovación energética de edificios: un camino hacia los gemelos digitales del edificio

La mayoría de los edificios en la Unión Europea (UE) fueron construidos antes de 1990, lo que los hace ineficientes desde el punto de vista energético y provoca un escaso confort térmico y acústico en su interior. Dado que los edificios son responsables del 40 % del consumo energético de la UE y del 36 % de las emisiones de gases de efecto invernadero (GEI), su renovación resulta fundamental para alcanzar los objetivos de sostenibilidad. En consecuencia, los proyectos de renovación profunda están cobrando cada vez mayor relevancia, impulsados por normativas europeas orientadas a mejorar el rendimiento energético y reducir los impactos ambientales, con el fin de lograr la neutralidad climática en 2050. De acuerdo con la Recomendación *(UE) 2019/786* de la Comisión Europea, los Estados miembros deben desarrollar estrategias de renovación que incorporen un análisis coste-beneficio adaptado a los tipos de edificios y zonas climáticas. Elaborar estrategias eficaces también requiere que los técnicos encargados conozcan el estado actual del edificio para poder proponer mejoras térmicas o acústicas específicas. Sin embargo, llevar a cabo diagnósticos térmicos o evaluar el confort acústico interior suele requerir cálculos extensos y complejos, propensos a errores si se realizan manualmente, lo que pone de relieve la necesidad de enfoques innovadores y automatizados.

Aspectos clave definidos en la Estrategia Europea *Renovation Wave*, como parte del Pacto Verde Europeo, incluyen la mejora de la eficiencia energética, la reducción de emisiones de carbono y la integración de herramientas digitales como BIM (*Building Information Modelling*) y los Gemelos Digitales (*Digital Twin*, DT) en los procesos de renovación, con el fin de garantizar la sostenibilidad y fomentar la circularidad en el sector de la edificación. No obstante, a pesar de la creciente adopción de BIM para la creación de modelos digitales de edificios y su potencial para automatizar procesos de renovación mediante el aprovechamiento de grandes volúmenes de datos, aún persisten importantes desafíos. Entre ellos se encuentran los problemas de interoperabilidad entre los modelos BIM y las herramientas de evaluación del rendimiento energético y acústico, así como la frecuente exclusión de los sistemas de monitorización del edificio en la digitalización de dichos modelos.

La investigación desarrollada en esta tesis aborda estos desafíos mediante la integración de tecnologías digitales avanzadas en el proceso de renovación, utilizando BIM como marco central,

con el objetivo de mejorar la eficiencia energética y avanzar hacia la integración de los Gemelos Digitales de Edificios (*Digital Building Twins*, DBTs). La investigación se estructura en torno a dos fases: (i) diseño de la renovación y (ii) digitalización de los datos existentes del edificio. Las metodologías desarrolladas se centran en mejorar los procesos de toma de decisiones en proyectos de renovación, específicamente en el diagnóstico energético y la evaluación acústica, así como en optimizar la digitalización del estado actual del edificio. Esta digitalización se ha abordado mediante la actualización de los modelos BIM con datos procedentes de redes de monitorización ya existentes.

En primer lugar, para el diagnóstico energético, se ha empleado un enfoque de Aprendizaje Automático (*Machine Learning*, ML) basado en un algoritmo de árbol de decisión (*decision tree*) para analizar modelos BIM As-Built, diagnosticar áreas críticas y proponer Medidas de Conservación de Energía (*Energy Conservation Measures*, ECMs) específicas. En segundo lugar, para las evaluaciones acústicas, se ha desarrollado una innovadora solución de Extracción, Transformación y Carga (*Extract, Transform, and Load*, ETL) que automatiza la recopilación y el procesamiento de datos geométricos y acústicos a partir de modelos BIM, mejorando significativamente la precisión y eficiencia de las evaluaciones de confort acústico. Por último, se ha logrado la integración de las Redes de Automatización y Control de Edificios (*Building Automation and Control Networks*, BACN) con modelos BIM, mediante la actualización automática del archivo en formato IFC (*Industry Foundation Classes*) del edificio para incluir los dispositivos de un sistema de monitorización existente. Esta integración resuelve problemas de interoperabilidad y permite conectar dispositivos del Internet de las Cosas (*Internet of Things*, IoT) con los datos IFC, facilitando a propietarios y técnicos la creación y gestión de redes de monitorización directamente en el entorno BIM. La vinculación entre datos estáticos (basados en BIM) y datos dinámicos posibilita la transición de los modelos BIM estáticos hacia Gemelos Digitales del Edificio.

Estas metodologías han sido validadas en diversos casos de estudio, demostrando reducciones significativas en el tiempo de procesamiento y una mayor precisión en comparación con los métodos manuales tradicionales. Mediante la integración de tecnologías digitales avanzadas con BIM, esta tesis aborda desafíos clave en la renovación de edificios, incluyendo la interoperabilidad de datos, facilitada por el estándar IFC, la automatización de flujos de trabajo, la mejora de la toma de decisiones y la integración de los sistemas de monitorización del edificio. Estas mejoras contribuyen a prácticas de renovación más eficientes y sostenibles.

Esta tesis doctoral se presenta en la modalidad de compendio de publicaciones científicas en revistas de alto impacto para optar al título de Doctora en Arquitectura por la Universidad de Valladolid.

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1. Introduction

1.1. Context and background

Buildings are responsible for around 40% of final energy consumption in the European Union (EU) [1]. This share can rise to approximately 50% of primary energy demand when the entire lifecycle of buildings is considered, including construction, materials, and end-of-life phases [2]. They are also responsible for approximately 36% of Greenhouse Gas (GHG) emissions, making the building sector a crucial area for energy-saving initiatives [3], that should contribute to the EU's efforts towards decarbonisation and energy efficiency improvements. The EU's building stock consists of approximately 131 million buildings, 90% of which are residential, covering 75% of the total floor area [4]. Many of these buildings were constructed before 1990, prior to the implementation of energy efficiency regulations, resulting in poor thermal and acoustic performance. Renovation of this building stock is essential to align with EU targets, including a 55% reduction in GHG emissions by 2030 and climate neutrality by 2050 [5].

The initial recommendation of the EU on building renovation, *(EU) 2019/786 of 8 May 2019* [6] set a 40% reduction in GHG emissions by 2030, compared to 1990 reference levels. This target was increased to 55% in the 2020 update [7]. This recommendation was part of the broader EU strategy to improve the energy performance of buildings, aligned with the *Energy Performance of Buildings Directive (EPBD)* [1] and the goals of the *European Green Deal* [8]. Improving the energy performance of buildings is not only essential for reducing environmental impact, but also for enhancing the quality of indoor environments. Achieving these goals requires upgrading construction materials and implementing more efficient energy systems, both of which are critical for creating sustainable and comfortable spaces for occupants.

The *Renovation Wave Strategy* [3], introduced by the European Commission, promotes faster and deeper renovations to create better-performing buildings in terms of energy efficiency, sustainability, comfort, and health. However, the low renovation rate across the EU, one of the core issues highlighted by this strategy, currently at around 1% annually, is far below the level required to meet the 2030 and 2050 energy and climate goals, particularly in the context of building decarbonisation. Key elements of this strategy include improving energy efficiency, reducing carbon emissions, and integrating digital tools like Building Information Modelling (BIM) and Digital Twins (DTs) into renovation processes to ensure sustainability and promote circularity. A DT can be considered as a digital representation of a physical asset, or a process or system, from the real physical world that enable real-time monitoring, simulation, and optimisation throughout a building's lifecycle. By integrating static (BIM-based) and dynamic data, DTs provide an advanced approach to managing renovation workflows, connecting information from various sources and supporting predictive analysis and decision making. Their ability to represent both geometric and operational data makes them a key component in advancing digitalisation efforts in the building sector [9, 10, 11, 12, 13, 14].

The adoption of the BIM methodology in building and infrastructure projects has opened up new possibilities for managing the entire lifecycle of buildings [15, 16, 17, 18, 19, 20]. These opportunities are further enhanced when BIM is combined with advanced digital technologies, such as Machine Learning (ML), Internet of Things (IoT), and automated data processing techniques [21]. BIM has become increasingly relevant for renovation projects [22, 23, 24, 25], facilitating the decision making thanks to the large amount of data it can contain [26, 27]. Among these, the Industry Foundation Classes (IFC) standard [28]—one of the most widely used BIM information interchange standards—plays a critical role [29]. By embedding semantic data within 3D geometric representations, IFC models enable the integration of information such as material properties, building performance metrics, and spatial relationships. This semantic richness makes IFC essential for supporting automated workflows in renovation projects, but several challenges remain. A lack of interoperability between BIM and other tools limits its full potential [30, 31, 32]. Currently, the use of BIM models is widespread among architects due to emerging regulations regarding its future mandatory use in administrative procedures [33, 34, 35, 36, 37]. However, its application is primarily focused on creating models for generating plans, details, and views, rather than promoting interoperability between different BIM software or leveraging the information produced by semantic models. Moreover, BIM models often fail to integrate building monitoring systems, which are essential for creating Digital Building Twins (DBTs) that combine geometric and logical data for advanced building management.

Prioritising efforts to improve the energy efficiency of buildings is crucial for meeting the targets set by Europe for 2050. This includes leveraging new digital technologies and their potential to enhance decision-making for building interventions, while considering the cost-effectiveness of the solution to be implemented, as recommended in *(EU) 2019/786 of 8 May 2019* [6] and in the revised EPBD, *(EU) 2024/1275 of 24 April 2024* [38]. In this context, the application of BIM plays a central role in managing and optimising the building renovation projects.

1.2. Justification

Achieving the decarbonisation targets set out in the EU Climate Target Plan 2030 [7] and the EU 2050 Climate Neutrality Strategy (*Regulation (EU) 2021/1119*) [5]—including the reduction of

CO_2 emissions in cities and the transition towards nearly zero-energy buildings (nZEB)—requires significant improvements in the existing building stock. This also involves enhancing how renovation actions are planned and implemented, while ensuring the cost-effectiveness of the adopted solutions. However, the EU faces considerable challenges due to the low renovation rate and the high number of energy-inefficient buildings, which hinder progress toward these goals. Under the concept of delivering faster and deeper renovation for better buildings promoted by the European Commission in the *Renovation Wave Strategy* [3], the adoption of BIM and advanced digital technologies can contribute to overcoming this barrier.

The application of BIM methodology, traditionally used for new construction, provides substantial decision-making support in renovation projects [22, 39, 40]. Despite its growing adoption, the full potential of BIM—particularly in terms of time reduction, accuracy, and automation—remains underexplored [41, 42, 43]. Key challenges include the manual nature of processes such as energy diagnostics and acoustic assessment, which remain time-consuming and prone to errors. These difficulties are further compounded by interoperability issues between BIM models and simulation tools, caused by heterogeneous data formats and the lack of standardisation for seamless integration [44, 45]. As a result, automating these workflows is often complex and limited in practice.

While digitalisation and monitoring technologies are becoming more prevalent, it is still uncommon for BIM models to include building control and monitoring systems. This is partly due to the traditionally top-down nature of BIM workflows [46], which have primarily focus on architectural elements and the definition of the building envelope during the design and construction phases [47]. As a result, control and monitoring systems—particularly sensors and IoT devices—are rarely modelled within BIM environments, especially in early design or renovation phases. These systems are typically associated with the operational stage and managed by different teams or external platforms, making their inclusion into BIM models less frequent. Bridging this gap is essential for advancing towards DBTs, which integrate both geometric and logical data to enable real-time connections with IoT systems.

This thesis tackles one of the core challenges highlighted by the *Renovation Wave Strategy*: the low renovation rate across the EU. The motivation for this research lies in demonstrating how the integration of BIM and advanced digital technologies can significantly enhance the energy efficiency and overall effectiveness of renovation projects. By leveraging the extensive data capabilities of BIM, this research focused on addressing interoperability challenges between semantic 3D models, such as IFC, and energy or acoustic assessment tools. It also addresses the integration of building automation and control networks (BACN) into these models. This is achieved by improving data exchange and automating key processes, facilitating the development and application of new methodologies for energy-efficient renovation.

By addressing these challenges, this research promotes the use of IFC and fosters the adoption of automated renovation methodologies that meet the demands of the Architecture, Engineering and Construction (AEC) sector and align with European directives for energy efficiency and decarbonisation. It is expected to provide practical solutions for technical users in multidisciplinary teams, leveraging real data from As-Built BIM models to improve decision-making processes and enhance renovation outcomes.

In this context, the three methodological directions explored in this thesis—automated energy diagnostics, acoustic assessment, and the integration of monitoring systems—were strategically selected for their relevance to current bottlenecks in digital renovation workflows and their potential to bridge the gap between static BIM environments and dynamic, data-rich models required for the implementation of DBTs. Although other relevant areas such as dynamic energy simulation, life cycle assessment (LCA), or life cycle cost (LCC) estimation are important for the overall renovation lifecycle, this research focuses specifically on the early phases, where robust data acquisition, diagnosis, and model integration are crucial for enabling effective and scalable downstream actions. These three areas were prioritised because they represent critical decision-making bottlenecks where automation and digitalisation can provide immediate improvements in accuracy, interoperability, and efficiency. Despite the growing interest in BIM-based digitalisation, these domains remain underdeveloped in practice: thermal diagnostics are frequently conducted manually, acoustic assessments are rarely automated despite their relevance for indoor comfort and compliance with regulations, and monitoring systems are almost never modelled within BIM at the renovation design stage. Notably, the acoustic workflow developed in this thesis serves as a demonstrative case of how an Extract, Transform, and Load (ETL) process can be generalised to other applications, such as energy simulation, thus highlighting the transferability of the approach. By addressing these persistent gaps, the thesis contributes to advancing workflow automation, improving data interoperability through IFC, and facilitating the inclusion of dynamic data in digital building models.

These directions were selected based on their potential to overcome key data and automation barriers in the early phases of renovation projects. Each contributes a distinct layer to DBT development: (1) energy diagnosis supports early-stage decision-making based on BIM data; (2) acoustic assessment incorporates comfort criteria that are rarely addressed in renovation processes; and (3) the integration of monitoring system introduces dynamic data that connect to the BIM models. Collectively, they contribute to a unified and scalable framework to support the transition from static BIM models to dynamic DBTs, in alignment with European renovation strategies and digitalisation goals.

1.3. BIM-SPEED project

Part of the research presented in this thesis was developed within the BIM-SPEED project (Harmonised Building Information Speedway for Energy-Efficient Renovation) [48], a European research project funded under the Horizon 2020 Framework Programme. During this project, various case studies of energy renovation projects in districts and buildings were analysed, where the initial data sources or models available at the start lacked a methodology to ensure interoperability with other BIM tools. Throughout this process, it became evident that the renovation and decision-making process could be significantly facilitated by better-structured BIM models, containing all the necessary information for their exchange with other software, such as energy simulation tools. A key goal of the BIM-SPEED project was to enhance deep renovation processes in residential buildings by reducing both time and costs while encouraging the adoption of BIM among various stakeholders. To achieve this, the project developed standardised procedures, including the creation of Use Cases, alongside a range of BIM-based tools within the BIM-SPEED web platform ecosystem [49]. Training materials were also provided to assist users in leveraging these services. Furthermore, to resolve interoperability challenges, different ETL processes and BIM connectors were deployed. Figure 1 depicts the interoperability framework between BIM tools and the BIM-SPEED web platform, showing the connections to the implemented ETLs and BIM Connectors, part of the work carried out by the PhD candidate. Various Checker tools were applied to ensure the reliability and accuracy of the data throughout the process.

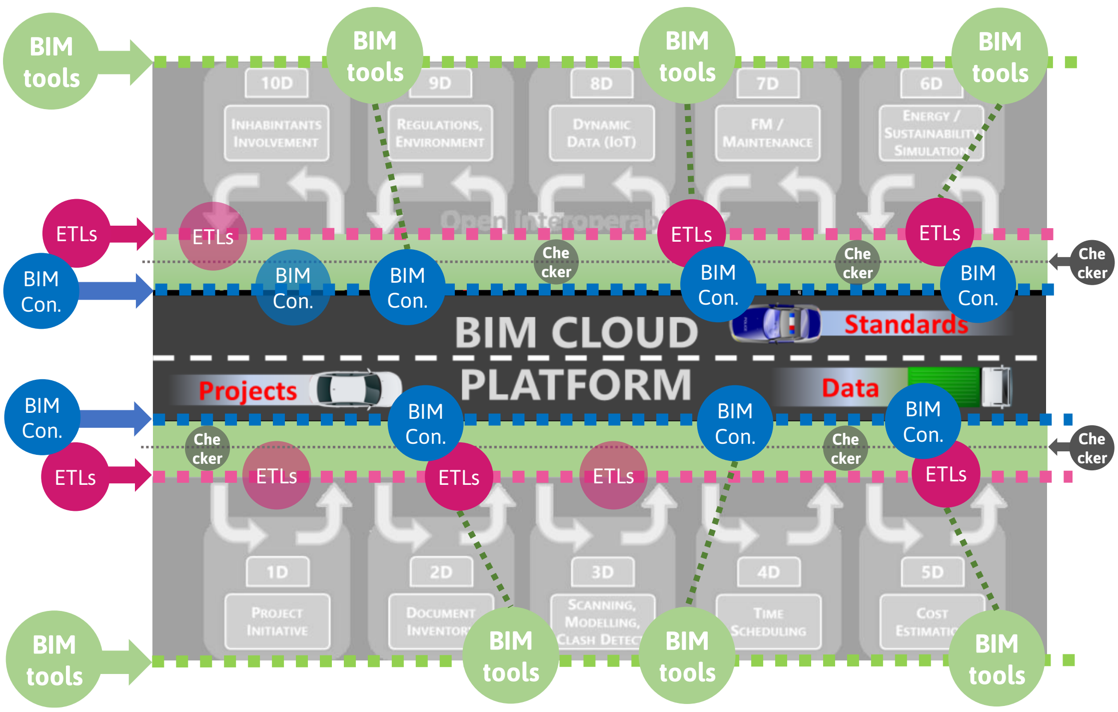

Figure 1: Own elaboration: Adapted from the original BIM-SPEED project concept to represent the connection between BIM tools and the BIM cloud platform via ETLs and BIM connectors.

1.4. BIM for renovation? Research questions

This thesis seeks to address the knowledge gap related to the use of BIM technology in the renovation process to improve building energy efficiency, enhance automation, accuracy, and workflow efficiency, while advancing towards the integration of DBTs. To achieve this, interoperability between tools will be promoted through the use of standards like IFC. Therefore, the following central research question is posed:

How can BIM and advanced digital technologies be integrated to enhance automation, accuracy, and workflow efficiency in building renovation projects, promoting energy efficiency while addressing interoperability challenges and advancing towards Digital Building Twins?

The three papers presented, as part of the compendium of scientific publications, contribute to answering this overarching question by tackling specific challenges and demonstrating the integration of BIM and advanced digital technologies in renovation projects. Each methodology contributes to the progression to DBTs by focusing on energy efficiency (thermal and acoustic performance), automation, and interoperability. Together, they form a holistic framework that supports the development and integration of DBTs in renovation workflows.

To address the central question, the following sub-questions are posed:

- **RQ1. How can BIM workflows and automated data processing support energy and acoustic diagnostics, improving decision-making and reducing errors in building renovation projects?**

The use of BIM can improve energy-related decision making by using the rich semantic data within BIM models and integrating advanced digital technologies. At the same time, dealing with renovation projects manually is time-consuming and not error-free due to the manual process. The automation of renovation workflows will allow initial estimates of the building's condition to be made in less time and with more accurate data, which will also reduce the cost. This question is answered in ***paper 1*** and ***paper 2***.

- **RQ2. How can BIM models be integrated with monitoring and control networks to enhance building status digitisation and enable real-time management of systems, supporting the development of Digital Building Twins?**

BIM models can integrate data from existing monitoring and control networks to create comprehensive As-Built BIM models that include both static and real-time data. However, including the devices that are part of the monitoring network manually, once the BIM model has been already generated, is time-consuming, as each device must be individually placed and characterised. The integration of BACN with BIM is a foundational step toward the development of DBTs, enabling real-time monitoring and management of building systems. This question is answered in ***paper 3***.

- **RQ3. How can interoperability between semantic 3D models, such as IFC, and energy or acoustic assessment tools be enhanced to facilitate data exchange and integration?**

One of the main challenges of the full adoption of BIM in renovation processes and the effective digitisation of building status is the lack of interoperability between tools. Standardisation through the adoption of open data formats like IFC will provide a way to address these challenges and facilitate better integration across different tools. This question is answered in ***paper 1***, ***paper 2***, and ***paper 3***.

1.5. Objectives

In order to answer the proposed research questions, the objectives of this thesis have been defined as follows. The main objective is:

To develop methodologies for integrating advanced digital technologies into the renovation process, with BIM as the central framework, to improve energy efficiency and indoor climate in building renovation projects, as well as reducing time and costs, while advancing towards Digital Building Twins.

To achieve this main objective, different sub-objectives have been identified:

- **OB1.** To improve decision-making processes for renovation projects by leveraging BIM-based automated diagnostic tools for energy and acoustic performance. **(RQ1)**
  - **OB1-1.** To develop a methodology for energy diagnostics, automating the retrieval of data from As-Built BIM models and enabling the identification of critical areas for targeted energy conservation measures.
  - **OB1-2.** To design and implement a solution that automates the retrieval and processing of geometric and acoustic data from BIM models, significantly improving the accuracy and efficiency of acoustic comfort assessments while supporting decision-making.

- **OB2.** To update BIM models by integrating data from existing monitoring networks, improving the digitalisation of building status and enabling real-time monitoring and management of building systems. **(RQ2)**

- **OB3.** To address interoperability challenges in renovation BIM workflows using the IFC standard to facilitate seamless data exchange. **(RQ3)**
- **OB4.** To validate the proposed methodologies in various case studies, demonstrating their effectiveness in reducing processing time, increasing accuracy, and improving outcomes compared to traditional renovation methods. This objective helps validate all the developed methodologies by demonstrating the effectiveness and advantages of the proposed solutions. It applies to the three papers, as each includes case studies for methodology validation.

1.6. Thesis outline

This thesis is structured as follows:

Chapter 1 – Introduction: It provides the context and background of the research, its justification, and the role of the BIM-SPEED project. This chapter defines the research questions and presents the objectives, defining the scope of the study and its contributions to the field of BIM-based energy-efficient renovation and the advancement towards DBTs.

Chapter 2 – State of the Art: It reviews the existing literature on automating BIM-based data collection for energy diagnostics and acoustic simulation, including an overview of Artificial Intelligence (AI) applications in the built environment and BIM-based acoustic simulation methods. It also examines IT solutions for integrating dynamic building data with BIM, covering BIM-to-BACN, BACN-to-BIM, and Real-data-to-IFC approaches. The chapter concludes by identifying the research gap and contributions of this thesis.

Chapter 3 – Methods: It details the methodologies developed in this thesis to address the research challenges identified in the state of the art, structured into three key approaches: automated ML-based energy diagnostics, automated acoustic comfort assessment, and automated integration of BACN with BIM to connect real-time monitoring data with BIM models. These methodologies have been validated with the application of the developed approaches in real and demo case studies.

Chapter 4 – Scientific Publications: This chapter includes the three scientific papers that support this research: ***paper 1*** and ***paper 2***, which address RQ1 and RQ3, and ***paper 3,*** which addresses RQ2 and RQ3. Each paper is preceded by a brief introduction outlining its context and highlighting the doctoral candidate's contribution.

Chapter 5 – Results: It summarises the findings of the three presented methodologies with those results obtained in the different validation case studies.

Chapter 6 – Conclusions: It compares the developed methodologies with traditional practices and background literature, discussing their contributions to the integration of DBTs in renovation workflows. It also outlines future research directions.

Additionally, a list of literature references is included and several annexes provide complementary information:

- **Annex A** presents the scientific dissemination and impact of this research, including publications, conference presentations, and outreach activities.
- **Annex B** documents the international mention of this thesis.
- **Annex C** details grants and awards received throughout this doctoral research.

2. State of the art

The use of new technologies applied in the AEC sector for the digitalisation of the built environment is becoming increasingly widespread. At the city-district scale, Geographical Information System (GIS) is the most commonly used, as it enables the representation and analysis of geographically referenced information. Additionally, CityGML [50], an open data model based on XML, is the standard used for the 3D modelling of urban objects sets.

At building scale, the adoption of BIM in the design phase of new buildings has grown significantly over the years, due to the advantages offered by digitisation throughout the construction process [21, 51], as well as the mandatory use promoted by public bodies [35]. It is also becoming increasingly relevant in the design of renovation projects to supporting decision making [22, 25, 39, 52, 53, 54, 55]. However, the application of BIM-based solutions to existing buildings presents several challenges. One of the most significant is the limited availability of input data: many existing buildings are not yet digitalised, and generating an accurate As-Built BIM model requires considerable effort. This is partly due to outdated or incomplete existing drawings that do not reflect the actual construction, and partly due to limitations in capturing non-visible or inaccessible elements, such as the thermal properties of envelope components—for instance, the composition of wall layers—which are often unknown. Additionally, interoperability issues persist between BIM models and common evaluation or simulation tools, requiring customised data mapping, complicating automated analyses of building performance. The most widely used data exchange standard for BIM is IFC. Developed by buildingSMART International [56], IFC facilitates interoperability between different software platforms by structuring building information into semantic, geometric, and relational data. Ongoing research is exploring new BIM-based tools to exploit the potential of the large amount of information contained in BIM models. These developments include BIM modelling guidelines for exporting models in standard formats that are interoperable with other tools [57]; automatic or semi-automatic generation of energy simulation models [58, 59, 60, 61, 62, 63, 64, 65, 66]; and integration of BIM and IoT devices [67, 68], among others. Studies have also focused on the connection between the building and city-district scale, seeking interoperability and data combination between IFC and CityGML models to support decision making in the design phase of renovation at the district level [69, 70]. With regard to the circularity of buildings, research is also being carried out on the creation of Material Passports obtained through BIM modelling [71, 72, 73], as well as on the analysis of the LCC and LCA [74, 75, 76, 77, 78, 79, 80, 81]. While the adoption of BIM has grown in recent years [82], its full potential, particularly in terms of time reduction and accuracy, remains underexplored.

After reviewing the broader context of digital models in the built environment, including city-district scale representations such as CityGML and building scale models using BIM, this state of the art narrows its focus to the scope of this thesis. The research is structured around two key phases: (i) renovation design and (ii) digitisation of the existing building data. Accordingly, the following sub-sections provide an overview of AI applications for the built environment, BIM-based acoustic simulation methods, and IT solutions to couple dynamic data of existing buildings to BIM.

2.1. Automating BIM-based data collection for energy diagnostics and acoustic simulation

The integration of multiple performance aspect, such as energy and acoustic analysis, within a shared digital environment (e.g. using BIM) is gaining increasing attention in the context of performance-based design [44]. However, BIM applications are primarily focused on improving the thermal aspects of renovation, with limited attention given to acoustic assessment [22, 53, 61, 83, 84]. This sub-section presents an overview of existing research to automate data retrieval from BIM models for energy diagnostics, focusing on the application of AI methods, and for acoustic simulation.

2.1.1. Overview of AI Applications for the Built Environment

AI has found increasing application in the built environment, particularly in areas such as element and materials identification through image recognition [85, 86], decision-making [87], diagnostics, optimisation, and predictive models. For example, ML techniques have been used to analyse LIDAR data for monitoring building changes, structural deformations, and construction progress [88]. In addition, progress has been made in integrating AI techniques with BIM workflows [89, 90, 91, 92, 93]. A similar approach based on image recognition has also been applied in the context of BIM: convolutional neural networks have been applied to classify building types based on images extracted from BIM software, achieving high accuracy in categorisation [94]. ML has also been used to automate several steps in the classification of BIM models that have to deal with multiple data types, as explored by Ryu et al. [95]. Furthermore, ML has been used to support cost estimation workflows in BIM environments. In [96], a BIM-based framework was developed using REVIT [97] software and MATLAB [98] to automate cost estimation by integrating cost components with neural network algorithms. The study focused on four building element categories (walls, floors, doors, and windows), and found that Adaptive Neuro-Fuzzy Inference System (ANFIS) achieved the highest accuracy. To support cost estimation aligned with national standards, a component library containing the name, ID, description, and unit cost was created in Excel and imported into REVIT. In diagnostics, mainly applied to the structural assessment of buildings, expert systems have been developed to address structural damage and propose repair solutions. Examples include the development of expert systems for diagnosing masonry defects caused by pollution or traffic, as in the work of Van Balen [99], and tools designed to provide repair recommendations for damaged concrete elements, as developed by Moodi and Knapton [100]. These expert systems often employ decision tables and production rules to support accurate assessments and recommendations [101, 102]. Bernat and Gil [101] presented an expert system for diagnosis, identifying pathologies in structural elements of buildings. A series of knowledge- and experience-based inspection, diagnosis, and repair of individual non-structural building elements was developed in [102].

Recent studies have explored the use of AI to predict and control indoor thermal comfort. A comprehensive review by [103] examines current AI-based methodologies, with a focus on ML algorithms used for comfort prediction and their integration into building control systems. It concludes that most of these models provide more accurate predictions than traditional methods such as the Predicted Mean Vote / Predicted Percentage of Dissatisfied (PMV/PPD) index [104], as confirmed by theoretical and experimental evidence. The study also discusses energy-saving implications and outlines future research directions to advance occupant-centric strategies. The combination of ML techniques and BIM has also been applied to energy consumption prediction, as shown in [105], where a specific dataset—an energy consumption patterns repository—was developed to enable the prediction of electricity demand in office buildings. The study combined BIM models generated in REVIT with ML algorithms and identified nine key design variables influencing energy use, demonstrating the potential of BIM–ML integration for early-stage performance assessment. Sen and Pan [106] proposed a systematic framework that combines BIM-based energy simulations and explainable ML to support sustainable building design. The method uses BIM models created in REVIT, exported in gbXML format [107], and simulated in DesignBuilder [108] software to generate energy performance data. This data trains a predictive model based on LightGBM [109], a ML algorithm, optimised through Bayesian techniques and interpreted using SHapley Additive explanation (SHAP) values. The model identifies which design variables most affect energy use, emissions, and indoor comfort. This enables informed design decisions and multi-criteria optimisation under uncertainty, even from early project stages.

In the context of the use with the IFC standard, AI and ML have been applied to detect internal problems and inconsistencies within BIM models. Lee et al. [110] proposed an inspection methodology using BIM and linked data technologies to facilitate the sharing of construction defect data. ML techniques have also been employed to identify anomalies and incorrect data classifications in BIM models [111, 112], and to detect errors using both supervised and unsupervised ML techniques [113]. AI and ML have also been applied to support automated valuation processes. Su et al. [114] developed a framework that integrates IFC-based information extraction with a ML model (GA-GBR) optimised by genetic algorithms. The system enables the automatic retrieval of value-related building data from IFC models to perform property valuation tasks. Although the focus is on economic assessment, the proposed workflow demonstrates how structured IFC data can be combined with ML for predictive applications in the built environment, with potential applicability to other domains such as energy optimisation and performance assessment. ML algorithms have also been designed to classify IFC objects into predefined categories and compare different IFC files using metrics like similarity rates and preservation rates [115]. An iterative, new data-driven method was proposed by Wu and Zhang [116] to develop an algorithm capable of classifying each object in an IFC model into predefined categories. BIM models have also been employed to verify compliance with building regulations using rule-based systems and ontologies. These approaches automate the detection of non-compliance, ensuring integrity and reducing the time required for regulatory verification [117]. Health and safety aspects have been addressed by developing frameworks that apply parametric rules to construction site safety plans, improving compliance with safety standards [118]. No examples have been identified in the field of thermal deficiency diagnosis. While these applications showcase the transformative potential of AI and ML in the built environment, challenges remain.

2.1.2. Overview of BIM-based acoustic simulation methods

Most BIM-based tools focus on energy simulations or the digitisation of buildings for As-Built models and are less commonly used for acoustic evaluations. Acoustic data, often handled manually, can nevertheless be integrated into BIM workflows to enable more comprehensive assessments. Several acoustic parameters can be included in a BIM model according to the IFC data exchange standard, such as acoustic rating information of building elements and external street noise level, but interoperability between acoustic simulation programs and BIM models remains limited [44].

Research into BIM-based tools for acoustic analysis has made progress, but fully automated solutions for data collection and analysis remain limited, as highlighted in previous reviews [44, 119]. Studies such as [44] have pointed out that the complexity and excess information in BIM models often require significant simplification to maintain the integrity of acoustic calculations. Early methodologies focused on calculating Reverberation Time (RT) [120] using tools like REVIT [97] combined with Dynamo [121] scripts, a visual scripting, as seen in [122, 123, 124, 125], to calculate the Indoor Environmental Quality (IEQ). These approaches typically involve semi-automated processes, where users manually select rooms or materials, as is the case of [122], limiting their efficiency. Others, like [123, 124], use external databases to automate material property assignments.

More advanced approaches include the work of Tan et al. [126], which used IFC files as input for acoustic analysis with finite element solvers like COMSOL Multiphysics. However, the use of finite elements methods for the acoustic comfort assessment remains time-intensive and does not necessarily improve accuracy. In [127], a BIM-based prototype was created to perform acoustic simulations, focusing on RT and sound intensity levels. The tool, developed in C# using the REVIT API, extracts BIM data such as room dimensions, materials, and surface areas. This information is exported to a spreadsheet, where the software assigns material absorption coefficients based on the wall finishing materials. However, users must manually select the rooms for calculation and configure the frequencies to be analysed. Similarly, Mastino et al. [128] developed a predictive acoustic analysis framework using user-defined *Property Sets* (Psets), assigning results directly to BIM model elements without relying on IFC standard.

In addition to traditional acoustic assessments, research like that of Marini et al. [129] has explored noise calculation in building services by leveraging IFC datasets, specifically *Pset_SoundAttenuation* [130] and *Pset_SoundGeneration* [131]. Mastino et al. [42] extended this by examining requirements for integrating acoustic and energy simulations into BIM workflows, considering the IFC class structure, emphasising correct geometry, correct identification of spaces and zones, and correct data integration. This work also analysed the gbXML schema [107]. Semantic approaches have also emerged, such as the transformation of IFC data into Resource Description Framework (RDF)[132] for rule-based validation, as demonstrated by Pauwels et al. [133].

2.2. Overview of IT solutions to couple dynamic data of existing buildings to BIM

In line with European directives aimed at achieving a reduction of CO_2 emissions from buildings by 2050 [5], an increase in building monitoring is foreseen. This will facilitate the adoption of more efficient thermal management systems [134] and improve the thermal comfort of occupants [135]. The integration of BACN with BIM represents a promising approach to centralising building information by digitally connecting its geometric and logical components. This integration lays the groundwork for the development of BIM-based DBTs, whose adoption has become increasingly widespread in recent years [9, 10, 11, 12]. However, it is not common for BIM models to incorporate existing control systems. This integration poses significant challenges, particularly in terms of interoperability [47]. This sub-section provides an overview of approaches to integrating BACN and real-time IoT data with BIM.

2.2.1. BIM-to-BACN and BACN-to-BIM

Few studies have explored the integration of BACN with BIM models. The BIM-to-BACN process has been studied by Sanz et al. [136], who developed a semi-automatic tool that identifies spaces in an IFC file, selects devices from a specific database, and automatically configures and updates the IFC with the designed control network. These devices support the LonWorks protocol (ISO 14908-1 [137]). Tang et al. [138] used the BACnet protocol (ISO 16484-5 [139]) to exchange Building Automation System (BAS) information through the IFC model, manually mapping the *IfcBuildingControlsDomain* [140] schema to BACnet, but without addressing time-series connections. Other studies, such as [141], created an integrated workflow to process and visualise real-time thermal monitoring in REVIT, using virtual sensors linked to a MySQL [142] database via Dynamo. However, this approach only worked within REVIT, without leveraging the IFC standard. A similar REVIT-based approach was followed in [143] to optimise indoor thermal comfort, again without IFC integration.

Regarding the BACN-to-BIM process, most studies focus on Facility Management (FM)-BIM. Quinn et al. [144] worked on pre-processing, storage, and time-series mapping, linking IoT data in REVIT with Dynamo. However, this study did not generate device geometry in the BIM model, relying instead on temperature data visualisation using colour coding, similar to [141], and did not use the IFC standard. Cheng et al. [145] developed a predictive maintenance framework for MEP elements, integrating BACnet communication with BIM, where sensors were manually modelled in REVIT, and real-time data were added to the *IfcSensorType* [146] entity within an IFC4 file. Dave et al. [147] also developed a framework for integrating IFC with IoT devices, again manually modelling existing sensors in REVIT.

2.2.2. Real-data-to-IFC

Several studies have explored the integration of BIM with real-time IoT data [141, 143, 145, 147, 148, 149, 150, 151], but the field is still in its early stages [67, 152, 153, 154]. Most research has focused on linking IoT data to BIM through REVIT, with limited work addressing IFC-based integration [145, 147, 148]. The challenge lies in connecting static BIM data with dynamic IoT data, as interoperability issues persist. The IFC standard includes the *IfcTimeSeries* entity [155], designed to store time-stamped data. Some studies have extended IFC models to integrate real-time data by adding sensors and occupancy patterns to entities like *IfcSensor* and *IfcOccupant*, facilitating applications like fire emergency management and evacuation planning [156]. However, due to IFC's file-based nature, updating dynamic data requires rewriting the file each time new information is added, making it computationally inefficient. Storing frequently recorded data, such as updates every 10 minutes, quickly becomes unmanageable due to increasing file size and poor user experience. Although this solution may be useful for cases where only a small amount of data is included in the IFC file, it becomes unfeasible for handling large sets of dynamic data.

2.3. Identifying research gaps and contribution

Despite advances in BIM-based renovation, data collection for energy diagnostics and acoustic simulation remains largely manual and fragmented. There is limited research that has dealt with the integration of automated ML with IFC, due to the complexity of completing the necessary data for decision-making, especially for a thermal diagnostic of the building. Limitations include the lack of semantic relationships in BIM models [111, 112]. Moreover, no examples have been identified in the literature applying ML techniques to the detection of thermal deficiencies. These gaps highlight areas for further research and development, particularly in enhancing interoperability and the semantic richness of BIM models. Similarly, acoustic simulation tools generally do not retrieve acoustic parameters from BIM models automatically, relying only on geometric data, with acoustic properties needing to be manually incorporated. Research on automating the extraction and processing of acoustic data using the IFC standard is still limited, presenting an opportunity to enhance the accuracy and efficiency of acoustic assessments in renovation projects. Moreover, existing studies tend to focus on RT as the primary indicator for acoustic analysis, which is mainly influenced by interior geometry and surface finishes rather than by the building envelope. However, indoor SPL—which is essential for assessing indoor acoustic comfort in relation to external noise and envelope performance—has been largely overlooked. Only one study has been identified in the literature that consider the SPL, but without automating the process [128].

This thesis addresses these limitations by developing an automated workflow for BIM-based energy diagnostics and acoustic assessment, integrating ML algorithms in ***paper 1***, and implementing an ETL solution in ***paper 2*** to extract both geometric and performance-related data from IFC models. In ***paper 1***, the ML-IFC connection is addressed, focusing on the identification of thermal deficiencies and the enhancement of design rules that comply with national thermal regulations. In ***paper 2***, the proposed methodology fully automates the retrieval and processing of both geometric and acoustic data directly from IFC-based BIM models. It also establishes the connection with an existing Acoustic Comfort tool to calculate indoor acoustic comfort in relation to the building envelope, for the optimisation of renovation scenarios.

Some previous studies have focused in improve the digitisation of the existing buildings, using Scan-to-BIM processes [157], but focused only in the architectural elements of the building. Previous studies on the BACN-to-BIM integration process have not addressed the digitalisation and virtual representation of devices, as seen in [144]. When sensors have been digitally modelled, the process has been manual [147, 149], highlighting the lack of automation in integrating monitoring systems with BIM. To address this, ***paper 3*** focuses on the automatic updating of IFC files with device information from existing monitoring systems. Additionally, while previous studies have explored IoT integration with BIM, most have relied on proprietary software like REVIT, with limited attention to the IFC standard. Some research has addressed challenges in linking time-series data to IFC or proposed extensions to the standard [156, 158]. In ***paper 3***, the integration of IoT data with IFC is addressed by developing a dynamic data repository capable of storing real-time sensor data from building demo sites while ensuring IFC compatibility. The BACN2BIM tool, based on the IFC4 Add2-TC1 schema [159], facilitates this connection by defining and managing dynamic data storage with BIM.

Although methodologies continue to evolve, barriers related to automation, interoperability, and the complexity of BIM data persist. By adopting the open IFC standard in the proposed methodologies, this research thesis fosters interoperability, promotes openBIM [160], and reinforces IFC as the key format for BIM data exchange.

3. Methods

This section summarises the methodologies developed in this doctoral thesis to address the integration of BIM and advanced digital technologies in building renovation projects. The approaches followed aim to address key challenges in energy diagnostics, acoustic performance assessment, and the integration of monitoring and control networks within BIM models, as identified in the state-of-the-art analysis.

Three methodologies have been developed, each corresponding to one of the main areas explored in this research work:

- **Energy Diagnostics** (***paper 1*** [161]): Use of ML algorithms to analyse As-Built BIM models, identify thermal deficiencies (diagnosis), and propose Energy Conservation Measures (ECMs) (optimisation).
- **Acoustic Performance Assessment** (***paper 2*** [162]): Development of an ETL solution to automate the retrieval and processing of geometric and acoustic data from BIM models, facilitating acoustic simulations.
- **BACN-to-BIM Integration** (***paper 3*** [163]): Implementation of the BACN-to-BIM process to automate the integration of real-time monitoring networks within BIM, ensuring a seamless connection between IoT data and IFC models.

The developments are based on the IFC 4.2 Addendum 2 schema, as specified in ISO 16739:2018 [164]. Each methodology follows a structured process and has been validated through case studies, summarised in the following subsections and detailed in the three scientific publications presented in Section 3.

3.1. Automated energy diagnosis with BIM

The application of advanced digital technologies, including AI-driven techniques such as ML, can significantly impact various stages of the deep renovation lifecycle by providing data-driven insights and optimisation processes. These techniques can analyse data from building sensors, simulate energy performance, and recommend optimised renovation strategies. It is in this last aspect—the optimisation of renovation solutions—where the focus of ML application lies within the context of this thesis. The methodology used to diagnose thermal deficiencies in As-Built BIM models using ML techniques and to propose targeted ECMs was developed in ***paper 1***. It follows a structured approach to support the optimisation of renovation solutions through the automated analysis of BIM-based data, applying AI-driven techniques, specifically a decision tree algorithm, within the energy diagnostics phase of the renovation process.

Figure 2 presents the overall workflow of the ML-based thermal diagnostics process. The diagram shows how BIM data, ECMs, national regulations, and user constraints are processed through the ML algorithm to detect thermal pathologies and determine the most suitable renovation strategy.

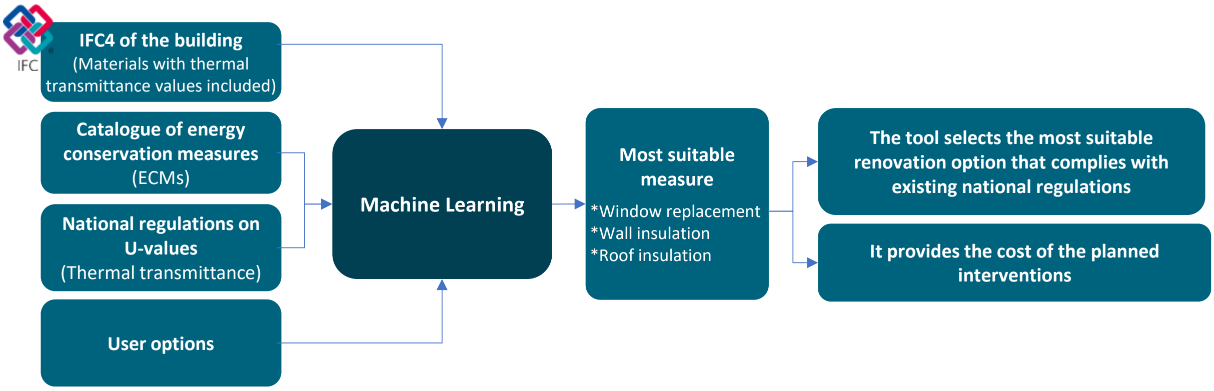

Figure 2: ML to BIM process diagram (own elaboration).

The research methodology was structured into a two-step process aimed at automating the identification of thermal pathologies and support informed decision-making in renovation projects: (i) data acquisition; and (ii) algorithm design.

3.1.1. Data Acquisition

Two main data sources were utilised: (i) building information extracted from the IFC file; and (ii) user-defined constraints along with other contextual data or restrictions.

The IFC data is retrieved using *IfcOpenShell* [165], an open-source library used in python language [166] that processes geometric and semantic data, including materials, dimensions, and thermal properties such as the U-value (thermal transmittance). The parameters extracted from the IFC file were selected to ensure applicability across typical as-built renovation models. The most relevant parameters extracted from external walls, windows, doors, and roofs include geometric dimensions and thermal attributes (e.g., U-value). Additional information includes material layers, the *IsExternal* property, connection to other elements (*ConnectedTo*, *RelatedOpeningElement*), and elevation level. For windows, further parameters such as solar heat gain coefficient and visual light transmittance are also retrieved. At the spatial level, the thermal Zone and thermal Space entities provide area, perimeter, and storey-related information. At the building level, geographic coordinates (if available) are used to determine the climate zone and identify the applicable national building regulations.

Additional constraints, such as heritage building restrictions or intervention limitations, are manually input by the user through a user-friendly interface (e.g., no wall or roof interventions.)

3.1.2. Algorithm design for identifying thermal pathologies

3.1.2.1. Definition of building thermal pathologies

CIB Committee W086 (Building Pathology Commission) defined a pathology as the systematic treatment of building defects [167]. The goal of the defined algorithm was to combine ML techniques with the capability to detect existing buildings defects, focusing specifically on thermal pathologies that require solving through deep renovation. In the context of this research, building thermal pathologies were defined as conditions where the building fails to meet national regulations on thermal transmittance values for building components. The algorithm was defined to check if the thermal transmittance (U-value) of individual building elements (walls, windows, roof) and the global heat transfer coefficient (K or K_{AVE}) of the thermal envelope comply with regulatory thresholds. These reference values are sourced from national building regulations, in this case tested in four countries:

- **Spain**: Basic document HE (Energy Saving)- Technical Building Code (2019) [168].
- **France**: Order related to the energy performance of existing buildings, when they are subject of major renovation work (2008) [169].
- **Germany**: Energy Saving Ordinance-EnEV (2014) [170].
- **Poland**: Implementation of the EPBD in Poland (2016)[171].

The decision tree method [172], a supervised learning algorithm that operates as a rule-based system, was selected to support the identification of the most suitable thermal renovation solution, following an analysis of various ML classification techniques, including rule-based classification [172] and expert systems [173]. Its main advantages include not requiring domain-specific knowledge or parameter tuning, the ability to handle multidimensional data, an intuitive representation, generally good accuracy, and suitability for exploratory knowledge discovery. The algorithm validates the relevant parameters (U-values) of building elements by following a sequence of steps that prioritises the least intrusive measures. The required information of the building needed by the algorithm to check the compliance with the regulations is obtained directly from the IFC file, as explained in the data acquisition section.

3.1.2.2. Decision logic and ECM selection

The algorithm processes the collected data to identify non-compliant elements and selects appropriate ECMs from a solutions catalogue, adapted from the TABULA WebTool [174], a webtool developed within the framework of the TABULA [175] and EPISCOPE [176] projects. The sequence of the proposed algorithm is as follows: If the global heat transfer coefficient of the whole building envelope exceeds the given limit, the process begins with window validation. If no suitable solution is found, it proceeds to walls and finally to roof renovation. For windows, the algorithm first checks the U-value and replaces the element with a new window that meets the respective regulation. If this is insufficient, the U-value is reduced by 10% in the next window used, and if still inadequate, the solution escalates to a higher-performance alternative, such as double or triple glazing. For walls, the process starts with insulation in the air cavity, if applicable (the thickness has to be between 40 and 100 mm in order to consider it viable). If this is not possible, insulation on the exterior surface is considered next, and as a last resort, insulation is installed on the interior side of the building. For roofs, the criteria differ slightly. In sloped roofs, insulation is preferably installed on the inside, as it is easier to implement. For non-sloped roofs, insulation on the outer layer is prioritised. The decision tree algorithm is shown in Figure 3.

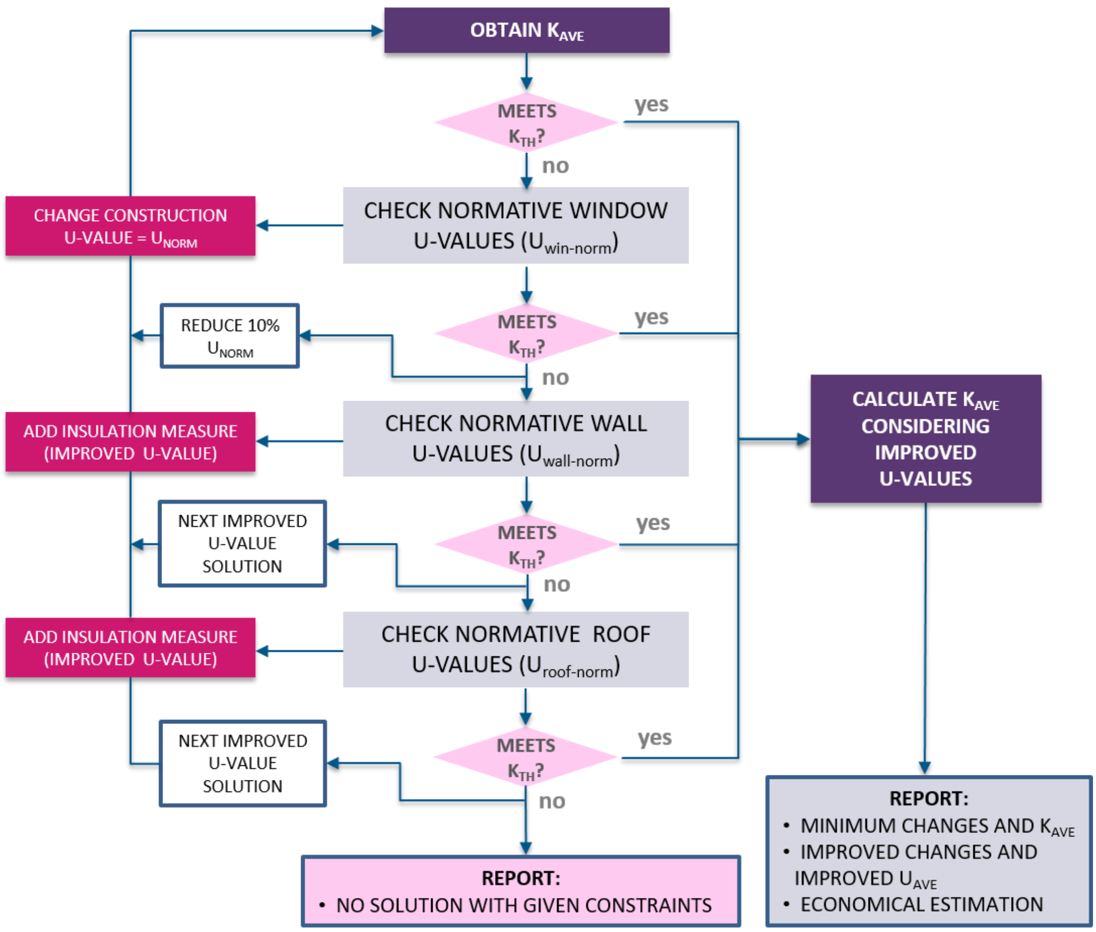

Figure 3: Flow diagram for the designed ML algorithm (own elaboration, published in paper 1 [161]*).*

The algorithm has been defined so that it is not possible to continue with roof renovation without renovating the wall before. This structured decision-making process ensures that the most efficient and least disruptive interventions are applied first. It is also possible that the algorithm does not find a solution because the constraints are too high, in which case the user is asked to consider changing some of the requirements in order to relaunch the process.

The total number of possible solutions of the decision tree was configured in 25 (including no solutions). Table 1 summarise the possible outputs.

Table 1: Possible decision tree outputs (own elaboration, published in paper 1 [161]*).*

Case	Number of solutions	Details about solutions
Tree ends in window	Up to 3 + no solution	
Tree ends in wall	Up to 10 + no solution	2 for insulation in air cavity 4 for external insulation 4 for internal insulation
Tree ends in roof	Up to 2 + no solution	Pitched roof: 1 for internal insulation 1 for external insulation
		Flat roof: 2 for external insulation

It should be noted that the structure of the decision tree and the selection of ECMs were defined by the authors of ***paper 1*** through a multidisciplinary consensus involving a specialist in ML techniques, an architect specialised in regulatory frameworks and energy efficiency, and an expert in energy systems and thermal comfort.

The decision tree classifier was trained and tested using a 70/30 split of synthetically generated data representing different building typologies and regulatory constraints (70% of the data for training and 30% to test performance). This supervised learning approach allowed for transparent rule extraction and ensured that the classification logic aligned with predefined renovation strategies

3.1.2.3. Definition of solutions catalogue

The ECMs included in the catalogue for each country were defined to align with the set of possible solutions provided by the decision tree, as shown in Table 1. The catalogue contains market-available products with cost estimations for each of the four analysed countries, based on prices adapted from [177]. To illustrate how the catalogue was defined, this section summarises the external insulation options selected for Spain.

External Thermal Insulation Composite System (ETICS) was chosen as the external insulation method because it is widely used across the European market [178, 179], and provides high indoor thermal comfort in both summer and winter, as demonstrated in studies such as [180]. Given the variety of insulation materials compatible with ETICS, this research selected three representative options for Spain: extruded polystyrene, mineral wool, and Expanded Polystyrene (EPS), the latter being the most commonly used across Europe [178].

For France, the same data was applied due to insufficient information in the TABULA database. In Germany and Poland, mineral wool was excluded, as it is not commonly used in those countries, with EPS being more widely adopted and applied in different average thicknesses compared to the Spanish context [178].

Table 2 shows the structure used for the ECMs catalogue and details the four external insulation options defined for Spain, all based on ETICS. The algorithm was designed to identify non-compliant elements and to select appropriate ECMs using the information provided in the catalogue.

Table 2: Proposed material solutions and associated costs for external wall insulation in Spain and France (own elaboration, published in paper 1 [161]*).*

		Insulation (ins.)						Finishing layer (FL)	
Category	Type	Thickness ins. [mm]	Material	**U-value [W/(m²·K)]**	Thermal resistance [(m²·K)/W]	Conductivity [W/(m·K)]	Cost [€/m²]	U-value [W/(m²·K)]	Cost [€/m²]
Ins. at the Ext.	ETICS (50 mm cement/mortar plaster+ins.)	60	Extruded polystyrene	**0.600**	1.667	0.036	10.24	1.600	20.05
		60	Mineral Wool	**0.571**	1.750	0.034	19.61	1.600	20.05
		100	Expanded Polystyrene	**0.380**	2.630	0.038	23.26	1.600	20.05
		100	Extruded polystyrene	**0.357**	2.800	0.036	14.14	1.600	20.05

Note: Ext., Exterior; Int., interior; ins., insulation.

3.2. Automated acoustic comfort assessments with BIM

The methodology used to automate the retrieval and processing of geometric and acoustic data from BIM models was developed in ***paper 2***. It follows a structured approach to enable the transformation of BIM-based information into acoustic simulation inputs, through an ETL solution that connects IFC data with an existing Acoustic Comfort tool.

Figure 4 presents the workflow of the ETL IFC4Acoustic parser, detailing how IFC data is processed to generate a structured output for acoustic assessment. The diagram shows the sequence from data extraction to acoustic evaluation, concluding with the generation of a JSON file containing the acoustic simulation results.

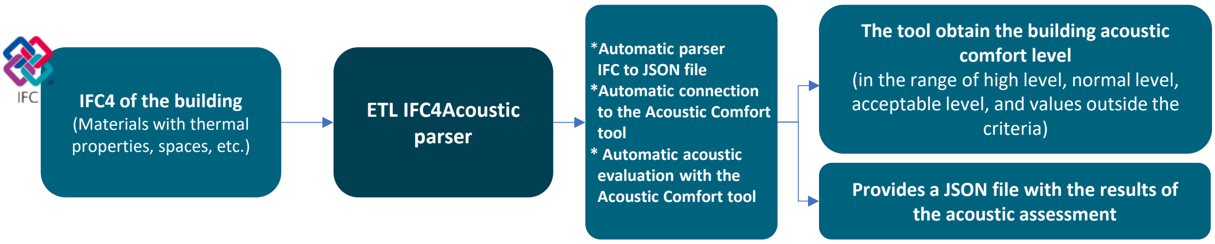

Figure 4: IFC4Acoustic parser process diagram (own elaboration).

The research methodology was structured into a three-step process to automate the extraction and processing of acoustic data from BIM models for integration into acoustic simulation tools: (i) identification and classification of input data; (ii) mapping IFC data to acoustic parameters; and (iii) development of the ETL solution.

3.2.1. Identification and classification of input data

The first step was to identify and classify all the input data required by an acoustic software tool to estimate indoor acoustic performance, ensuring compliance with existing acoustic regulations. The methodology developed in this research is demonstrated using an Acoustic Comfort tool [181, 182], which estimates indoor Sound Pressure Level (SPL) [183] in accordance with EN ISO 12354-3:2017 [184]. This standard applies to the design, construction, and renovation phases. It provides a calculation model for estimating indoor SPL by considering external noise levels, the weighted standardised façade level difference ($D_{2m,nT,w}$), using Equation (1), and the sound transmission properties of the building envelope, including both elements and openings.

The Acoustic Comfort tool calculates acoustic performance at two levels, following these steps:

- **Room level**: (i) it obtains the external noise level from strategic noise mapping, if available; otherwise, a direct measurement is required; (ii) it calculates the standardised sound level difference of the room façade based on its material layers and the façade elements from the BIM model, using Equations (1)–(4); (iii) it evaluates the equivalent continuous sound pressure level ($L_{A,eq}$); (iv) it assigns the room acoustic class (A–E) based on predefined thresholds.

- **Building level**: (v) it performs an analysis for the assignment of the building acoustic class.

The calculations follow the methodology outlined in Annex E of EN ISO 12354-3:2017, with the weighted standardised façade level difference determined by Equation (1).

$$D_{2m,nT,w} = R'_w + \Delta L_{fs} + 10\log\left(\frac{V}{6 \cdot T_0 \cdot S}\right) \text{[dB]} \quad (1)$$

where R'_w is the façade sound reduction index [dB], used to determine the noise difference between the exterior and the interior, calculated according to Equation (2); V is the volume of the receiving room [m^3]; T_0 is the reference reverberation time [s] (generally 0.5 s for dwellings), S is the total area of the façade facing the inner part touching the room [m^2]; ΔL_{fs} [dB] is the level difference due to the shape of the façade (e.g. balconies), with respect to the central face of the façade.

$$R'_w = -10\log\left(\sum_{i=1}^{n}\frac{S_i}{S}10^{\frac{-R_{w,i}}{10}} + \sum_{i=1}^{n}\frac{A_0}{S}10^{\frac{-D_{n,e,w,i}}{10}}\right) - K \text{ [dB]} \quad (2)$$

where $R'_{w,i}$ is the sound reduction index [dB] of the element (i), calculated according to Equation (3), and S_i the area of the element (i) of the façade [m^2]; S is the total area of the façade facing the inner part touching the room [m^2]; Ao is the reference equivalent sound absorption area equal to 10 m^2; $D_{n,e,w,i}$ is the weighted normalised sound level difference of each small element [dB], calculated according to Eq. (4); n is the total number of elements in the façade; and K is a correction factor for the flanking sound transmission [dB].

$$\begin{aligned} R_{w,wall} &= 37.5\log(m') - 42\ [dB] \\ R_{w,window} &= 12\log(m') + 17\ [dB] \\ R_{w,door} &= 20\log(m')\ [dB] \end{aligned} \quad (3)$$

where m' is the mass per unit area of the element.

$$D_{n,e,w} = -10\log\left(\frac{S_{open}}{A_0}\right)[dB] \quad (4)$$

where S_{open} is the area of the small elements [m^2]; and A_0 is the reference equivalent sound absorption area equal to 10 m^2. The equivalent continuous sound pressure level is calculated according to Equation (5):

$$L_{A,eq} = L_{1,2m} - D_{2m,nT,w} + 10\log\left(\frac{T}{T_0}\right) \text{[dB(A)]} \quad (5)$$

where $L_{1,2m}$ is the average sound pressure level at 2 meters in front of the room façade [dB]; $D_{2m,nT,w}$ is the weighted standardised façade level difference [dB] Equation (1); T_0 is the reference reverberation time [s] (generally 0.5 s for dwellings); and T is the reverberation time [s] in the receiving room. Having estimated the equivalent continuous sound pressure level ($L_{A,eq}$) for each room bordering to the external environment, an acoustic class is assigned to the room itself. Acoustic class depends on the space use (offices, bedrooms, living rooms, classrooms, etc.).

All data required as input for Equations (1)–(4) are retrieved from the BIM model of the building using the developed ETL.

The required data for the Acoustic Comfort tool has been structured into a JSON file, which serves as its input format. This JSON file contains building data extracted from BIM, including only the information related to rooms adjacent to the external environment. Table 3 summarises the required data used in the calculations.

Table 3: Inputs needed to perform the acoustic calculation by the Acoustic Comfort tool (own elaboration, published in paper 2 [162]*).*

Associated element	Input
Building information	District land use (Countryside/residential area/urban area)
Room information	End use (Bedroom, etc.)
	Volume (m^3)
	Floor area (m^2)
	Shape (i.e., open/ closed fence)
	Floor level
	External equivalent noise pressure level (dB)
	Balcony width (m)
	Balcony material
Elements in façade information	Element type (window, door, small element)
	Surface (m^2)
Walls information	Layer thickness (m^2)
	Layer density (kg/m^3)

3.2.2. Mapping IFC data to acoustic parameters

The mapping between the JSON data structure and the IFC schema was carried out to align the required acoustic input data with their corresponding attributes in the IFC model. This process ensures that acoustic parameters are correctly extracted and structured for use in the Acoustic Comfort tool, maintaining consistency between the IFC representation and simulation requirements. Most of the parameters required for the parsing process can be extracted directly from the IFC file. However, some values cannot be mapped directly, as the IFC file does not provide the final value required by the JSON file. Additionally, certain parameters have been fixed by default to ensure compatibility. Table 4 presents in detail this mapping.

Table 4: Mapping between the JSON parameters and the standard IFC (own elaboration, published in paper 2 [162]*).*

JSON parameter	Ifc class (entity) or fixed parameter
RoomFacade	
Room	IfcSpace/GlobalId
Room use	IfcSpaceType
Room volume	IfcSpace/IfcQuantityVolume/GrossVolume
Room floor area	IfcSpace/IfcQuantityVolume/GrossFloorArea
Room shape	Fixed in 1 (no shape)
Room floor	IfcBuildingStorey
District_Land use category	Fixed in 2 (residential area)
District_Total number of buildings	Fixed in 1
Building_ID	IfcBuilding
Building_Total number of room facades of each building	IfcWall/ *IsExternal*
RoomFacade_ID	IfcWall/ GlobalId
Room_ID	IfcSpace/GlobalId
RF_Surface	Calculated directly by the ETL
RF_Strategic Noise Mapping value	Fixed in 0
RF_Balcony material	Fixed in -99
RF_Balcony width	Fixed in -99
External equivalent sound pressure level	*IfcSoundPressureLevelMeasure*
ElementFaçade	
Wall	IfcWallType/GlobalId
Number of wall id	IfcWalltype/GlobalId
Wall id	IfcMaterialLayerSet
Wall layer thickness	IfcMaterialLayer/ LayerThickness
Wall layer density	IfcMaterialProperties/ *MassDensity*
Element Building_ID	IfcBuilding/GlobalId
Element RoomFacade_ID	IfcWall/ GlobalId
Element type	IfcWindow/IfcOpeningElement/IfcDoor/IfcWall
Element surface	Calculated directly by the ETL
Element id*	IfcOpeningElement/GlobalId IfcWindow/GlobalId

**The Element id is obtained from each of the elements in the IFC, but then renamed to comply with the JSON requirements. In the case of the windows elements, the identifier (ID) is fixed according to the internal classification of the Acoustic Comfort tool for the different types of glazing, is a static value.*

Specific BIM guidelines were prepared, outlining the correct parameters that need to be included in IFC files to facilitate the acoustic assessment process.

3.2.3. Development of the ETL solution

The final step focused on developing the ETL solution, defining its structure, functionalities, and key features to ensure compatibility with a wide range of acoustic software tools. The implementation included an API to connect the ETL solution with the Acoustic Comfort tool. While this methodology was validated using the Acoustic Comfort tool, it is designed to be adaptable for broader applications.

3.3. Automated Integration of BACN with BIM

The methodology used to address the digitisation of building monitoring data through BACN-to-BIM integration, and to automate the connection with real-time IoT data, was developed in ***paper 3***. It follows a structured approach to enable dynamic data integration within BIM models through the BACN2BIM tool, effectively linking static building information with real-time monitoring data.

Figure 5 presents the BACN-to-BIM workflow, demonstrating the integration process between real-time monitoring data and BIM models. The diagram presents how IFC-based building information, monitoring network configurations, and raw sensor data are processed by the BACN2BIM tool to update the IFC file with installed devices, ensuring interoperability and real-time data management.

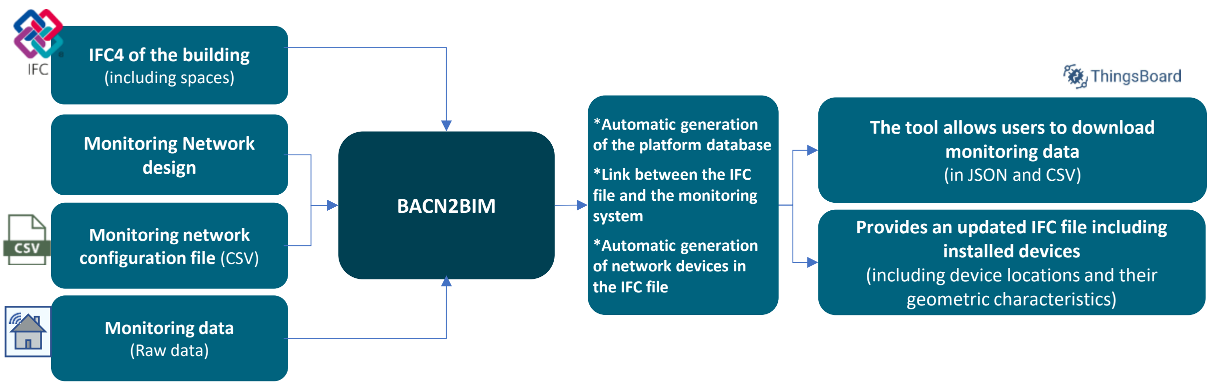

Figure 5: BACN-to-BIM process diagram (own elaboration).

The research methodology was structured into a four-step process to establish a dynamic link between BIM models and monitoring data: (i) defining the BIM-based dynamic data integration framework; (ii) data acquisition; (iii) mapping IFC data to BACN parameters; and (iv) developing the BACN2BIM tool, specifying its main characteristics and functionalities to guide its structured development.

3.3.1. Definition of a BIM-based dynamic data integration framework

The first step was to define the connection between static (BIM model) and dynamic (real-time monitoring information), addressing key research gaps. Various approaches for integrating dynamic data were analysed to identify the most suitable solution. The selection of the IoT platform, ThingsBoard [185], and its API connections with BIM-SPEED protocols and devices was also established. The decision to use ThingsBoard in the BACN2BIM tool was based on the functionalities offered by the platform, including its ease of use for adding new *devices*, *users*, and other *assets (e.g., rooms)*. Additionally, the ThingsBoard API enables communication between the BACN2BIM tool and various protocols and devices used in the BIM-SPEED project, as well as store the data linked to the IFC standard.

3.3.2. Data acquisition

The BACN2BIM tool requires two input files: (i) an IFC4 file containing the building's geometry, semantic data, and spatial structure—including thermal spaces (*IfcSpace*); and (ii) a Comma-Separated Values (CSV) configuration file with the necessary parameters to connect to the monitoring—such as device details, network credentials, and access information—following the structure shown in Table 5. The model can be updated by modifying the configuration file if the monitoring network changes or new devices are added.

Table 5: Example of a correct parameter configuration file (own elaboration, published in paper 3 [163]*).*

Building	Sensor Location	Sensor Type	Device	User Name	Password	Address/ IP	Sensor/ Actuator/ Controller
Building name	*IfcSpace* name	User Defined	ENERGOMONITOR/ other	******	******	https://www.ccc.ddd/	SENSOR

The configuration file must meet specific criteria for the tool to function correctly:

- Building name must match the IFC file name.
- Sensor Location corresponds to the *LongName* of the *IfcSpace* where the device is installed.
- Sensor Type defines the measured variable (e.g. temperature, humidity);
- Device refers to the hardware installed (e.g. ENERGOMONITOR).

- User Name, Password, and IP address provide access to the platform or device.
- Sensor / Actuator / Controller, defines the device function—some may measure, control, and act simultaneously.

3.3.3. Mapping IFC data to configuration file

Each parameter in the CSV file corresponds to a specific IFC class or property. Table 6 presents the mapping between the parameters specified in the configuration CSV file and their corresponding IFC classes or attributes. This mapping ensures that device information is correctly located and associated with thermal spaces within the BIM model.

Table 6: Mapping between the CSV parameters and the standard IFC (own elaboration).

CSV parameter	Ifc class (entity) or another parameter
Building	IfcBuilding/Name
Sensor Location	IfcSpace/LongName
Sensor Type	IfcSensor/SensorType
Device	Not mapped in IFC – The hardware device installed on buildings, such as ENERGOMONITOR
User Name	Not mapped in IFC – used only for platform access
Password	Not mapped in IFC – used only for platform access
Address/ IP	Not mapped in IFC – online access point
Sensor/ Actuator/ Controller	IfcDistributionControlElement/PredefinedType

3.3.4. Development and structuring of the BACN2BIM tool

Based on the framework and IoT platform selection, the main characteristics and functionalities of the BACN2BIM tool were established to guide its development. These functionalities include:

- **Creation of a new monitoring project**: the tool manages the *ThingsBoard* database and updates the IFC file with the geometrical and geographical properties of the installed devices. Its operation requires the two input files (the IFC file of the building and the CSV configuration file). All IFC file parsing activities were performed using the xBIM toolkit [186], which enabled structured access to and modification of IFC entities. The BACN2BIM tool also has a module to deploy communication drivers to retrieve data from monitoring systems.
- **Real-data download and storage**: Users can download data directly from BACN2BIM to the BIM-SPEED platform, avoiding the need for separate data extractions from multiple monitoring systems.

These features were integrated to ensure seamless connection between the BIM model and real-time monitoring data, supporting the generation of enhanced IFC models enriched with information on sensors, actuators, and controllers that form part of the existing monitoring system.

3.4. Validation of methodologies in case studies

The presented methodologies have been demonstrated and validated through case studies at different Technology Readiness Levels (TRLs), assessing their applicability and effectiveness in both controlled and real-world environments:

- **Energy Diagnostics *(paper 1)***: Validated in a laboratory environment (TRL 4), testing the methodology for automated thermal diagnostics using simulated case studies.
- **Acoustic Performance Assessment *(paper 2)***: Validated in a relevant environment (TRL6), demonstrating the automated acoustic comfort assessment in an operational environment, applied to a real demo case.
- **BACN-to-BIM integration *(paper 3)***: Evaluated at both TRL4 and TRL6, validating the BACN-to-BIM integration in a controlled setting (TRL4) and testing its real-time IoT data connection with BIM models in a real demo case (TRL6).

The validation of the different methodologies has only been tested on residential buildings. However, it can be extrapolated to commercial or other building types, as long as they comply with the input requirements of the IFC models and, in the case of the BACN2BIM, with the required configuration file. The proposed methodologies, although motivated by the need to improve the renovation process, are also applicable and useful in the design of new projects.

3.4.1. Case study prototype (TRL4)

In ***paper 1***, the energy diagnostics tool was validated at TRL4 using simulated case studies, rather than real buildings. This approach ensures controlled testing conditions while assessing the methodology's effectiveness across different regulatory and climatic contexts. To account for country-specific constraints, the methodology incorporates:

- Regulatory requirements: Different U-value constraints for constructive elements influence the decision tree and the selection of ECMs.
- Reference renovation solutions: The ECMs considered are based on national market availability, and reflect the cultural and climatic characteristics of each region.

For the validation, three building models were analysed:

- Two models share the same typology with a pitched roof but differ in material quality for walls, windows, and roofs: (i) medium quality; (ii) low quality (Figure 6).
- The third model maintains the same material qualities as the second (low quality) but features a flat roof instead of a pitched one (Figure 7).

For each case study, a building model in IFC4 (ADD2-TC1 schema version) format was generated to ensure interoperability and consistency in the validation process, as shown in Figure 6 and Figure 7.

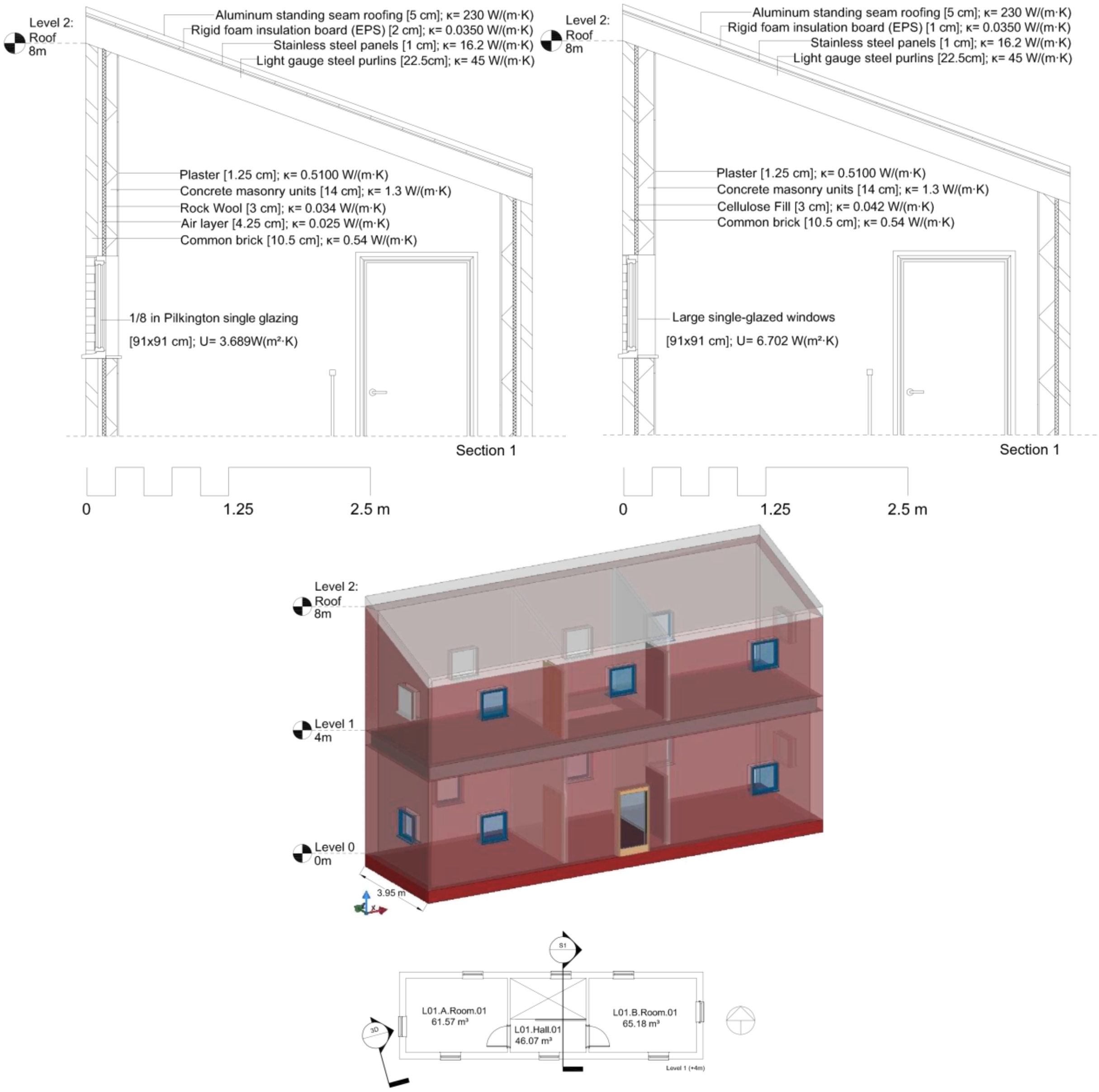

Figure 6: Construction sections and 3D view of the BIM model with pitched roof used for TRL4 validation. (Left) High-quality prototype; (Right) Low-quality prototype (own elaboration, published in paper 1 [161]*).*

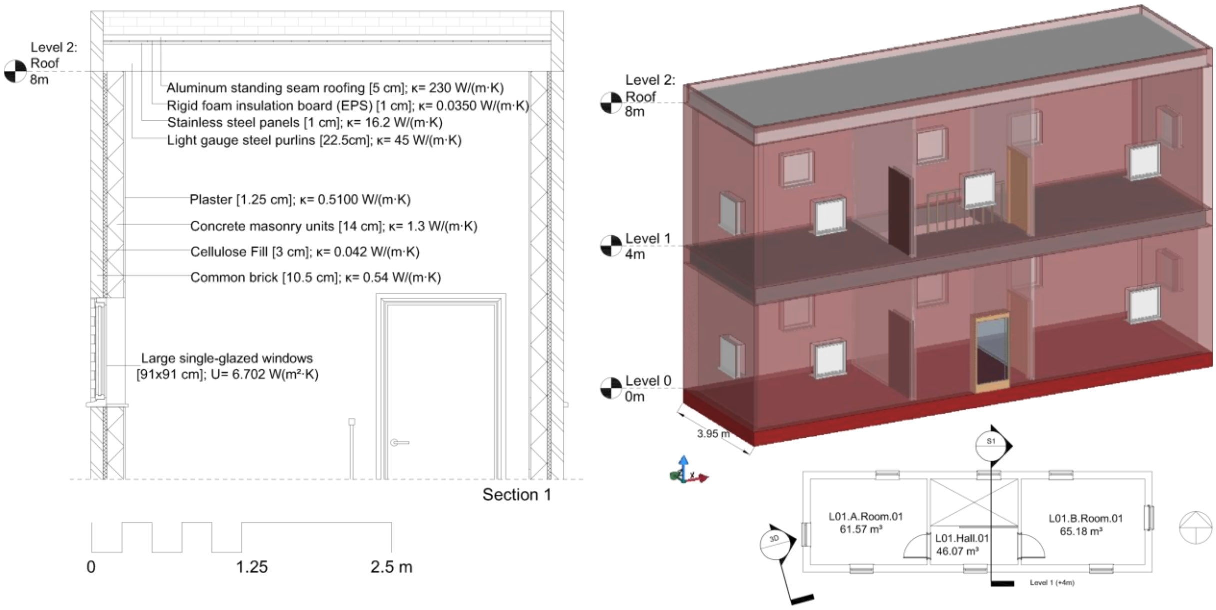

Figure 7: Construction section and 3D view of the BIM model used for TRL4 validation: Low-quality building prototype with flat roof (own elaboration, published in paper 1 [161]*).*

The selected test locations include four EU countries—Spain, Poland, France, and Germany—which represent the main climatic zones and building regulations in Europe. Additionally, three Spanish cities from different climatic zones were included to examine regional variability: Málaga (zone A), Bilbao (zone C), and León (zone E). The other selected cities were Warsaw (Poland), Massy (France), and Berlin (Germany).

In ***paper 3***, the BACN2BIM tool was validated at TRL4 using a simulated case study to assess its functionality in automating the integration of monitoring devices into IFC models and generating a digital representation of a control network. This controlled testing environment ensured a structured evaluation before applying the tool to real-world scenarios. For this validation, an IFC4 (ADD2-TC1 schema version) file of a residential building developed by the Institute for Applied Computer Science (IAI) at the Karlsruhe Institute of Technology (KIT) was used [187]. The model represents a seven-space residential house, as shown in Figure 8.

As part of the hypothesis to simulate a temperature control system, it was assumed that each thermal space (*IfcSpace* class) would require a sensor-controller-actuator package, emulating an HVAC-based configuration using split units or similar elements. Although this package often consists of a single device (e.g. a thermostat), the IFC standard does not support multi-signal elements. Therefore, each sensor, controller, and actuator had to be defined separately in the IFC mode. Since this was a fictitious case study, two key validation aspects were addressed:

- Automatic integration of monitoring devices into the IFC model.
- Auto-generation of a control network configuration file, as the model lacked a predefined monitoring system.

Figure 8: Ground floor of the original IFC showing the spaces empty (without elements) before the application of the BACN2BIM tool, highlighted in yellow (own elaboration).

3.4.2. The Vitoria-Gasteiz case study

For the validation in a relevant environment, two real case studies were used: ARCAYA 5 and ALDABE 26, two residential buildings located in the *Coronación* district of Vitoria-Gasteiz, Spain. These buildings, part of the BIM-SPEED project, are named after their respective addresses: *Manuel Díaz de Arcaya* Street 5 and *Aldabe* Street 26. Figure 9 and Figure 10 show the aerial view and the map indicating their locations.

Figure 9: Aerial view of the buildings used as case studies highlighted (own elaboration).

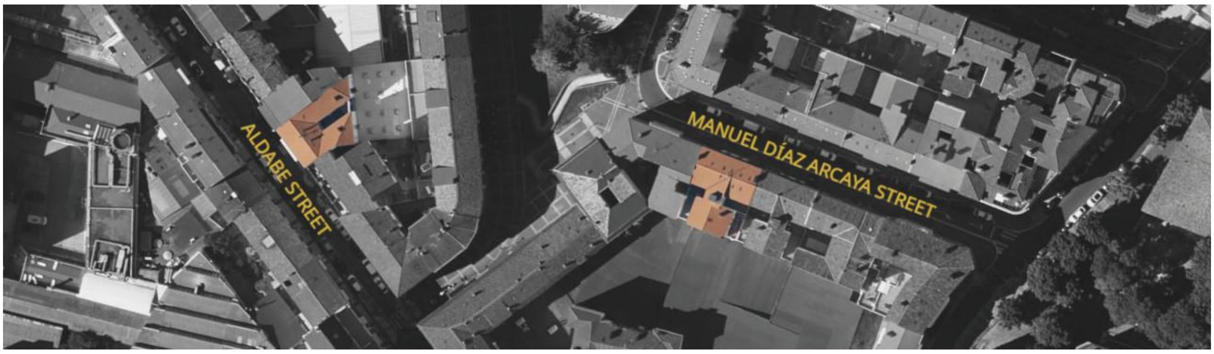

Figure 10: Map of part of the Coronación district with the two buildings used as case studies highlighted (own elaboration).

3.4.2.1. Building ARCAYA5

ARCAYA 5 is a residential building from 1950, with a ground floor, four upper levels, and a fifth floor under the roof. Its layout forms a Latin 'I' shape, with a central corridor connecting front and rear dwellings. This case study was used for the TRL6 validation of the methodology presented in ***paper 2***, in a real environment. For this purpose, an IFC4 (ADD2-TC1 schema version) file was generated, following the requirements defined therein for the IFC4Acoustic parser. The sound pressure level at street level, a required parameter to be included in the IFC model, was obtained from the city's strategic noise map [188], assigning a value of 57 dB to the main façade (north, facing *Manuel Díaz Arcaya* Street), while a value of 50 dB was assumed for the courtyard façades (south). Both values were integrated into the BIM model of the building.

3.4.2.2. Building ALDABE26

ALDABE26 is a residential building from 1958 located in Vitoria-Gasteiz, Spain. It has four floors with eight dwellings (two per floor), and a ground floor that includes a parking area and a commercial unit. The building has a U-shaped floor plan with a diagonal cut at the rear. This case study was used for the TRL6 validation of the methodology presented in ***paper 3***, conducted in a real environment. For this case study, a building model in IFC4 (ADD2-TC1 schema version) format was generated, in accordance with the requirements defined for the BACN2BIM tool. The original IFC file, received in IFC 2x3 format, required adaptation due to geometric inconsistencies and the absence of thermal space definitions—an essential input for the BACN2BIM tool to parser the CSV file correctly. The model was corrected and re-exported in IFC4 format. Although the building was already equipped with an ENERGOMONITOR [189] monitoring system—a commercial IoT platform designed to measure indoor comfort conditions and energy consumption in residential buildings—installed in several dwellings, this information had not been previously integrated into its BIM model. The validation involved the complete integration of the BACN2BIM tool with the BIM-SPEED platform, starting with the definition of a new monitoring project using a CSV configuration file containing real sensor-specific data for the building. This file contained information for seven sensors, corresponding to seven of the building's eight dwellings—one per dwelling.

In the case of residential buildings, the use of BACN is still uncommon. However, some smart monitoring solutions are beginning to be adopted, as is the case in some demo sites of the BIM-SPEED project. In these cases, systems such as ENERGOMONITOR, which offer APIs for data access, has been deployed. For this reason, ALDABE26 was included as a validation case to test the integration of real-time data with BIM models.

4. Scientific papers that support the research work

Chapter 4.1 - Paper 1:

[161] Machine Learning for the Improvement of Deep Renovation Building Projects Using As-Built BIM Models

Chapter 4.2 - Paper 2:

[162] An innovative approach to automate BIM data retrieval and processing for building acoustic comfort calculations based on the IFC standard

Chapter 4.3 - Paper 3:

[163] A tool based on the industry foundation classes standard for dynamic data collection and automatic generation of building automation control networks

4.1. Machine Learning for the Improvement of Deep Renovation Building Projects Using As-Built BIM Models

S. Mulero-Palencia, S. Álvarez-Díaz, and M. Andrés-Chicote,

4.1.1. Abstract

In recent years, new technologies, such as Artificial Intelligence, are emerging to improve decision making based on learning. Their use applied to the Architectural, Engineering and Construction (AEC) sector, together with the increased use of Building Information Modelling (BIM) methodology in all phases of a building's life cycle, is opening up a wide range of opportunities in the sector. At the same time, the need to reduce CO_2 emissions in cities is focusing on the energy renovation of existing buildings, thus tackling one of the main causes of these emissions. This paper shows the potentials, constraints and viable solutions of the use of Machine Learning/Artificial Intelligence approaches at the design stage of deep renovation building projects using As-Built BIM models as input to improve the decision-making process towards the uptake of energy efficiency measures. First, existing databases on buildings pathologies have been studied. Second, a Machine Learning based algorithm has been designed as a prototype diagnosis tool. It determines the critical areas to be solved through deep renovation projects by analysing BIM data according to the Industry Foundation Classes (IFC4) standard and proposing the most convenient renovation alternative (based on a catalogue of Energy Conservation Measures). Finally, the proposed diagnosis tool has been applied to a reference test building for different locations. The comparison shows how significant differences appear in the results depending on the situation of the building and the regulatory requirements to which it must be subjected.

Keywords: machine learning; artificial intelligence; BIM; IFC; deep renovation; design rules.

Reference: S. Mulero-Palencia, S. Álvarez-Díaz, and M. Andrés-Chicote, "Machine Learning for the Improvement of Deep Renovation Building Projects Using As-Built BIM Models," Sustain. 2021, Vol. 13, Page 6576, vol. 13, no. 12, p. 6576, Jun. 2021, DOI: 10.3390/su13126576.

4.1.2. Contribution of the doctoral candidate

S. Álvarez-Díaz: Conceptualisation, Methodology, Validation, Investigation, Resources, Writing–original draft, Writing–review & editing, Visualisation, Supervision, Project administration, Funding acquisition.

4.1.3. Contribution of the co-authors

S. Mulero-Palencia: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing–original draft, Writing–review & editing, Visualisation.

M. Andrés-Chicote: Methodology, Investigation, Writing–review & editing, Funding acquisition.

4.1.4. Author order and doctoral candidate's leading role

Although the doctoral candidate appears as second author in the published version, a leading role was played in the conceptualisation, methodological development, investigation, validation, and coordination of the work, as well as in drafting and revising the manuscript. These contributions are formally recognised both in the published paper and in the *Author Contributions* section (4.1.2 of this thesis). The authorship order was a strategic decision made by the doctoral candidate, who led the project and defined the scope of the research, based on the interdisciplinary nature of the work and the complementary expertise of the co-authors. The first author, a telecommunications engineer with expertise in machine learning, was responsible for the implementation of the algorithm. The doctoral candidate, as an architect and BIM specialist, was essential in framing the problem within the renovation context, ensuring regulatory adaptation, and structuring the integration between the BIM-based input data and the algorithm logic, which enabled the system to operate effectively in real renovation scenarios.

The doctoral candidate also acted as corresponding author during the peer-review process, alongside the first author, and was responsible for managing all communication with the journal, including the preparation of responses to reviewers and coordination of the required revisions until final acceptance. However, the name of the doctoral candidate was omitted in the final published version due to an editorial error, and only one corresponding author was retained in the published version.

4.2. An innovative approach to automate BIM data retrieval and processing for building acoustic comfort calculations based on the IFC standard

S. Álvarez-Díaz, S. Mulero-Palencia, M. Andrés-Chicote, and M. Martarelli

4.2.1. Abstract

Nowadays, there is a growing demand for deep renovation projects aimed at improving the energy efficiency of buildings while enhancing indoor comfort conditions for the inhabitants, both thermal and acoustic. To design effective renovation strategies, technicians need to know the current state of the building to propose acoustic or only thermal improvements. However, evaluating indoor acoustic comfort requires time-consuming and tedious calculations, which can be prone to errors when handled manually. While Building Information Modelling (BIM) can facilitate this process by leveraging the extensive contained data and offering the potential to automate these processes, such automation is not yet widespread. Typically, only geometric data is retrieved automatically from BIM models in acoustic software, while acoustic parameters must be provided manually. This paper addresses these challenges by introducing a novel approach that integrates automated data extraction from BIM with acoustic simulation tools. Specifically, an Extract, Transform and Load (ETL) solution was designed to automatically retrieve both geometric and acoustic data for an Acoustic Comfort tool, which calculates an estimation of indoor acoustic comfort, from an Industry Foundation Classes (IFC). This approach was tested in a demonstration case located in Spain, showing a significant reduction in processing time and increased accuracy compared to traditional methods of manually extracting data from BIM for acoustic assessment. This research represents a significant advance in acoustic simulations by integrating IFC data with automated processing, improving accuracy and offering practical advantages for developing more efficient and reliable BIM-based applications, thus supporting the design of deep renovation projects.

Keywords: Acoustic comfort; Building information modelling (BIM); Industry foundation classes (IFC); Building renovation.

Reference: S. Álvarez-Díaz, S. Mulero-Palencia, M. Andrés-Chicote, and M. Martarelli, "An innovative approach to automate BIM data retrieval and processing for building acoustic comfort calculations based on the IFC standard," Build. Environ., vol. 266, p. 112072, Dec. 2024, DOI: [10.1016/J.BUILDENV.2024.112072](https://doi.org/10.1016/J.BUILDENV.2024.112072).

4.2.2. Contribution of the doctoral candidate

S. Álvarez-Díaz: Conceptualisation, Methodology, Validation, Investigation, Resources, Visualisation, Writing–original draft, Writing–review & editing, Supervision, Project administration, Funding acquisition.

4.2.3. Contribution of the co-authors

S. Mulero-Palencia: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing–review & editing.

M. Andrés-Chicote: Writing–review & editing, Funding acquisition.

M. Martarelli: Conceptualisation, Writing–review & editing.

4.3. A tool based on the industry foundation classes standard for dynamic data collection and automatic generation of building automation control networks

R. Sanz-Jimeno and S. Álvarez-Díaz

4.3.1. Abstract

The use of Building Automation and Control Networks (BACN) is becoming increasingly widespread, largely due to the benefits to end-users and energy management companies of controlling the systems installed in buildings. At the same time, the digitalisation of buildings is increasing every day with the adoption of technologies such as Building Information Modelling (BIM), allowing a high level of digital control in all phases of the building life cycle. However, although the use of BIM is spreading to obtain a digital model of the building, it is not very common to include the existing control systems in BIM models. The integration of BACN-to-BIM seems to be the most appropriate process to have all the information of a building, as it would allow to digitalise and connect both the geometric and the logical part, but it is a challenge to be faced in terms of interoperability. This paper shows the BACN2BIM tool, a tool to make it easier for technical users the creation of monitoring networks linked to BIM models of a building, based on Industry Foundation Classes (IFC) standard. The BACN2BIM tool will allow owners and technical users to easily download dynamic monitoring data, real-time data of the measurements obtained from devices installed in their buildings (temperature, humidity, energy consumption, CO_2 concentration, etc.) The tool has been tested in a case study and in a real demo case located in Spain, showing a time reduction in updating a BIM model with the devices of an existing monitoring system and in the download of existing monitoring data.

Keywords: Building Automation control networks (BACN); Building information modelling (BIM); Industry Foundation Classes (IFC); Internet of things (IoT); real-data.

Reference: R. Sanz-Jimeno and S. Álvarez-Díaz, "A tool based on the industry foundation classes standard for dynamic data collection and automatic generation of building automation control networks," J. Build. Eng., vol. 78, p. 107625, Nov. 2023, DOI: 10.1016/J.JOBE.2023.107625.

4.3.2. Contribution of the doctoral candidate

S. Álvarez-Díaz: Conceptualisation, Methodology, Validation, Investigation, Resources, Visualisation, Writing–original draft, Writing–review & editing, Supervision, Project administration, Funding acquisition.

4.3.3. Contribution of the co-authors

R. Sanz-Jimeno: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing–review & editing.

4.3.4. Author order and doctoral candidate's leading role

Although the doctoral candidate appears as second author in the published version, a leading role was played in the conceptualisation, methodological development, investigation, validation, and coordination of the work, as well as in drafting and revising the manuscript. These contributions are formally recognised both in the published paper and in the *Author Contributions* section (4.3.2 of this thesis). The authorship order was a strategic decision made by the doctoral candidate, who led the project, based on the interdisciplinary nature of the work and the complementary expertise of the co-authors. The first author, an electrical engineer with expertise in control and monitoring networks, contributed to the code development for the integration framework with BACN systems. The doctoral candidate, as an architect and BIM specialist, provided the core conceptual knowledge base, leading the analysis of how BACN elements should be modelled and structured in IFC format to ensure their correct identification and linkage with monitoring data in the automated process. The candidate also developed IFC-compatible elements used in the case studies—defining their typology, properties, and geometric representation—to support the overall objective of automating the digitisation of building monitoring systems into BIM models.

The doctoral candidate also acted as the sole corresponding author throughout the peer-review process, managing all communication with the journal, preparing the responses to reviewers and carrying out the required revisions until final acceptance.

5. RESULTS

This section summarises the main results of the thesis, which are structured around the three scientific papers presented in Section 1. Each publication addresses a specific methodological development aimed at improving building renovation processes through the integration of BIM and advanced digital technologies. The proposed approaches were validated through a range of case studies—both simulated and real—corresponding to different levels of technological maturity.

Paper 1 detailed the development and implementation of a methodology for energy diagnostics based on the analysis of As-Built BIM models using ML techniques. The main results included the identification of thermal deficiencies and the selection of tailored ECMs according to national regulations and material characteristics. This methodology was validated through simulated case studies at TRL4, considering multiple building typologies and European climatic zones. The results confirm that optimal renovation measures vary significantly depending on climate zone, regulatory requirements, model thermal quality, and roof typology. In warmer regions like Málaga, a double-glazing window combined with wall insulation suffices, whereas in colder areas such as León or Berlin, more robust interventions—including roof insulation and higher-performance windows—are needed to meet regulatory thresholds. The algorithm developed in this research supports both the diagnosis stage—used in preliminary analyses to detect thermal deficiencies—and the optimisation stage, where different renovation options are evaluated and simulated during design. The performance of the decision tree model was evaluated using several common metrics in classification tasks: accuracy, precision, recall, and the F1-score. The F1-score is particularly relevant because it combines both precision and recall into a single indicator. In this case, the F1-score reached 0.86, which indicates that the algorithm was able to identify the appropriate renovation measures with a high degree of reliability and consistency. This confirms that the model performs well in suggesting solutions that are both accurate and complete, helping reduce manual errors and support decision-making.

In ***paper 2***, the automated acoustic comfort assessment methodology based on BIM was presented. The proposed ETL solution enabled the automatic extraction and transformation of acoustic data from IFC models for use in simulation tools. The validation was carried out at TRL6 using a real demo case from the BIM-SPEED project, the ARCAYA5 building, demonstrating the tool's performance in integrating acoustic parameters and improving acoustic assessment workflows. The results demonstrated that the entire data processing cycle—from extraction to simulation—was completed in 1 hour and 38 minutes for this case study. In addition, a manual verification performed for Level 1 confirmed the accuracy of the extracted room data and the correct mapping of exterior wall properties, including thickness and material density, demonstrating the robustness of the automated process for acoustic data preparation.

Paper 3 presented the methodology developed for the integration of monitoring and control networks within BIM. The proposed BACN-to-BIM process, with the BACN2BIM tool, automated the inclusion of IoT devices into IFC-based BIM models and established a dynamic connection with an IoT platform for real-time data management. The methodology was validated in two scenarios: (i) a fictitious building model used for testing at TRL4; and (ii) a real demo case, the ALDABE26 building, used for validation at TRL6. TRL4 validation demonstrated the tool's ability to automatically detect thermal spaces, generate sensor-controller-actuator packages, position them within appropriate wall elements, and produce the associated control network configuration file. The TRL6 validation confirmed full interoperability with an existing monitoring system, including the automatic enrichment of the IFC model and retrieval of real-time sensor data. These results confirm the tool's ability to enhance BIM models with monitoring network data and ensure interoperability, supporting the development of DBTs for renovation and building operation. The enhanced IFC file generated for the TRL4 case study, which includes the devices automatically created by the BACN2BIM tool, can be downloaded from this source [190].

5.1. Reflection on limitations and future validation

The results demonstrated the feasibility and robustness of the proposed methodologies in controlled scenarios. However, the limited number of case studies and their homogeneous characteristics, represent a constraint in terms of generalisability. Although these case studies serve to demonstrate technical feasibility at TRL4 and TRL6, they do not cover the full variability of building geometries, construction systems, or energy behaviour encountered in real-renovation contexts.

In the case of ***paper 1***, the validation was primarily focused on testing the methodology under different climatic contexts using the same BIM input model, in order to evaluate its adaptability and relevance across various locations. This approach was chosen to explore the influence of climate on the selection of ECMs, rather than validating the methodology in a single real building. However, for future work, it would be important to test the proposed energy diagnosis process in operational renovation projects, involving buildings with complex geometries, varying construction systems, and incomplete or inconsistent BIM data. This would demonstrate its robustness in real-world conditions and allow for comparisons with traditional diagnostic methods. Additionally, incorporating post-renovation performance monitoring would support a feedback loop to evaluate the effectiveness of the proposed ECMs and refine the methodology accordingly.

Future work should consider a broader range of typologies and climate zones, including non-residential use cases, to further validate the scalability and adaptability of the proposed solutions. Moreover, the tools developed assume a minimum quality and consistency of BIM input data, which may not always be available in real renovation contexts.

6. Conclusions

The research conducted in this doctoral thesis is closely aligned with the key elements defined in the European *Renovation Wave Strategy*, including improving energy efficiency, reducing carbon emissions, and integrating digital tools such as BIM and DTs into building renovation processes. These technologies have been demonstrated to play a crucial role in promoting sustainability and circularity within the building sector, and the adoption of BIM is further expanding due to the benefits it provides throughout the building life cycle. However, the inefficiencies in data management, interoperability issues, and the need for more automated, accurate assessment methods, is still a challenge in building renovation using BIM.

This thesis has addressed these challenges by integrating advanced digital technologies into the renovation process, with BIM acting as the central framework. By leveraging BIM's rich semantic data, the research developed and validated innovative methodologies to improve automation, accuracy, and efficiency in key areas of renovation—energy diagnostics, acoustic assessment, and integration of monitoring systems. The methodologies developed in this research directly fulfil the main objective of the thesis (*to develop methodologies for integrating advanced digital technologies into the renovation process, with BIM as the central framework, to improve energy efficiency and indoor climate in building renovation projects, as well as reducing time and costs, while advancing towards Digital Building Twins)*, and address the other proposed objectives.

Paper 1 and ***paper 2*** focused on enhancing decision-making processes for renovation projects, specifically targeting energy diagnostics and acoustic assessment, as part of the renovation design phase *(OB1. To improve decision-making processes for renovation projects by leveraging BIM-based automated diagnostic tools for energy and acoustic performance).*

For energy diagnostics, in ***paper 1***, a ML algorithm was developed to analyse of As-Built BIM models, IFC-based *(OB3. To address interoperability challenges in renovation BIM workflows using the IFC standard to facilitate seamless data exchange)*, enabling the identification of critical areas for improvement and proposing targeted energy-saving measures. This tool facilitated informed decision-making in renovation projects by reducing reliance on manual processes and providing accurate insights into energy inefficiencies. The approach demonstrated adaptability across different climatic zones and regulatory contexts, showcasing its flexibility *(OB1-1. To develop a methodology for energy diagnostics, automating the retrieval of data from As-Built BIM models and enabling the identification of critical areas for targeted energy conservation measures).*

For acoustic assessments, in ***paper 2***, an ETL solution, the IFC4Acoustic parser, was developed to automate the retrieval and processing of data from BIM models, IFC-based *(OB3)*. This solution was integrated with an acoustic comfort tool to enhance the accuracy and efficiency of acoustic evaluations. The results showed an improvement in the time to perform the acoustic calculation, as well as an error reduction by not having to enter the data manually *(OB1-2. To design and implement a solution that automates the retrieval and processing of geometric and acoustic data from BIM models, significantly improving the accuracy and efficiency of acoustic comfort assessments while supporting decision-making)*.

The digitisation of the existing building data was addressed in ***paper 3*** with the integration of BACN with BIM through the IFC standard *(OB3)*. As a result, the tool is able to update the BIM model by digitising the building's monitoring system, incorporating the precise location of monitoring devices in their real-world positions. This integration of monitoring systems in BIM facilitated real-time monitoring of building systems and addressed longstanding interoperability barriers *(OB2. To update BIM models by integrating data from existing monitoring networks, improving the digitalisation of building status and enabling real-time monitoring and management of building systems)*.

These methodologies were validated through case studies, showcasing significant reductions in processing time and increased accuracy compared to traditional methods *(OB4. To validate the proposed methodologies in various case studies, demonstrating their effectiveness in reducing processing time, increasing accuracy, and improving outcomes compared to traditional renovation methods)*. This comparison is shown in detail in Section 6.1.

This thesis contributes to the advancement of sustainable and efficient renovation strategies by leveraging BIM's extensive data capabilities and integrating advanced digital tools. The outcomes highlight: (i) enhanced decision-making through automated energy diagnostics and acoustic assessments *(OB1)*; (ii) improved digitisation of building status by integrating real-time monitoring networks into BIM workflows *(OB2)*; (iii) overcoming interoperability barriers using the IFC standard for seamless data exchange *(OB3)*; (iv) validation of methodologies *(OB4)*.

The research presented in this doctoral thesis demonstrate the potential of digital transformation in the AEC sector, enabling more sustainable and efficient building renovations through the seamless integration of advanced digital technologies with BIM.

6.1. Comparison with traditional methods

For each methodology developed in this research, a comparison with traditional methods was conducted. The findings demonstrate that the proposed methodologies offer substantial advantages in reducing time, increasing accuracy, enhancing interoperability, and reducing renovation costs. The conclusions and advantages obtained for each of them are summarised below.

6.1.1. Comparison with the common practice in renovation decision making though the application of ML

While traditional methods may offer reliable but slower results, AI, using ML methods, provide optimised, data-driven renovation solutions. This comparison (Figure 11) has been done using BIM with and without the application of ML, developed in ***paper 1***, for energy diagnostics and proposing targeted energy conservation measures.

In the traditional approach to calculating the global heat transfer coefficient (K_{AVE} [$W/m^2 \cdot K$]) through the building envelope, the user must first manually extract the areas and the thermal transmittances values of each building element in contact with the thermal envelope (e.g., windows, walls, floors, and roofs), either directly from the BIM model or from conventional, non-digitalised building documentation. Once this data is gathered, the user needs to input all the collected values into the formula for calculating the K_{AVE} value. This process is time-consuming and prone to errors due to its manual nature, especially when dealing with complex models. The next step is to check the results if they are compliance with country regulations, regarding buildings' thermal properties. After that, users manually select possible ECMs to apply in the building to improve the K_{AVE} value (e.g., insulation, windows, HVAC upgrades). The iterative process can be slow when multiple ECMs need to be evaluated for their feasibility and efficiency. The cost of implementing the selected ECMs is calculated manually or through external tools. This complete process is estimated to take 2-3 hours to gather the necessary data and calculate the K_{AVE} value of the building for each country, and approximately 2-3 days to identify and calculate the optimal ECMs.

Using the BIM-ML process developed in ***paper 1***, the workflow begins by selecting the user's preferences (e.g., avoiding interior wall renovations and focusing on the exterior side) and uploading the BIM model in IFC4 format, which must meet the tool's input requirements. The developed algorithm, using a decision tree classification method, will processes the input data. This method, which learns from labelled tuples, identifies the optimal solutions and verifies whether the transmittance values for each element or the entire thermal envelope fall within the desired range, as specified by the country's regulations. In the final step, the tool generates a detailed report for the user, including the selected optimal ECMs, the new calculated values for K_{AVE} and U-values for the different building elements, and the associated costs of the proposed measures. The time required to obtain the results by the tool depends on the complexity of the building, but for more complex building structures, it is estimated to take around 1 hour.

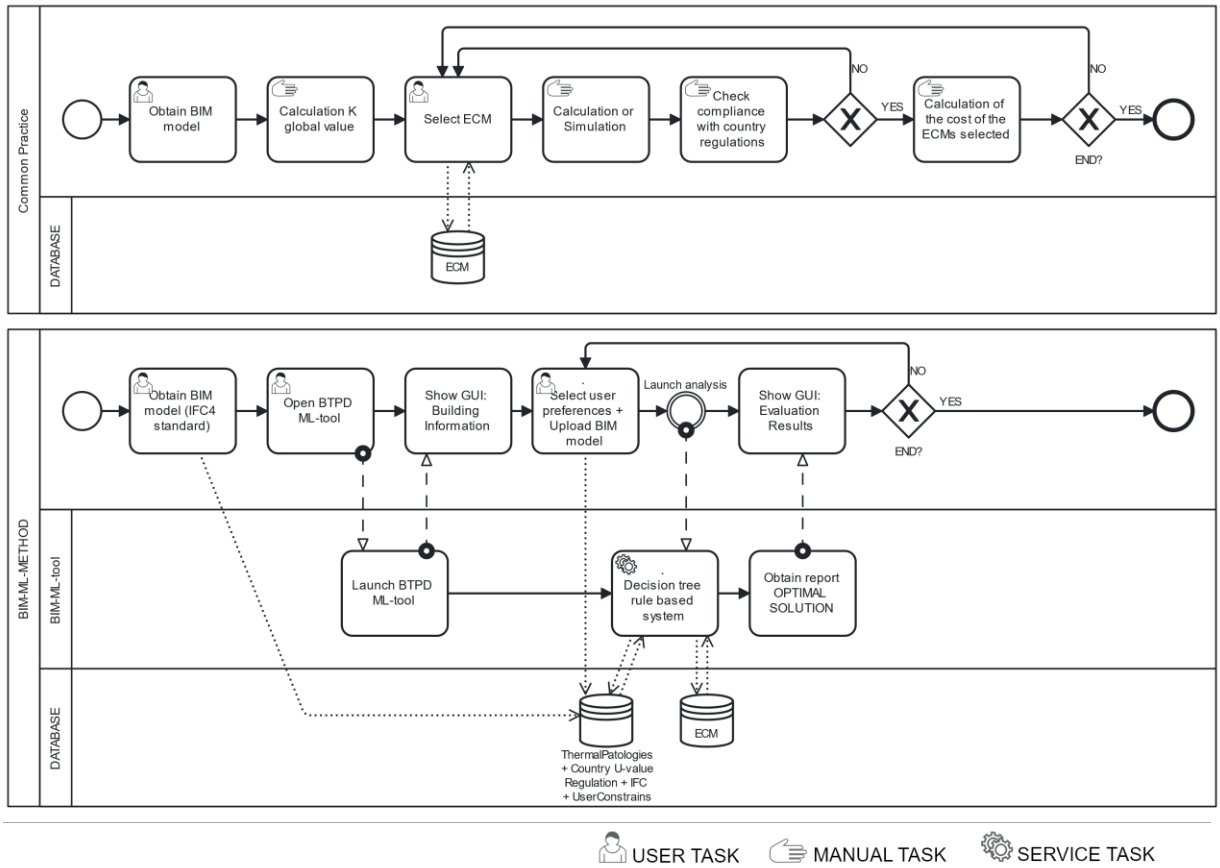

Figure 11: Workflow comparison of the manual data collection process for energy diagnostics and optimal selection of ECMs for renovation with the proposed BIM-ML solution. Note: BTPD is the developed tool for building thermal pathologies diagnosis (own elaboration).

In ***paper 1*** three building models were analysed: a medium-quality prototype, a low-quality prototype, and a low-quality prototype with a flat roof. These models were evaluated for four countries: Spain, Poland, France, and Germany. Based on the results from the case studies, the advantage of the automated process can be summarised as:

- **Time reduction**: The automated process reduced the total time required for energy diagnostics and ECM selection from an estimated 2-3 days (manual approach) to approximately 1 hour, depending on the building's complexity—representing a time saving of over 85%.
- **Accuracy**: The ML-based tool achieved an accuracy of 86% in classifying thermal deficiencies, based on a test dataset following a 70/30 training-testing split. The model also

reached 0.86 in both precision (correctness of proposed solutions) and recall (coverage of correct solutions), leading to an F1-score of 0.86. This indicates a reliable and balanced performance in identifying and recommending renovation measures. Additionally, the automated extraction of input data directly from IFC-based BIM models reduces the risk of errors typically introduced during manual data entry, significantly improving reliability in calculations and decision-making.

- **Compliance**: Built-in regulatory checks ensure that the proposed solutions automatically align with country-specific building codes, eliminating the need for additional manual intervention.
- **Cost reduction**: The ability to automatically evaluate multiple ECMs enables the identification of more cost-effective renovation solutions.

The integration of BIM and ML enabled precise data extraction from building models, optimised renovation workflows, and improved resource management, enabling significant improvements over traditional practices.

6.1.2. Comparison with the common practice for retrieving BIM data for acoustic comfort calculation

The steps required to calculate the acoustic class of a building differ significantly between the traditional method, manual process, and the automated solution developed in ***paper 2***, the IFC4Acoustic parser. This comparison is shown in Figure 12. Both processes begin with the creation of the building's IFC file, but key differences arise in the subsequent steps.

In the manual process, the user must extract data such as wall surface dimensions and other required parameters directly from the BIM model. These values are then manually added into a JSON file for use in the Acoustic Comfort tool. This method is labour-intensive and requires at least two hours of manual effort and introducing potential errors at multiple stages, due to the complexity of the JSON file to be filled, which includes details such as the dimensions of wall surfaces and other essential parameters.

Using the IFC4Acoustic parser, developed in ***paper 2***, the process of retrieving BIM data for acoustic comfort calculation is simplified. Once the IFC file is created and the ETL solution is launched, the tool automatically retrieves, processes, and transforms the necessary data. For the specific case study analysed in ***paper 2***, a residential building in Vitoria-Gasteiz, Spain, the time taken by the ETL to generate the result was 1 hour and 38 minutes, and the manual intervention is only required to launch the tool.

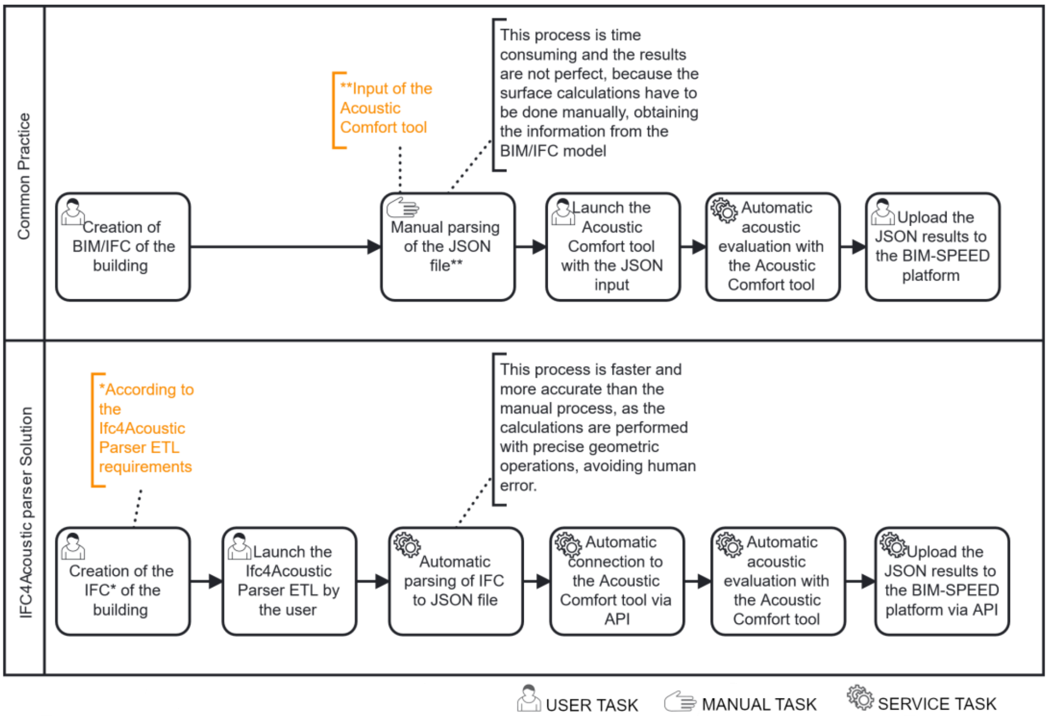

Figure 12: Workflow comparison of the manual data collection process for the acoustic comfort calculation with the proposed IFC4Acoustic parser solution (own elaboration, published in paper 2 [162]*).*

In the case of the acoustic parser, validated with a real demo case located in Vitoria, the process demonstrated a significant reduction in processing time and an improvement in result accuracy. This was achieved by minimising manual user iterations for data acquisition and employing more precise geometric operations for calculating acoustic comfort. Based on the results obtained in the analysed case study, the advantage of the automated process can be summarised as:

- **Time reduction**: The automated process reduced the total time required for acquiring real building data and identifying the acoustic class of the building. Specifically, the time to retrieve BIM data and transform it into a compatible format for the acoustic simulation tool was reduced from approximately 2 hours (manual approach) to 1 hour and 38 minutes using the IFC4Acoustic parser—representing a time saving of around 18%, with manual effort limited to launching the tool.
- **Accuracy**: The elimination of manual iterations minimises errors, as the collection and transformation of data is based on mathematical algorithms. This ensures consistent and reliable extraction of parameters directly from the IFC-based BIM model, significantly reducing the potential for human error.
- **Cost reduction**: By providing accurate and detailed data on the building's current state, the tool enables the selection of more appropriate materials and acoustic solutions. This improved decision-making helps avoid over-dimensioning and costly errors, supporting more cost-effective renovation strategies.

6.1.3. Comparison with the common practice of the BACN-to-BIM process

The comparison of the integration of BACN with BIM between the traditional method of generating monitoring networks by control engineers based on the building designs and the solution proposed in ***paper 3*** with the BACN2BIM tool is shown in Figure 13.

The traditional approach involves designing the BIM model and monitoring network separately, with no automatic connection between the IFC file and the monitoring system. The integration requires manual creation of storage databases or platforms and manually adding monitoring devices to the IFC file. This process is time-consuming and prone to errors, as there is no direct link between the IFC file and the monitoring system.

The BACN2BIM tool automates the integration process by streamlining the connection between the BIM model, IFC-based, and monitoring system. After exporting the BIM model to IFC, the tool uses a configuration file (CSV) to automatically generate device information aligned with the IFC file and link it to the storage database or platform. The tool generates an updated IFC file containing detailed information about the monitoring devices, including their exact locations, and enables users to download data of the database based on the device identifiers of the IFC.

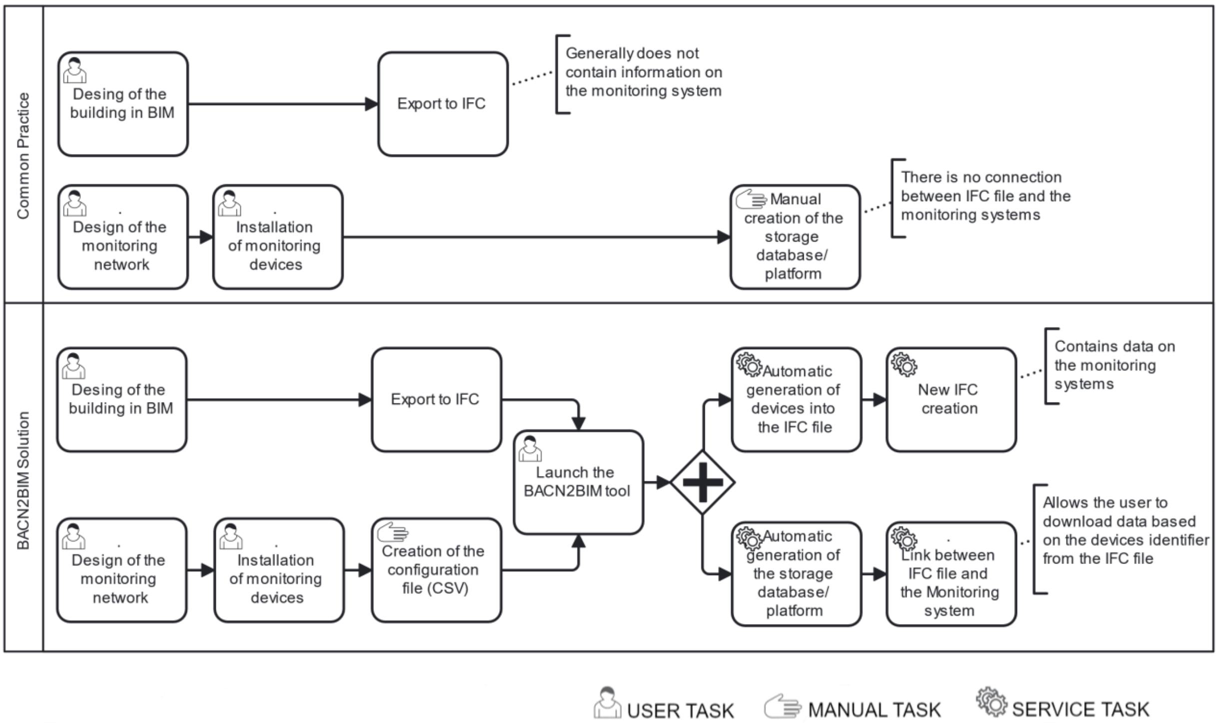

Figure 13: Workflow comparison BACN-to-BIM process between the common practices and the BIM-SPEED solution with the use of the BACN2BIM tool (own elaboration, published in paper 3 [163]*).*

In the specific TRL4 case study analysed in ***paper 3***, the BACN2BIM tool completed the updated IFC4 file in just a few seconds. In contrast, the traditional method would require almost 2 hours to establish the connections and configure the monitoring network, not including the additional time needed to manually update the IFC file with the monitoring devices. The complete process of the BACN2BIM tool was validated with a real demo case located in Vitoria-Gasteiz, Spain. Based on the results obtained in the case studies analysed, the advantage of the automated process can be summarised as:

- **Time reduction**: The automated process reduced the time required to configure the monitoring network and update the BIM model. In the TRL4 case study, the BACN2BIM tool completed the task in seconds, compared to approximately 2 hours using the manual approach—excluding the additional time needed to update the IFC file. This represents a time saving of over 95%, with minimal manual input. Additionally, users can download data from different demo sites through a single platform, saving time in data collection.
- **BIM model updated**: The IFC file of the building is automatically enhanced with information about the monitoring system, including sensors and their actual locations in the real space. This provides users with a clear visual representation of the installed system, offering the possibility to review and adjust the network layout directly within the BIM environment.

The application of the BACN2BIM tool streamlines the BACN-to-BIM process, improves accuracy, and creates a seamless connection between the IFC file and the monitoring system.

6.2. Comparison with background literature

The increasing demand for sustainable building renovations that improve energy efficiency, comfort, and overall building performance, remarks the role of the BIM as a critical part for managing and optimising these projects. However, while BIM models are widely used for building digitalisation, their integration into automated workflows for energy diagnostics and acoustic performance assessments remains limited. Existing studies predominantly rely on manual or semi-manual extraction and processing of BIM data, making these workflows time-consuming and error-prone. Moreover, the integration of automated ML processes with IFC remains limited, primarily due to the complexity of completing the data required for informed decision-making, particularly in thermal diagnostics. One of the key limitations is the lack of semantic relationships in BIM models, which hinders their usability in automated analysis. In the case of acoustic simulations, most acoustic simulation tools do not automatically retrieve acoustic parameters from BIM models, relying only on geometric data, with acoustic properties needing to be manually incorporated. Additionally, research on automating the extraction and processing of acoustic data using the IFC standard remains limited. Similarly, monitoring and control network devices are rarely modelled within BIM models, preventing the connection of real-time dynamic data to static building information. Previous research on BACN-to-BIM integration has either overlooked the connection to time-series data or not addressed the digitalisation and virtual representation of monitoring devices. In cases where sensors have been digitally modelled in BIM, this has been done manually and without considering their integration within the IFC standard.

This thesis makes several key contributions to the field of building renovation projects, addressing limitations identified in previous studies by integrating IFC data with advanced digital technologies and automated workflows. Firstly, it demonstrates the feasibility and benefits of automating the extraction, processing, and transformation of BIM data for energy diagnostics and acoustic performance simulations, effectively leveraging the rich semantic data within IFC models. Secondly, it provides practical implementations of these automated processes, including the development of a ML-based energy diagnostic tool, an ETL solution for acoustic assessments, and a BACN-to-BIM integration tool for the digitisation of devices and real-time monitoring of building systems. These implementations demonstrate significant improvements in accuracy, efficiency, and decision-making when compared to traditional, manual methods. Finally, it highlights how the integration of BIM with monitoring and control networks lays the foundation for advancing towards DBTs, enabling dynamic management of building systems and lifecycle optimisation.

6.3. Digital Building Twins as the future of renovation

Smart building technologies are essential for creating a dynamic energy system focused on renewable resources, which is critical for achieving the EU's 2030 energy efficiency and renewable energy targets, as well as the goal of a fully decarbonised building stock by 2050. Among these technologies, the development of DBTs is fundamental to advance sustainable and intelligent buildings. In this context, BIM models serve as a facilitator for integrating the static and dynamic aspects of buildings, supporting the management of all life cycle phases and providing the structured digital foundation necessary for the development of DTs. In Figure 14, the concept of linking physical and digital domains through BIM-based DTs is represented.

As the building sector advances toward sustainability and circularity, BIM-based DBTs play a pivotal role in the transformation of renovation strategies by enabling predictive simulations, real-time data integration, and improved decision-making processes.

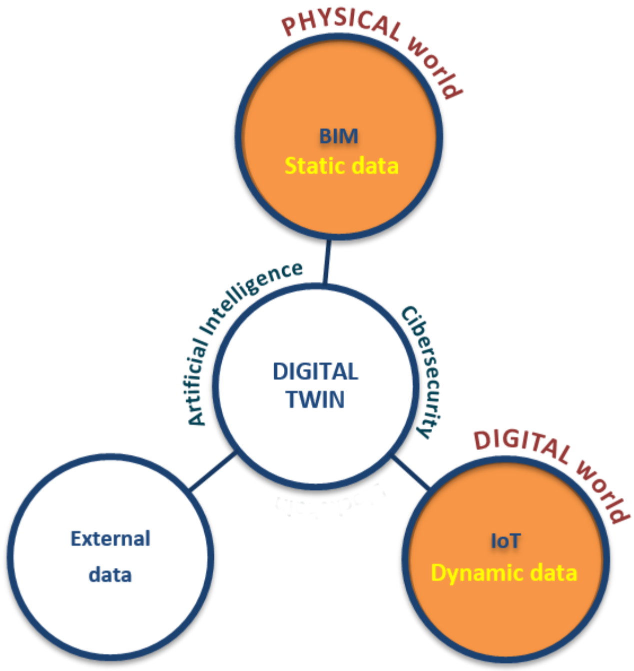

Figure 14: Concept of linking the Physical and Digital world through BIM-based DTs (own elaboration).

The alignment between BIM technology and the evolution of DBTs signifies an important step forward in the automation and optimisation of building renovation workflows. By advancing towards DBTs, this approach not only enhances energy performance but also supports sustainability, offering a comprehensive, data-driven solution to modern renovation challenges. In this sense, the DBT represents a transformative system for managing buildings across various dimensions, including those that have been part of this doctoral thesis—acoustic analysis, real-time building control, and automated diagnostics for renovation. The research done in this thesis represents an important step toward the integration of BIM technology with DBTs, offering a path for ongoing improvements in energy efficiency, sustainability, and building renovation practices. By integrating BIM technology, BACN, and ML techniques, connected through open standards such as IFC, DBTs offer a comprehensive and automated approach to addressing the complexities of modern building management and renovation workflows. This progress will be essential for the future of sustainable and smart buildings.

6.4. Limitations and future research lines

The research conducted in this thesis, focused on the integration of advanced digital technologies into the renovation process using BIM as the central framework, has identified certain limitations and opportunities for further exploration. These findings open avenues for future research and development in building renovation workflows.

Tool Flexibility and Parameter Adaptation

The tools and methodologies developed in this research work, while effective, face limitations due to fixed assumptions and predefined parameters, which limits their adaptability to diverse building scenarios. For instance, in ***paper 2***, the IFC4Acoustic parser uses some fixed inputs, such as district land use category and room façade shape, while the BACN2BIM tool in ***paper 3*** assumes standardised sensor placements at a fixed height and only on walls without openings. While functional, this method may fail in certain scenarios where suitable wall surfaces are unavailable. These constraints reduce the tools' ability to handle more complex configurations or scenarios. Future work should focus on enhancing the adaptability of these tools by minimising reliance on fixed parameters and introducing more flexible algorithms for processing diverse building configurations. In the case of BACN2BIM, future versions should refine these placement rules to allow sensors to avoid openings while ensuring accurate positioning for reliable indoor measurements, such as those required for IEQ monitoring. For the thermal diagnostics tool, in ***paper 1***, future iterations will incorporate the calculation of thermal bridges, which were not explicitly addressed in this research. These heat losses, which can be significant depending on the construction type, were compensated for in this study by using the extended volume of the second-level space boundaries for the thermal volume. These boundaries, as represented in the IFC geometry of the used case studies, extend beyond the actual space reaching halfway into adjoining walls and including half the slab height. This expanded exchange area compensates, at least partially, for thermal bridging losses not directly considered in this research.

Interoperability and Data Validation

Interoperability remains a significant challenge in leveraging BIM for advanced renovation workflows. The use of open standards like IFC proved essential in achieving reliable and scalable solutions. The tools developed as part of the three papers requires input IFC files to meet strict data quality standards. These constraints underscore the importance of improving interoperability between BIM models and external tools. Addressing this issue will require the development of automated mechanisms to validate input IFC data, ensuring compliance with the requirements of the tools. Additionally, updates to the IFC standard can be leveraged to enhance interoperability, enabling more effective integration between BIM models and performance evaluation tools.

Integration of Thermal diagnostic and Acoustic Simulations

While each methodology developed in this thesis addresses specific aspects of building performance, there is a need for more integrated approaches to evaluate multiple performance metrics, such as thermal and acoustic conditions, within a single framework. Combining the methodologies from ***paper 1*** and ***paper 2***, to integrate thermal diagnostics with acoustic analysis, would enable comprehensive evaluations of building performance, aligning with regulatory requirements. The application of AI and ML techniques, as demonstrated in ***paper 1***, could further enhance automation and optimise combined simulations, considering also the acoustic performance.

Towards Digital Building Twins

The potential of BIM extends beyond the renovation phase of a building. These models can also play a crucial role during the Operation and Maintenance stage [191]. By developing DBTs from BIM models, it is possible to optimise building performance and enhance energy efficiency through more effective monitoring and control strategies, provide real-time feedback, and support predictive maintenance [192, 193, 194]. In line with this, I have started connecting the research from this doctoral thesis to the development of a digital building twin BIM-based aimed at monitoring and optimising the energy performance of non-residential historical buildings. I am leading this initiative as part of the SMARTeeSTORY project (Integrated, interoperable, smart and user-centred building automation and control system for better energy performance of non-residential historic buildings coupling physics & data-based approaches) [195], a European research project funded under the Horizon Europe Programme.

In addition, I have involved in future research to explore the role of DBTs in supporting the circularity of building materials and the development of innovative documentation systems. These include the creation of Material Passports [71, 72], which provide detailed information about the materials used in construction, and Buildings' Digital Logbooks [196], which serve as comprehensive records of a building's lifecycle, including maintenance, updates, and material reuse potential. These tools represent a new paradigm in building lifecycle management, promoting sustainability and circularity, particularly in the maintenance and end-of-life phases of buildings. Such advancements not only align with the objectives of decarbonisation and energy efficiency but also support the transition to a more sustainable construction sector by addressing material reuse and lifecycle documentation challenges.

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Abbreviations

AEC Architectural, Engineering and Construction

AI Artificial Intelligence

ANFIS Adaptive Neuro-Fuzzy Inference System

API Application Programming Interface

BACN Building Automation and Control Network

BAS Building Automation System

BEM Building Energy Model

BEP Building Execution Plan

BEPS Building Energy Performance Simulation

BIM Building Information Modelling

C# C Sharp (programming language)

CSV Comma-Separated Values

dB Decibels

DBL Digital Building Twins

EeB Energy-Efficient Buildings

EIR Exchange information Requirements

EPBD Energy Performance of Buildings Directive

EPS Expanded Polystyrene

ETICS External Thermal Insulation Composite System

ETL Extract Transform and Load

FM Facility Management

gbXML green building XML schema

GEI *gases de efecto invernadero*

GHG greenhouse gas

GUID Global Unique Identifier

HVAC	Heating, Ventilation and Air Conditioning
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LTRS	Long-Term Renovation Strategies
MEP	Mechanical, Electrical, Plumbing
ML	Machine Learning
MVD	Model View Definition
nZEB	nearly Zero-Energy Buildings
OGC	Open Geospatial Consortium
O&M	Operational & Maintenance
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
Pset	Property Set
RDF	Resource Description Framework
RES	Renewable Energy Source
RT	Reverberation Time
SHAP	SHapley Additive explanation
SPL	Sound Pressure Level
TRL	Technology Readiness Level
XML	eXtensible Markup Language

List of Symbols and Units

Symbol	Definition	Unit
A_0	Reference equivalent sound absorption area equal to 10 m^2	[m^2]
ΔL_{fs}	Level difference due to façade shape	[dB]
$D_{2m,nT,w}$	Weighted standardized sound level difference of façade	[dB]
K or K_{AVE}	Global heat transfer coefficient of the building envelope	[W/(m²·K)]
R-value	Thermal resistance of a material layer.	[(m²·K)/W]
R'_w	Façade sound reduction index	[dB]
R'_{wi}	Sound reduction index of the element (*i*)	[dB]
$L_{A,eq}$	Indoor A-weighted equivalent continuous sound pressure level	[dB(A)]
$L_{1,2m}$	Average sound pressure level at 2 meters in front of the room façade	[dB]
S	Total area of the façade facing the inner part touching the room	[m^2]
S_i	Area of the element (*i*) of the façade	[m^2]
S_{open}	Area of the small elements	[m^2]
T_0	Reference reverberation time	[s]
U-value	Thermal transmittance of a building element.	[W/(m²·K)]
V	Volume	[m^3]
λ	Thermal conductivity	[W/(m·K)]

ANNEX A: Scientific publications & dissemination

Publications Impact Factor

- ***Paper 1:*** S. Mulero-Palencia, S. Álvarez-Díaz, and M. Andrés-Chicote, "Machine Learning for the Improvement of Deep Renovation Building Projects Using As-Built BIM Models," Sustainability. 2021, Vol. 13, Page 6576, vol. 13, no. 12, p. 6576, Jun. 2021, DOI: 10.3390/su13126576.

  Cited 31 times as of 9 July 2025, according to Scopus, which demonstrates its impact and relevance within the scientific community.

SUSTAINABILITY Publisher: MDPI.

Journal Impact Factor ™ 2021 = 3.89 / Five Year (2020-2024) = 3.6

Journal Impact Factor Summary **2021**		
JCR Category	**Category Rank**	**Category Quartile**
ENVIRONMENTAL SCIENCES in SCIE edition	133/279	Q2
ENVIRONMENTAL STUDIES in SSCI edition	57/128	Q2
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY in SCIE edition	35/47	Q3
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY in SSCI edition	7/9	Q4

- ***Paper 2:*** S. Álvarez-Díaz, S. Mulero-Palencia, M. Andrés-Chicote, and M. Martarelli, "An innovative approach to automate BIM data retrieval and processing for building acoustic comfort calculations based on the IFC standard," Building and Environment, vol. 266, p. 112072, Dec. 2024, DOI: 10.1016/J.BUILDENV.2024.112072.

  According to SCOPUS, ***paper 2*** had received one citation as of 9 July 2025, likely reflecting its recent publication.

BUILDING AND ENVIRONMENT Publisher: PERGAMON-ELSEVIER SCIENCE LTD
Journal Impact Factor ™ 2024 = 7.6 / Five Year (2020-2024) = 7.9

Journal Impact Factor Summary **2024**		
JCR Category	**Category Rank**	**Category Quartile**
CONSTRUCTION & BUILDING TECHNOLOGY in SCIE edition	9/95	Q1
ENGINEERING, CIVIL in SCIE edition	9/183	Q1
ENGINEERING, ENVIRONMENTAL in SCIE edition	16/83	Q1

- ***Paper 3:*** R. Sanz-Jimeno and S. Álvarez-Díaz, "A tool based on the industry foundation classes standard for dynamic data collection and automatic generation of building automation control networks," J. Building Engineering, vol. 78, p. 107625, Nov. 2023, DOI: 10.1016/J.JOBE.2023.107625.

  According to SCOPUS, ***paper 3*** had received four citations as of 9 July 2025, indicating early recognition of its contribution.

JOURNAL OF BUILDING ENGINEERING Publisher: ELSEVIER.
Journal Impact Factor ™ 2023 = 6.7 / Five Year (2020-2024) = 7.5

Journal Impact Factor Summary **2023**		
JCR Category	**Category Rank**	**Category Quartile**
CONSTRUCTION & BUILDING TECHNOLOGY in SCIE edition	8/92	Q1
ENGINEERING, CIVIL in SCIE edition	9/182	Q1

Other publications in peer review process

- S. Álvarez-Díaz, M. Regidor-Sánchez, M. Andrés-Chicote "An innovative BIM-to-BEPS conversion process for automated generation of building energy models based on the Industry Foundation Classes Standard."

  This manuscript is currently under preparation to be submitted to the journal of *Energy and Buildings*.

Publications in international conferences

- Redmond AM, Álvarez-Díaz S, Pastorelly N., "Investigating the Conditions of Emerging Requirements of Advanced Technologies for BIM-SPEED Platform," in *Proceedings of the MODERN SYSTEMS 2022 : International Conference of Modern Systems Engineering Solutions*, Jul. 2022, pp. 1–7. Available: https://www.thinkmind.org/index.php?view=article&articleid=modern_systems_2022_1_10_10004

- Álvarez-Díaz S, Román-Cembranos J, Lukaszewska A, Dymarski P., "3D modelling of existing asset based on point clouds: A comparison of Scan2BIM approaches," in *2022 IEEE International Workshop on Metrology for Living Environment (MetroLivEn)*, May 2022, pp. 274–279, DOI: 10.1109/MetroLivEnv54405.2022.9826964

- Antolín-Gutiérrez J, Álvarez-Díaz S, Samaniego-Muñoz J., "Energy efficiency for a historic market: the case study of the Mercado del Val," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 863, no. 1, p. 012037, Oct. 2021, DOI: 10.1088/1755-1315/863/1/012037

- Antolín Gutiérrez J, Álvarez Díaz S, Hidalgo Barrio MD, Castro Bustamante J, "Proyecto Houseful: soluciones y servicios circulares innovadores para nuevas oportunidades de negocio en el sector de la vivienda de la Unión Europea," in VI Congreso Edificios Energía Casi Nula, 2019, pp. 266–271. Available: https://www.construible.es/comunicaciones/comunicacion-proyecto-houseful-soluciones-servicios-circulares-innovadores-nuevas-oportunidades-negocio-sector-vivienda-union-europea

Other dissemination

- Speaker at the international conference *Sustainable Places 2022*, as part of the final conference of the BIM-SPEED project, with the presentation "Innovative BIM tools for Building Renovation: 3DASH tool", 6-9th Sep 2022, Nice, France.

- Speaker at the international conference *2022 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv)*, 25-27th May 2022, Cosenza, Italy.

- Participation as instructor of the *CBIM PhD School on BIM-based Sensing and Data Collection* from the Cloud BIM European Training Network [197], in the session "Practical Exercise: Operational Data Collection and Management", 24-26th May 2021, Valladolid, Spain.

- Member of the Scientific Committee of the international Congress *SBE21 Sustainable Built Heritage*, 14-16th April 2021 Bolzano, Italy.

- Speaker at the conference CONAMA 2020: *Congreso Nacional de Medio Ambiente* in the session "Circular economy in construction: The possibilities of digitalisation to overcome barriers", 3rd June 2020, Madrid, Spain.

Blog articles

During the development of this thesis, I have also contributed by authoring blog articles focused on the application of BIM in renovation projects and the concept of DBTs:

- (2023) BIM for renovation? [198]
- (2022) From Apollo 13 to the Digital Building Twins [199]

ANNEX B: International Mention

This thesis opts for the 'International Doctorate' mention in accordance with Royal Decree 99/2011 of 28 January, as modified by Royal Decree 576/2023, by fulfilling the requirements of Article 15.1, and the Regulation of Doctoral Studies of the University of Valladolid. This includes completing one or more research stays abroad, totalling at least three months, to enhance the candidate's research training. The candidate completed an international research stay at the *Technische Universität Berlin*, in Berlin, Germany, for three months, from 15 September 2021 to 15 December 2021. The stay was supervised by Professor Timo Hartmann in the Civil and Building Systems Department, Institute for Civil Engineering.

One of the scientific articles included in this thesis resulted from work initiated by the candidate during her research stay, which was later continued and culminated in a high-impact publication. A special mention was made in the acknowledgements to the supervisor of the stay, and to the funding provided by the University of Valladolid through a mobility grant:

- S. Álvarez-Díaz, S. Mulero-Palencia, M. Andrés-Chicote, and M. Martarelli, “An innovative approach to automate BIM data retrieval and processing for building acoustic comfort calculations based on the IFC standard,” Build. Environ., vol. 266, p. 112072, Dec. 2024, DOI: 10.1016/J.BUILDENV.2024.112072.

ANNEX C: Grants and Awards

Grants

- **Short Research Stay:** Awarded a mobility grant for short research stays in the development of doctoral theses for the year 2021, granted by the Vice-Rectorate for Research, Innovation and Transfer of the University of Valladolid, under the programme *MOVILIDAD DOCTORANDOS Y DOCTORANDAS UVa 2021*.

- **Erasmus+ Mobility for Traineeships:** Awarded financial support from the Erasmus+ Mobility for Traineeships Call, for the academic year 2021-2022, granted by the Vice-Rectorate for Internationalisation of the University of Valladolid on 27 May 2021.

- **Excellence Scholarship:** Awarded the Excellence Scholarship, intended for students of the University of Valladolid, for the academic year 2021-2022, granted by the Vice-Rectorate for Internationalisation of the University of Valladolid.

Awards for Scientific Publications

- **Best Paper Award:** Award at the International Conference of Modern Systems Engineering Solutions 2022, Nice, France, July 2022, for the paper "**Investigating the Conditions of Emerging Requirements of Advanced Technologies for BIM-SPEED Platform**" [49]. The award recognises the paper as one of the best at the conference, considering the reviews of the original submission, the final version of the paper, and its presentation during the conference.

- **Best Paper Presented by a Woman:** Award at the IEEE International Workshop on Metrology for Living Environment (MetroLivEn) 2022, Cosenza, Italy, May 2022, for the paper **"3D modelling of existing asset based on point clouds: A comparison of Scan2BIM approaches"** [157]. The award recognises the best paper written and presented by a woman, based on technical merit, originality, and the quality of the presentation during the conference.