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Article

Practices of BIM-Enabled Assessment of Politehnica University Timisoara Building Stock for a More Sustainable Future

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Abstract: The aim of the paper is to identify energy inefficiencies and to propose energy-saving solutions to reduce the carbon footprint of the structures, considering Building Information Modelling—Existing Conditions Model as an enabling tool. The initiative underscores the role of Building Information Modelling—Existing Conditions Model in facilitating data-driven strategies for improving energy efficiency, highlighting its potential to transform the infrastructure and built environment into a paradigm of responsible energy consumption. In this context, the paper presents a comprehensive assessment of the thermal performance of student accommodations using advanced technologies, such as Unmanned Aerial Systems and Terrestrial Laser Scanners equipped with thermal cameras. The findings illustrate potential areas for improvements in thermal efficiency, offering a roadmap for targeted interventions to enhance the energy performance of buildings. The results of the study not only advance the green campus at Politehnica University Timisoara (Romania), but also serve as an educational model that demonstrates the integration of technology to promote sustainability in the built environment.

Keywords: building information modelling; existing condition modelling; unmanned aerial systems; terrestrial laser scanning; thermal imaging; sustainable energy consumption; Scan2BIM process

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1. Introduction

The building sector is a major consumer of energy globally, accounting for a significant portion of total energy consumption and greenhouse gas emissions. Therefore, there is substantial potential for energy savings. Research [1] indicates that the adoption of energy-efficient designs and technologies in buildings can yield significant reductions in energy consumption.

Currently, techniques and methods based on Non-Destructive Testing (NDT) in the inspection of buildings to assess their energy aspects and performance are becoming increasingly popular [2].

The integration of UAVs (Unmanned Aerial Vehicles) with sensors, thermal mapping, and the creation of a BIM model is an advanced technique used in the construction and building management sector. This methodology combines different technologies to obtain a detailed and comprehensive survey, useful for multiple applications, including energy efficiency and building maintenance [3].

In fact, the data collected by the thermal sensors equipped on the UAVs can be integrated within a BIM model, which digitally represents the building in 3D, with all its physical and functional characteristics. In this way, it will be possible to manage and interrogate all the thermographic information, making it possible to visualise and analyse energy issues in an accurate spatial context, as well as plan energy improvement interventions, monitor the effectiveness of the solutions adopted, and manage the building's maintenance more efficiently. In this context, the authors of [4] utilised aerial imagery sourced from a UAV to construct a geometric model of a residential building in Suzhou, China, which supports energy assessment efforts. While specialised software is capable of converting images into a detailed 3D representation, the lack of semantic information limits its functionality beyond visualisation purposes. In the same manner, the authors of [5] presented a method for integrating building data obtained by photogrammetry and thermography into the BIM environment, using only a UAS.

In addition to UAV devices, the integration of TLS with thermal sensors represents a powerful technology to perform detailed and accurate thermal surveys, improving the diagnosis, maintenance, and management of building structures. Indeed, Terrestrial Laser Scanners (TLS) are advanced tools that are mainly used to survey the geometry of buildings and structures with high accuracy. However, when combined with thermal imaging cameras or thermal sensors, they can also be used to perform thermal surveys. This combination makes it possible to integrate detailed geometric data with thermal information, providing a complete picture of the state of a building or structure. This is proven by the authors of [6], who analysed the use of point clouds from extended intensity mobile laser scans extracted from thermal infrared (TIR) image sequences. Thermal point clouds are projected onto the façades using a mapping algorithm that uses a neighbour search to find an optimal point while preserving the original temperature values.

BIM contributes significantly to energy efficiency and thermographic analysis by integrating thermal data and simulations into the digital building model. It makes it possible to visualise thermal anomalies, perform energy simulations, optimise design and manage predictive maintenance across its entire lifecycle, encompassing design, construction, operation, and demolition phases. Consequently, the management of geometric and thermal information is an efficient method of information management. Indeed, the authors of [7] discussed how to interface a Building Information Modelling (BIM) tool and simulation software to determine the potential influence of phase-change materials on the design of zero-energy homes.

Thus, issues related to digital management with modern active and passive sensors, as well as aspects of thermal data management within BIM models, respond to sustainability approaches included in the 2030 Agenda goals. Therefore, this research paper focuses on a case study in Romania within a project of high scientific value aiming at the improvement of energy efficiency in buildings of the Politehnica University Timisoara.

The study investigates the identification of energy inefficiencies and proposes energy-saving solutions for reducing the carbon footprint of existing structures. By the methodology starting from the data collection process to the future utilisation of Building Information Modelling—Existing Conditions Model (BIM-ECM) as a foundational tool, the research specifically addresses the challenge of inadequate energy performance data in legacy buildings. Through BIM-ECM-based simulations, discrepancies between design parameters and actual operational energy consumption, subsequently exploring and recommending retrofitting strategies, optimised building management systems, and renewable energy integration to achieve quantifiable carbon emission reductions and enhance overall building sustainability can be realised.

Initially, we frame the necessity of this study within the context of ongoing projects funded by European grants, which focus on the sustainability and rehabilitation of buildings constructed in the 1970s–1980s. Subsequently, we propose a working methodology developed by the authors, which includes field data collection using modern and distinct methods and models, processing and interpretation of the obtained data, as well as their preparation for future integration into Building Information Modelling (BIM) for thermal evaluation of the studied buildings.

2. Contribution of the USE-REC Project in the Sustainability Objectives of the United Nations' Agenda 2030

The "University Students Engaging in Responsible and Sustainable Energy Consumption—USE-REC" initiative [8] represents a strategic push for the promotion of responsible and sustainable energy practices. The initiative is distinguished by its holistic approach to cultivate a culture of energy consciousness among students at Politehnica University Timisoara. The essence of USE-REC is to combine energy efficiency improvements in student accommodations with participatory student initiatives, thus generating a collective commitment to sustainability. The aim of the project is to encourage the mobilisation of students to promote energy-efficient behaviours to lead community change and contribute significantly to global efforts to reduce greenhouse gas emissions.

In line with Politehnica University's broader sustainability objectives, which echo the United Nations' Agenda 2030 [9], the project emphasises an integrative approach to sustainability that spans education, research, governance, and everyday campus life. It prepares students for autonomous living in an era that demands judicious resource utilisation and upholds the principles of intergenerational and intragenerational equity. On the other hand, the increasing imperative to mitigate anthropogenic climate change and reduce energy consumption has driven a significant trend towards the integration of bio-architectural principles and ecologically sustainable design methodologies within urban and building construction paradigms [10]. Therefore, having the student's dormitory according to new EU recommendations and regulations can be a good practice example for the next generations of engineers.

Implementing this project within the university's dormitories marks a pivotal advance toward establishing a green campus ethos in Timișoara, demonstrating a deep-rooted commitment to environmental stewardship and sustainable development that resonates with the values and aspirations of the students.

The projects' key objectives are to:

i. Identify energy losses,
ii. propose solutions for energy efficiency, and
iii. reduce the carbon footprint of student accommodations from the Politehnica University Timișoara.

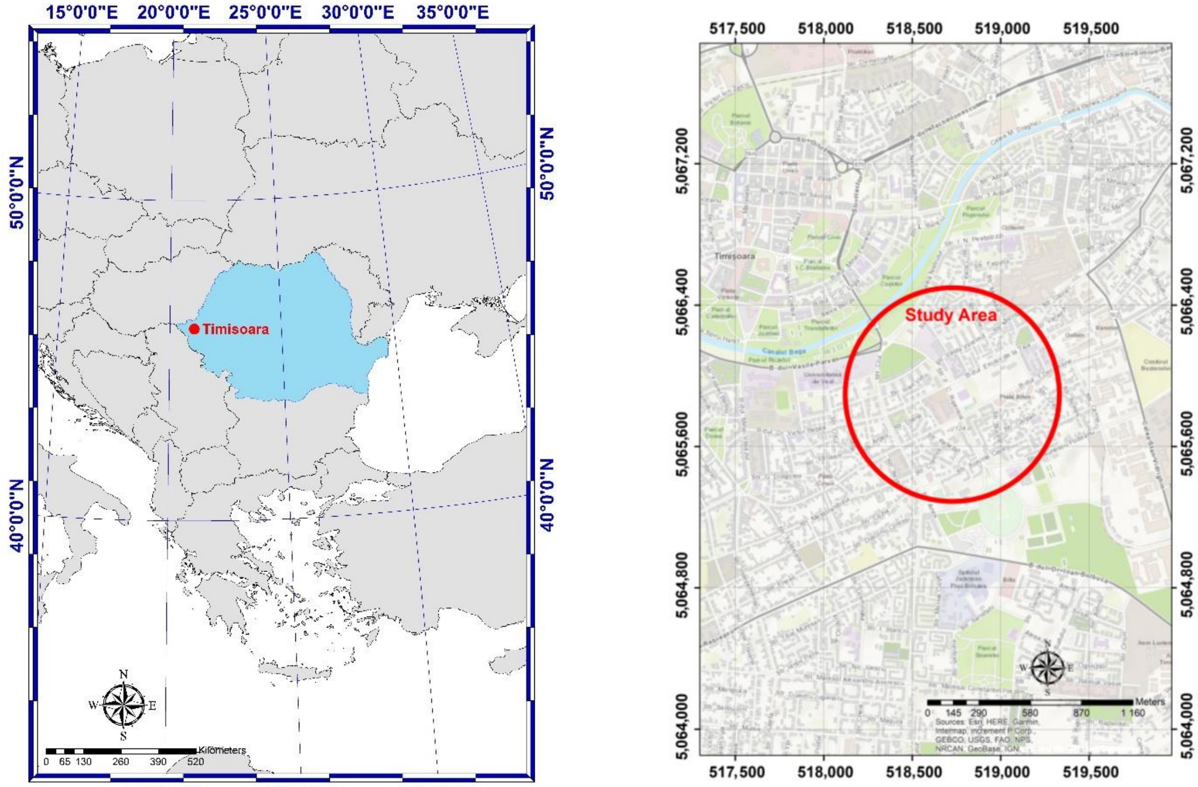
By using two methods for data collection (methods that represent in themselves two technologies and two approaches), an innovative character is given to the workflow. The thermography method facilitates a rapid and comprehensive quantitative assessment of building envelope thermal performance through the acquisition of temporally synchronised infrared image datasets, offering a significant improvement in efficiency compared to traditional walkthrough inspection techniques [11].

Using BIM-ECM, the program aims to implement innovative strategies to collect and analyse data on students' energy consumption within the university campus. These data will form the foundation for developing educational initiatives and practical solutions to reduce the university community's energy footprint. Developing a BIM for existing conditions can be approached in multiple ways and tailored to the project. Once the model is constructed, it can be accessed for various information, facilitating strategic planning for new construction or projects. This BIM application can contribute significantly to identifying energy inefficiencies and defining targeted interventions, thus extending the principles of responsible and sustainable energy consumption to the realm of infrastructure and the built environment.

3. Data and Method

3.1. Study Area

The study area consists of four buildings, used as dormitories, in the Politehnica University complex in Timișoara. The student campus is illustrated in Figure 1.



(**a**) (**b**)

Figure 1. Location (**a**) and area of interest of Politehnica University Timisoara, Student Campus (**b**).

The dormitories are located in close proximity to the Politehnica University campus, making it easy for students to reach their classes and university facilities. The dormitories typically consist of multi-storey residential buildings that vary in size and design; C2-C7 four-level buildings; C19-C22 six-levels (Figure 2). The buildings were constructed during 1975–1980, primarily using reinforced concrete, brick, and other durable materials suitable for long-term residential use. Most dormitories range from two to four people per room, depending on the specific building. All dormitories are connected to a central heating system, ensuring a comfortable temperature during the cold months. Natural ventilation is commonly used in these buildings, with windows that allow fresh air circulation. In some cases, mechanical ventilation systems may also be present. A continuous supply of electricity and water is provided, with regular maintenance checks to avoid any interruptions. Additionally, waste disposal units are placed on each floor, with regular collection and recycling services in place.

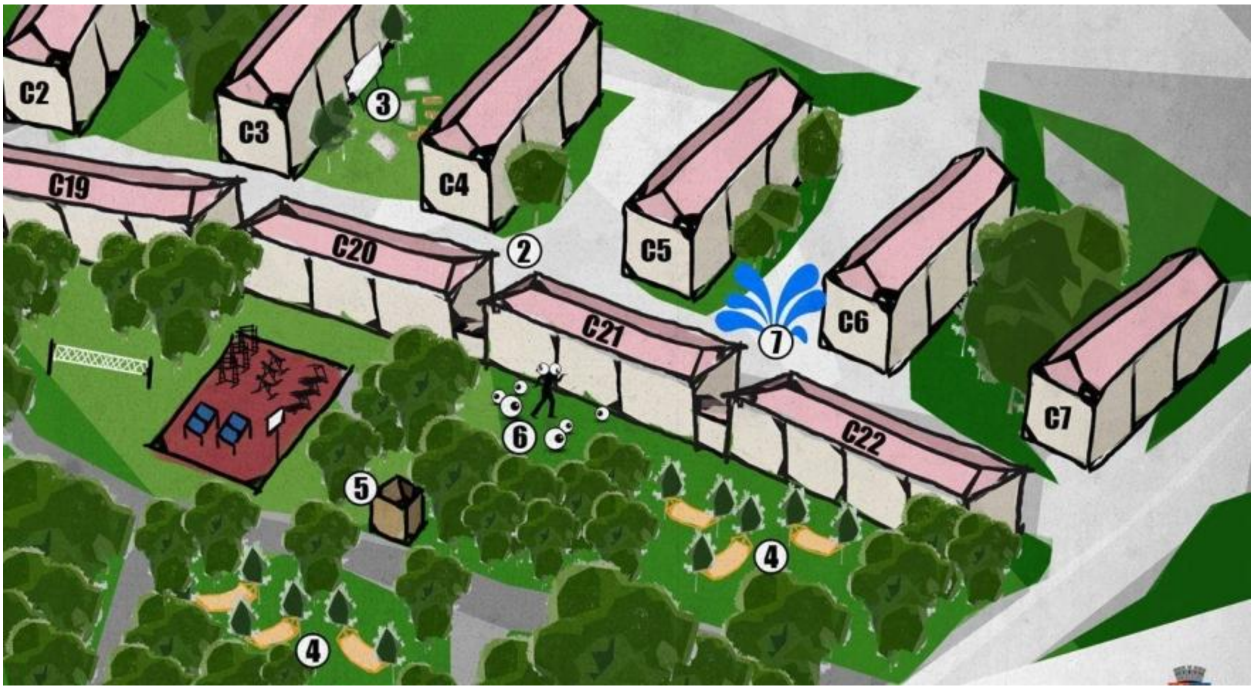


Figure 2. Layout of the dormitories (C2–C7 four-level buildings; C19–C22 six-levels buildings; 2—sidewalk, 3–7 relaxation areas).

In Romania, the study of heat loss through thermography is in a developmental phase, with a significant increase in interest and applications across various domains. Therefore, best practice case studies for a student campus area with buildings constructed in the 1970s are essential for large-scale studies.

3.2. Workflow of the Developed Methodology

The workflow developed can be summarised as shown in Figure 3. Workflow of the developed methodology.

The methodology that we proposed implied data collection, which included the geometric survey (TLS, ALS, UAS, etc.), thermal survey, sensors and platform; data processing of both thermal and geometric data collected on field, project and management planning in order to prepare an output and the BIM requirements for ECM.

Figure 4 shows the line of work that can be implemented in order to obtain 3D models capable of representing the geometric and energy aspects of buildings.

3.2.1. Data Collection

To obtain the 3D geometry of buildings, it is necessary to acquire data using techniques and methods, such as laser scanning (LiDAR) [12], photogrammetry, traditional surveying methods (total stations, inclinometers and levels), and GPS/GNSS surveying.

At this stage, it is necessary to define the target data to be obtained and the relevant study area, paying greater attention to the level of detail and precision required. Furthermore, it is necessary to determine the appropriate sensors according to the type of data needed and subsequently integrate them into a coherent dataset.

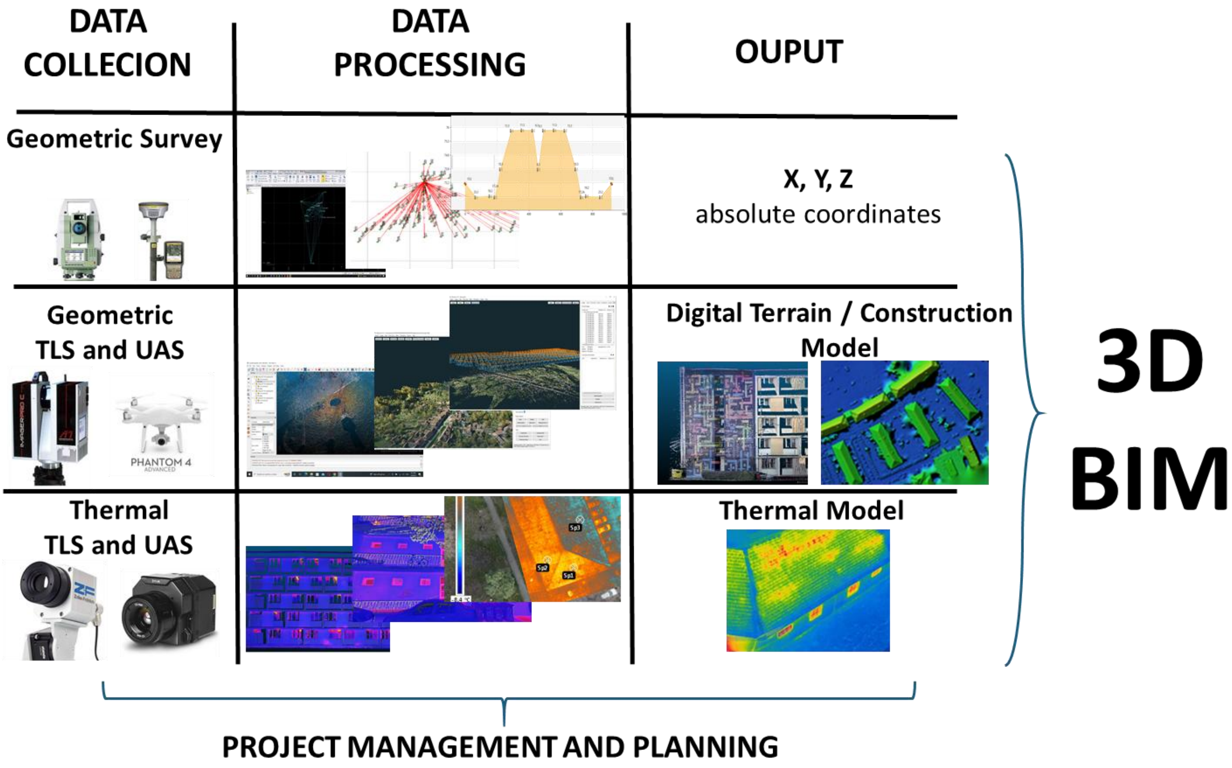


Figure 3. Workflow of the developed methodology.

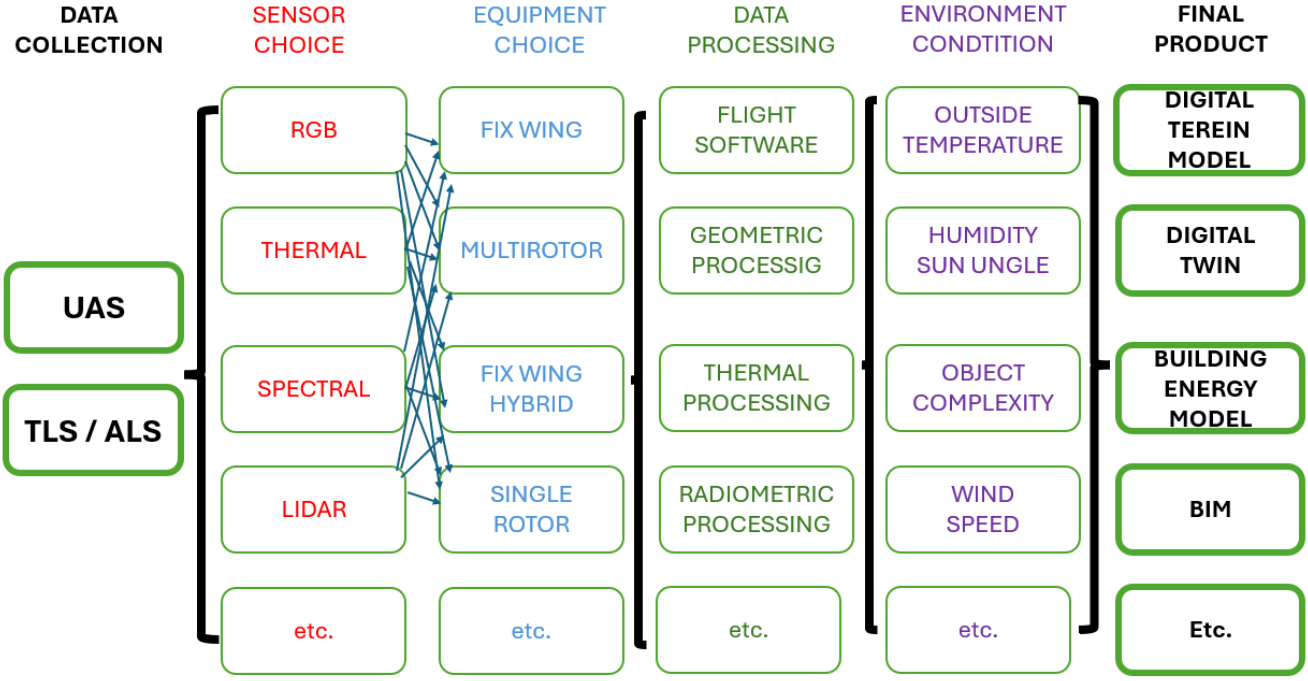


Figure 4. The influence of different UAS and TLS factors in determining the energy characteristics of a building.

Another important aspect is represented by environmental conditions starting with the temperature of the external environment, the radiance, the complexity of the model and the morphology of the land. All these aspects must be taken into account in the study design.

3.2.2. Data Processing

The constituent materials of building envelopes and structural elements exhibit dynamic responses to fluctuations in environmental parameters, including ambient temperature and humidity. Consequently, longitudinal analysis of three-dimensional thermal point cloud data offers a robust methodology for the identification and mitigation of material degradation, while simultaneously enabling the optimization of building energy efficiency [13].

Following established protocols [14], thermographic data acquisition was conducted pre-sunrise to minimize solar radiative heating. To ensure data integrity, the infrared camera was orthogonally aligned with the target façade and calibrated, with a 50% overlap between sequential thermograms. Post-acquisition, environmental parameters (ambient temperature, humidity) and contact temperature measurements at discrete façade locations were recorded to facilitate calibration and validation of the thermographic data [15].

The thermal images were then orthorectified in order to be applied to the 3D digital model using the projective transformation. This type of transformation introduces two plane coordinate systems using a central projection. All projection rays are straight lines passing through the centre of the perspective; the equations that allow this type of projection are as follows: [16,17]

$$x = \frac{a_1 x' + a_2 y' + a_3}{c_1 x' + c_2 y' + 1} y = \frac{b_1 x' + b_2 y' + b_3}{c_1 x' + c_2 y' + 1} \tag{1}$$

where:

- x, y coordinates of thermal original images;
- x', y' coordinates of rectificated thermal images in a local frame;
- a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2 projective parameters.

3.2.3. Project and Management Planning

Project planning is a multi-faceted process that starts with the establishment of clear objectives, i.e., identifying energy losses, proposing energy efficiency solutions, and reducing the carbon footprint of the university's dormitories. The successful development of these objectives is supported by the deployment of up-to-date technologies (e.g., Unmanned Aerial Systems (UAS) with thermal cameras, GNSS receivers, and Terrestrial Laser Scanners), which enables reliable thermal performance assessment. The planning phase also includes designing educational and participatory activities to engage students in sustainable energy practices, seamlessly blending technical interventions with community involvement.

Project management activities ensure the coordination of various tasks, from the technical assessment of building stock to the implementation of energy-saving measures and the support of student engagement initiatives. This involves scheduling, resource allocation, budgeting, and continuous monitoring to ensure that project milestones are met, goals are achieved, and resources are utilised efficiently. A critical aspect of project management is to obtain the necessary permits for drone surveys and comply with the regulations set by the European Union Aviation Safety Agency (EASA). Addressing potential risks and challenges that range from technical hurdles in data collection, equipment functionality and data accuracy to the variability of environmental conditions affecting thermal assessments, the project team employed a proactive approach to risk management, identifying potential risks, assessing their impact, and developing contingency plans to mitigate them.

An important aspect that has to be considered is UAS legislation and regulations. Familiarity with local UAS regulations and restrictions is the first consideration for any UAS application. Three key issues encapsulated in most UAS regulations include the following [18]: (1) the regulated use of airspace by UAS; (2) the imposition of operational limitations; (3) addressing procedures for the administration of flight permissions, pilot licenses and data collection authorisation [19].

The integration of Unmanned Aerial System (UAS)-derived thermal imagery of building façades into Building Information Models (BIM) offers significant potential for enhanced building energy audits. However, the accurate spatial registration of these images within the BIM environment is impeded by inherent characteristics such as low textural complexity and high geometric distortion [3,20].

Additionally, in both the United States and Europe, various standards and guidelines promote energy-efficient building rehabilitation. In the U.S., standards like ASHRAE 90.1 set the baseline for energy-efficient design, while programs like LEED encourage sustainable building practices. European standards, such as the Energy Performance of Buildings Directive (EPBD), mandate energy performance requirements for new and existing buildings, driving renovation efforts across the continent. Moreover, in the context of digitalisation within the EU, the University, as a public institution, must in the future adopt and standardise domains such as its heritage, taking into account ISO 19650-2019, which refers to the organisation and digitisation of information about buildings and civil engineering works, including Building Information Modelling (BIM).

Asset Information Models (AIM) and Project Information Models (PIM) are structured databases that centralise critical decision-making information throughout the lifecycle of a construction asset. These models encompass the design and construction phases of new assets, as well as the rehabilitation of existing ones, plus the operation and maintenance of assets. An expansion in the volume and diversity of information stored in these information models is anticipated, which will be increasingly used, especially in the project completion and asset management phases.

Figure 5 presents the information requirements hierarchy for a BIM-enabled project.

According to the recommendations presented in references [18,21], it is essential that the appointing party (e.g., the customer) understands exactly what asset and/or project-related information is required to achieve organisational and project objectives. Information requirements can come from both within the organisation and from external project stakeholders involved in the development, operation, and maintenance of the asset. The appointing party must be able to clearly communicate these requirements to all project stakeholders. It is important to mention that these principles apply in a proportionate manner (i.e., only provide the necessary information, at the required level of detail, to actors actively using the information). Additionally, appointed parties (i.e., general contractor and subcontractors) may introduce information requirements in addition to those defined by the employing party.

Existing Conditions Modelling (ECM) [22] is one of 50 specific Building Information Modelling (BIM) use cases defined by buildingSMART [23] with the goal of exchanging experiences from already implemented or ongoing BIM projects among experts. It refers to the development of a digital model that represents the existing conditions of a built asset and involves precise modelling and documentation of the current state of a building or infrastructure, prior to any intervention. The ECM case is very important for efficient planning and to avoid problems during project implementation. The resulting digital model provides a detailed reference for all parties involved in the project (customer, designer, contractor, etc.) and allows them to make informed decisions based on accurate field data.

Figure 6 presents the information requirements definition for a BIM-enabled ECM project.

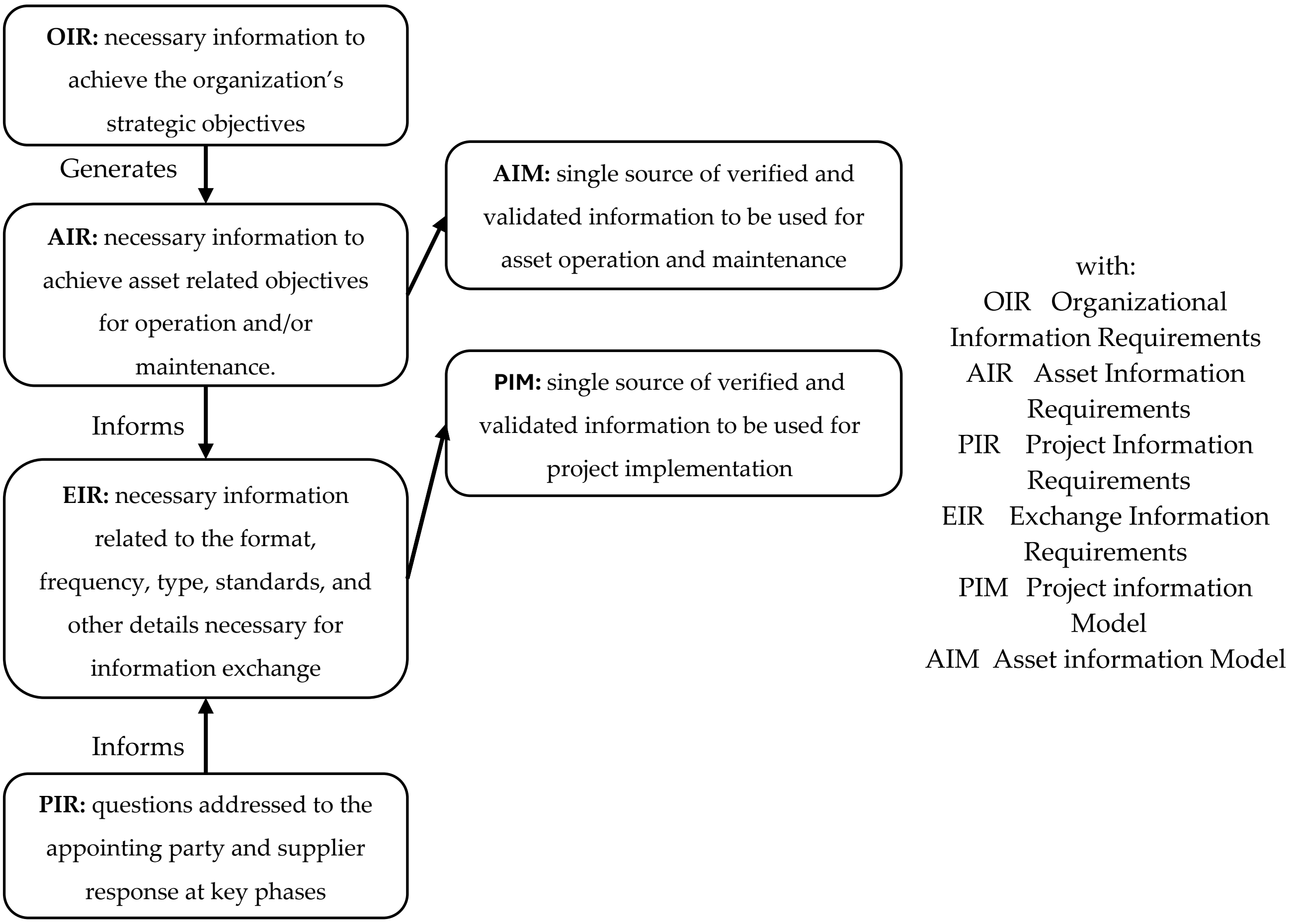


Figure 5. Information development process for a BIM-enabled project.

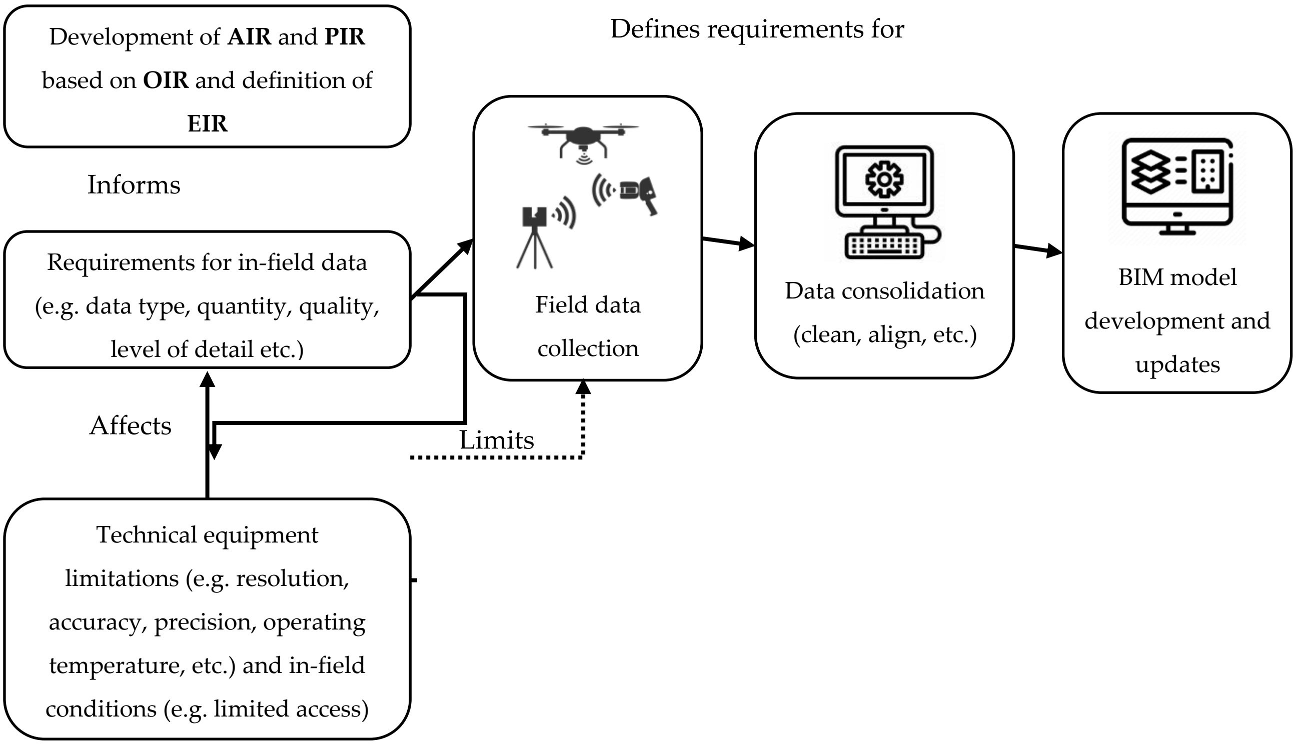


Figure 6. Information development process for a BIM-enabled ECM project.

The model development according to the requirements of the ECM use case includes three steps:

- In the first stage, data collection is achieved through technologies such as 3D laser scanning (TLS) and/or photogrammetry, where data about the conditions of the physical asset are collected. The result is an accurate digital representation that includes the structural elements, installations, finishes and other relevant characteristics of the asset in accordance with the defined requirements; for collecting data related to elements that are not visible (e.g., underground installations), GPR (Ground Penetration Radar) can be used.
- In the second stage, field data are consolidated and used to create a detailed BIM model (at the minimum agreed LoD—Level of Detail) that includes digital representations of all relevant components of the asset. This model constitutes the Project Information Model (PIM), a vital tool for consolidating information about the current state of the asset;
- In the third stage, the PIM is further augmented with detailed information (e.g., history of previous interventions, material testing results, technical expertise, etc.) reflecting the current state of the asset; within this step, the PIM consolidates as the single source of truth for the project.

In all subsequent steps, the ECM model is used by all project stakeholders (i.e., BIM specialists, architects, design engineers, project managers) to perform detailed analyses, identify potential problems and efficiently plan interventions, ensuring that they are carried out in a manner that minimizes risks and optimises resource use.

All stakeholders involved in the development and implementation of a BIM project contribute to the development of related documents. For instance, considering that the OIR is usually an internal document of the appointing party, its content is not discussed during the project initiation phase, but the requirements stemming from it directly influence the content of AIR and PIR. The content of AIR and PIR focuses on:

- The BIM model purpose and use (e.g., building geometry, location, orientation, envelope thermal characteristics) to support the assessment of building environmental impact (current and future), as well as architectural elements that may influence interventions (i.e., envelope thermal rehabilitation). The model will also be used for visualisation by all actors involved (including facility managers, engineers, architects and other associated consultants).
- The Level of Detail (LoD)/Level of Development (LOD) [24] shall be sufficiently high to allow assessment of the current state and support the project development of planned interventions. Furthermore, the model must provide a way to compare the digital model with the real building, allowing differences to be identified and quantified to facilitate the identification of areas that require special attention and subsequent intervention.
- The geometric model shall be accompanied by information (e.g., metainformation in the form of attributes, properties or additional details) and additional documentation from field data. Further information related to the modelling procedures used and any initial assumptions and limitations is also expected. The rationale for this information is to ensure transparency and facilitate model verification and validation.
- Scanning resolution and precision shall ensure a specific maximum relative error for the point clouds (e.g., below 10 mm) to ensure an accurate representation of the existing structure.

In addition to AIR and PIR, the EIR document contains information related to the interoperability of data within the project, which shall be compatible with modelling software and simulation programmes, as well as with other tools used by the specialists involved in the project (architecture, building services, etc.) to enable efficient exchange of information and collaboration between different project actors.

4. Experimentation on the Case Study

4.1. Data Collection: Project Planning and Equipment

In particular, a Total Station Leica TCR 1205 R400 (manufactured by Leica Geosystems AG—Part of Hexagon, Heerbrugg, Switzerland) was used to reference the process; this T.S. is characterised by an angular accuracy of 5″ (1.5 mgon) and a distance measurement accuracy of 1 mm + 1.5 ppm under standard conditions.

For georeferencing processes, a multi-band RTK GNSS receiver module, the South GALAXY G7 (manufactured by South Surveying & Mapping Technology Co., Ltd., Guangzhou, China), was used, with centimetre accuracy.

API Imager Pro C (manufactured by Zoller + Fröhlich GmbH (Z+F)—Baden-Württemberg, Wangen im Allgäu, Germany) with added thermal camera was used. Specifically, the maximum scanning distance is 180 m with an angular accuracy (horizontal/vertical) less than 0.007° and point acquisition speed more than 1,000,000 points/s.

The resolution of the equipped thermal camera is 382 × 288 pixels with an infrared spectrum between 7.5 and 13 µm and 32 images for a complete panorama (four rows) with 2500 pixels/360°.

In addition, a UAS equipped with an RGB camera and a thermal camera was used.

Specifically, the thermal camera has a resolution of 640 × 512 with a Sensor Technology Uncooled VOx Microbolometer, Lens (manufactured by FLIR Systems, Inc.—Wilsonville, OR, USA) (FOV for Full-Sensor Output) of 13 mm; 45° × 37°, spectral band between 7.5 and 13.5 µm and measurement accuracy of ±5 °C or 5%.

4.2. Experiments and Equipment

To assess the thermal efficiency of the students' accommodation, a suite of current technological equipment is used. The tools used within the process were meticulously selected to ensure the precision and reliability of data collection, paramount for a comprehensive analysis and the subsequent implementation of energy-efficient solutions. The equipment includes devices ranging from Unmanned Aerial Systems (UAS) with thermal imaging capabilities to ground-based Terrestrial Laser Scanners (TLS) and high-accuracy GPS receivers. Each piece of equipment plays an important role in capturing detailed thermal profiles and structural details of the buildings.

This equipment not only shows technical robustness, but also underlines the project's commitment to technical excellence in sustainable energy consumption and the creation of a green campus ethos.

In addition, the use of RGB cameras on UAS for building surveying offers a balance of detailed visual information, cost-effectiveness and versatility, making them indispensable tools in the field of remote sensing and aerial surveying. They capture images in the colour spectrum that are visible to the human eye, providing detailed and intuitive visual information, identification and assessment of the real-life condition of various structural elements, materials, and surfaces in buildings and surrounding infrastructure. In addition to RGB equipment, thermal cameras mounted on UAS offer a non-invasive, efficient and effective method for detecting thermal anomalies, facilitating the assessment, maintenance, and optimisation of building performance. These systems are instrumental in identifying heat losses and inefficiencies in buildings, pinpointing areas where insulation may be lacking, or where there are gaps in the building envelope. Furthermore, thermal imaging can reveal the presence of moisture (e.g., infiltrations or leaks) within a building's structure, as water has a different thermal signature than surrounding materials. Thermal cameras can help locate moisture intrusion, thus preventing mould growth and structural damage. By detecting temperature variations, thermal cameras can help identify structural problems that might not be visible to the naked eye (e.g., faulty insulation, thermal bridging, or hidden structural defects).

4.3. Surveyed Area and Considered Assets

Planning for a drone survey is crucial to ensure legal compliance, operational safety, and the collection of high-quality data. According to the European Union Aviation Safety Agency (EASA), different geographic zones (i.e., Excluded, Restricted and Facilitated geo-zones and U-Space airspace) have specific regulations that govern drone operations as follows [25]:

Excluded geo-zones (marked red) prohibit flights for operations in all or certain classes; hence, drone flying is not allowed.

- Restricted geo-zones (marked yellow) limit Unmanned Aerial System (UAS) operations which are subject to fulfilment of an imposed set of conditions, since these areas are usually near airports, heliports, national parks, military installations, hospitals, nuclear power plants or any kind of key industrial site.
- Facilitated geo-zones (marked green) rate UAS operations to 'Open', so drones can be flown without restrictions.
- U-Space airspace (marked blue) represents a portion of the lower space where operations are managed for drones and other vehicles that operate in it.

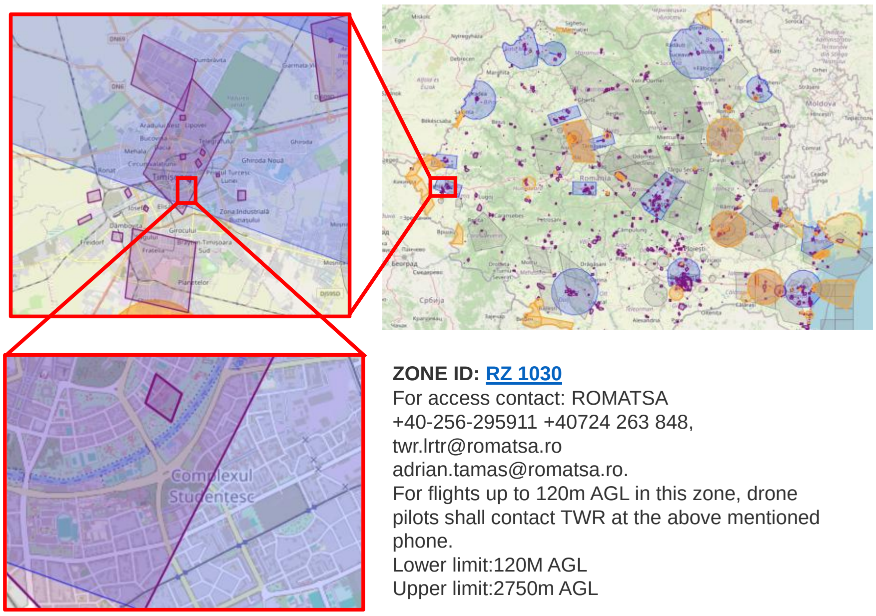
Securing the appropriate flight permit ensures that the drone survey adheres to local and national aviation regulations, preventing legal issues and potential fines. Additionally, flight planning helps identify potential hazards, ensuring the safety of both the drone and the surrounding environment. It allows operators to clearly define the survey's scope and objectives and ensure optimal flight paths for comprehensive data collection. Effective planning ultimately leads to more efficient operations, better data quality, and more reliable survey results, aligned with the project's goals and requirements.

The UAS (restricted and restrictable) geographical zones for Romania are available at the Romatsa Aeronautical Information Portal. Figure 7 displays UAS zones, with a detailed view of the area of interest valid from 1 February 2024. The regulation [26] issued on 24 May 2019 outlines the rules and procedures that govern the operation of UAS within the European Union (EU) airspace and dictate the rules that apply to all operators and remote pilots and are related to airworthiness, organisations, and personnel involved in UAS operations. Following these specifications, and based on the UAS flight area (Zone ID RZ 1030), the necessary flight permit was diligently obtained.

4.4. Photogrammetric and Scanning 3D Reconstruction

Preparing for a detailed building assessment involves setting up various technologies employed for the task (i.e., UAS, survey equipment (total station, GNSS receiver) and laser scanner). Each piece of equipment plays a paramount role in ensuring the accuracy and comprehensiveness of the data collected and, finally, project success.

A standardised thermographic data acquisition methodology was employed to minimise solar-induced thermal anomalies, limiting data collection to periods outside direct solar irradiance (pre-sunrise and post-sunset). The infrared camera, calibrated to a predetermined focal length, was positioned orthogonally to the façade at a distance of 15–20 m, commensurate with the desired spatial resolution. A minimum of 70% thermogram overlap was ensured to enable subsequent image processing and 3D reconstruction [27].



ZONE ID: RZ 3213
For access and aero
photogrammetry email to
aerofoto@mapn.ro
Lower limit:GND
Upper limit:120 m AGL

ZONE ID: RZ 1030
For access contact: ROMATSA
+40-256-295911 +40724 263 848,
twr.lrtr@romatsa.ro
adrian.tamas@romatsa.ro.
For flights up to 120m AGL in this zone, drone
pilots shall contact TWR at the above mentioned
phone.
Lower limit:120M AGL
Upper limit:2750m AGL

Figure 7. UAV flight areas in Romania (detail for Timisoara).

However, for the photogrammetric flight, a flight altitude of 100 m has been considered to be a balanced approach that enhances coverage and data acquisition efficiency, maintains a high level of detail, ensures safety and compliance, and accounts for environmental factors, making it an optimal choice for conducting comprehensive and effective assessments. At this altitude, the UAS can capture a wide area in a single frame, allowing for efficient data collection, enabling the assessment of large areas in a relatively short time. While higher altitudes provide broader coverage, 100 m represents a practical height that still ensures a good level of detail in the imagery, allowing for sufficient resolution to identify and assess building features. At the same time, flying at this altitude was considered to minimise risks associated with lower-altitude flights, such as potential collisions with buildings, trees, or other obstacles, thus reducing the likelihood of disturbing occupants or passers-by within the area. Flying at 100 m is also aligned with regulatory limits (falling below the 120 m limit) and ensures that the survey adheres to legal requirements while still achieving its objectives. In addition, at moderate altitudes like 100 m, UAS are more stable and less affected by wind gusts compared to flying at higher altitudes, which results in more consistent and reliable data collection.

When evaluating the model's accuracy, the height of the objects and the shutter area were taken into account. The experimental design employs simplified, idealised shading scenarios to elucidate the practitioner's methodology for quantifying the influence of obstruction amplitude on calculations pertaining to standardised building height assessments [28].

To enhance the precision, reliability, and utility of UAS mapping, it is essential to integrate georeferenced targets at the ground level, as they ensure that the captured data are not only visually representative but also spatially accurate and aligned with real-world coordinates. These targets, also known as Ground Control Points (GCPs) (Figure 8a) are specific, marked locations on the ground. Their coordinates were determined using high-accuracy GNSS equipment (Figure 8b). When UAS captures images from the air, georeferenced targets help to accurately align aerial data with real-world coordinates, improving the spatial accuracy of resulting maps or 3D models. The GCPs provide additional reference points that can be used to correct systematic errors in the UAS's positioning data (e.g., GPS inaccuracies, camera lens distortion, or UAV's flight instability). They are also useful for defining the aerial image scale, ensuring that measurements are precise and reliable. The inclusion of GCPs allows for a robust quality control process, where the accuracy of the UAS mapping can be validated by comparing the locations of the GCPs as they appear in the aerial data against their known coordinates. Regardless of the terrain's complexity, GCPs ensure that the aerial data collected are accurate and reliable, particularly important when mapping urban areas.

(**a**). Ground Control Points (GCPs) (**b**). GNSS receiver (**c**). UAS

Figure 8. Equipment setup and calibration.

Before the actual flight, an in-depth evaluation of actual conditions (i.e., temperature, wind speeds, humidity, and chance of rain) was conducted to establish an effective and efficient flight trajectory. Initial planning included the appropriate altitude, speed, and image overlap to guarantee thorough coverage and data precision. A series of pre-flight checks (Figure 8c) were carried out to ensure that the UAS was performing as anticipated, confirming that all its systems were operational and working correctly.

To enable spatial registration of thermal data, corresponding Red-Green-Blue (RGB) imagery is utilized. Three-dimensional reconstruction is achieved through Structure-from-Motion (SfM) photogrammetry, a process that leverages feature point correspondence across multiple images to determine camera pose and generate a dense 3D point cloud representing the building's geometry [29].

The UAS was equipped with a suitable camera, ensuring it was securely attached and properly calibrated, namely an integrated RGB camera for image/video capture, and a FLIR VUE PRO R640 camera (manufactured by Teledyne FLIR LLC, Wilsonville, OR, USA) for thermal assessment.

While the orthophotography provides detailed imagery, the Digital Elevation Models (DEMs) offer essential elevation data. Together, they deliver a more complete and multi-dimensional understanding of a geographic area. An orthophoto (Figure 9) is a geometrically corrected aerial photograph that combines the image characteristics of a photograph with the geometric qualities of a map, and shows ground features in their true positions, allowing for accurate measurements of distance, angles, and areas. Orthophotos serve as a base layer in Geographic Information Systems (GIS) to overlay additional spatial data, analyse changes over time, and support decision-making processes.

Figure 9. Orthophoto of the studied area (Politehnica students' accommodations: C6, C8, C22 and G24).

A DEM (Figure 10) provides a representation of a terrain, showing elevation values over a geographic area. It is a 3D model of the terrain's surface, excluding trees. DEMs are used in topography, hydrology, geology, and other fields to model water flow, perform terrain analysis, calculate slope and aspect, and for simulations in environmental and engineering applications.

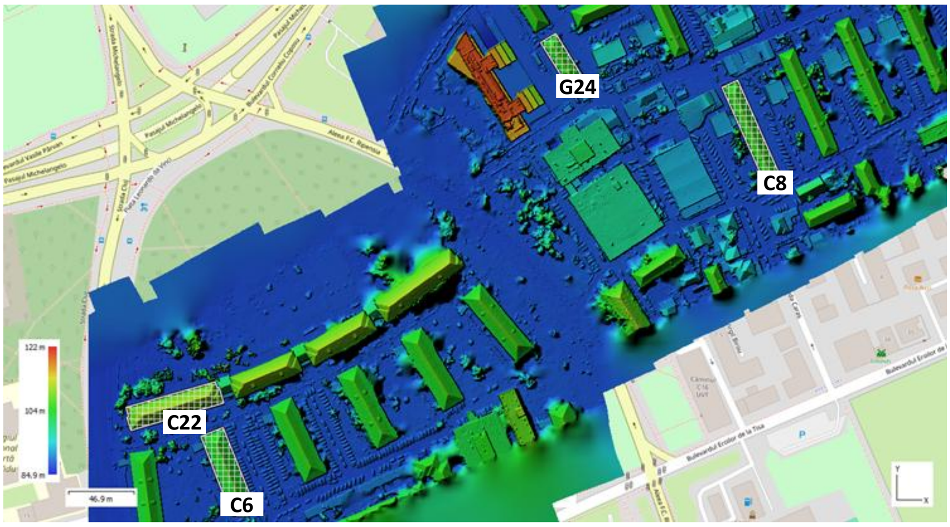
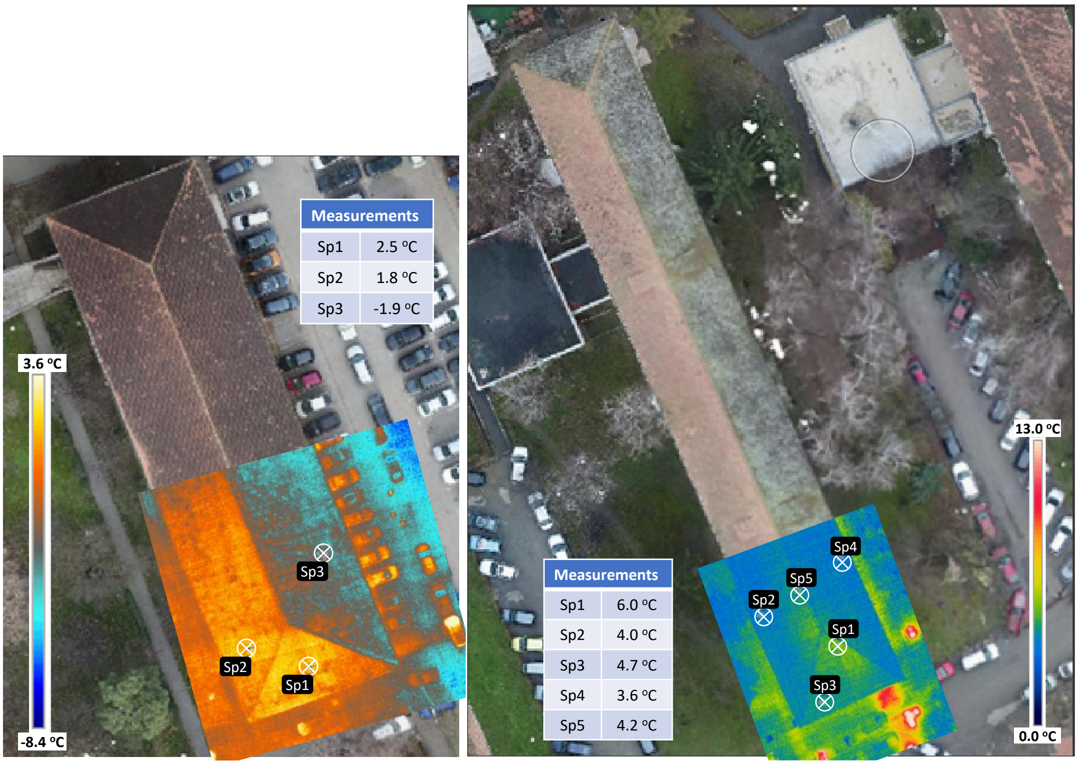


Figure 10. Digital Elevation Model (DEM) of the studied area (Politehnica students' accommodations: C6, C8, C22 and G24).

While an orthophoto provides a 2D representation of the surveyed surface with accurate spatial and visual information, a DEM offers a 3D representation of it, with a focus on elevation. Furthermore, orthophotos show vegetation, buildings, and other features as they appear from above, while DEMs represent the terrain's elevation and do not include details like colours or textures of the surface features. Orthophotos and DEMs complement each other, providing detailed visual context about the land surface (orthophoto) and a quantitative understanding of the terrain's shape and elevation (DEM). Integration of orthophotos and DEMs in GIS enables better decision-making, aiding in infrastructure development, risk assessment, and environmental conservation.

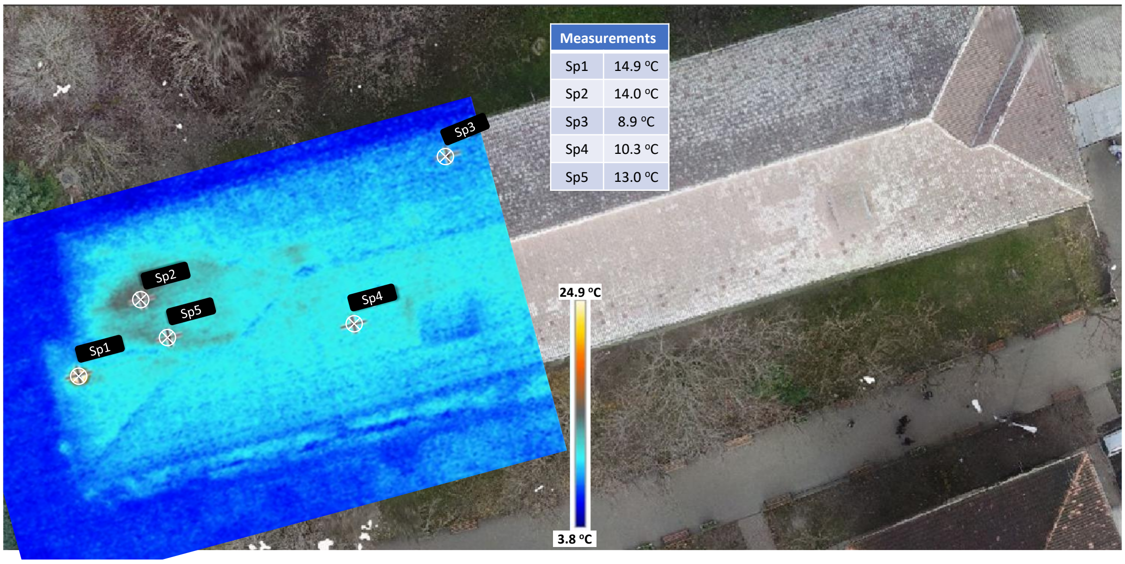
Using the UAS equipped with thermal camera (i.e., FLIR VUE PRO R640), the thermal efficiency assessment of three student dormitories (i.e., C6 and C8 presented in Figure 11, C22 presented in Figure 12 and G24 presented in Figure 13) was performed to identify potential areas of energy loss and opportunities for insulation enhancement. The aerial perspective offered a great overview [30], allowing the detection of the thermal profiles of the dormitories, which might be overlooked otherwise. The analysis will serve as a guide for future initiatives aimed at ensuring the sustainability of buildings and comfort for their occupants.



Measurements	
Sp1	2.5 °C
Sp2	1.8 °C
Sp3	-1.9 °C

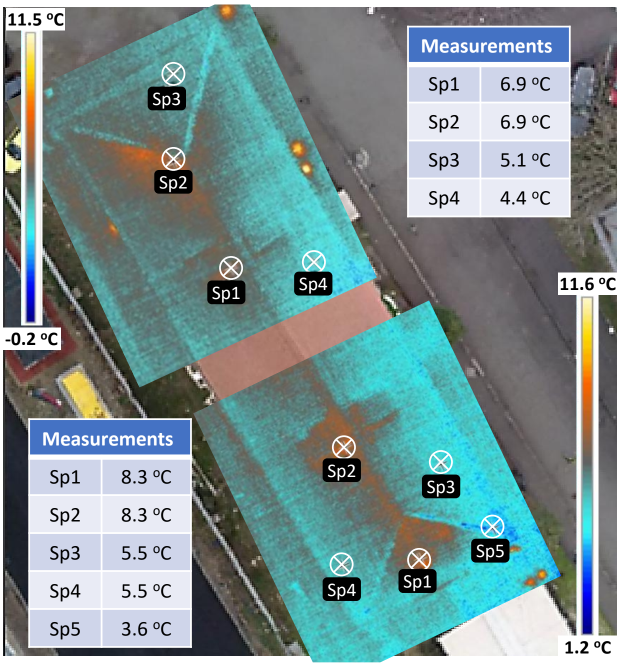
Measurements	
Sp1	6.0 °C
Sp2	4.0 °C
Sp3	4.7 °C
Sp4	3.6 °C
Sp5	4.2 °C

Figure 11. Thermal assessment of C6 and C8.



Measurements	
Sp1	14.9 °C
Sp2	14.0 °C
Sp3	8.9 °C
Sp4	10.3 °C
Sp5	13.0 °C

Figure 12. Thermal assessment of C22.



Measurements	
Sp1	6.9 °C
Sp2	6.9 °C
Sp3	5.1 °C
Sp4	4.4 °C

Measurements	
Sp1	8.3 °C
Sp2	8.3 °C
Sp3	5.5 °C
Sp4	5.5 °C
Sp5	3.6 °C

Figure 13. Thermal assessment of G24.

The spatial registration of thermographic imagery presents a unique challenge due to inherent data characteristics, including limited spatial resolution, significant geometric variability, and the absence of a direct linear correlation between pixel intensity gradients and radiometric temperature gradients [27].

The aerial thermal scanning revealed mild heat losses, with a limited temperature difference (i.e., less than 6 °C). This finding indicates a relatively good level of thermal efficiency, suggesting that existing insulation and construction materials are performing adequately in minimising energy leakage. Although the observed temperature differences are minimal, improvements are still possible, as even small enhancements in thermal insulation can lead to significant energy savings and increased comfort for the inhabitants. The data obtained will be used to pinpoint specific areas where targeted interventions may optimize thermal performance, potentially leading to more substantial energy conservation and additional cost savings (e.g., Sp1 and Sp2 for G24—Figure 13).

Comparative analysis of acquisition protocols revealed a critical dependence of thermal data colour representation on the initial acquisition point, attributed to the system's calibration for absolute colour values. Optimal colourimetric fidelity was achieved when the acquisition sequence commenced with a representative Thermal Building Element (TBE) exhibiting extreme thermal differentials relative to other system components. This methodology facilitated a precise colourimetric representation of both RGB and thermal data, resulting in accurate point cloud generation [31].

Terrestrial laser thermal scanning was used to assess the thermal performance of the student dormitory walls, complementing the initial aerial thermal survey of the roofs. The objective of terrestrial laser thermal scanning was to detect and analyse thermal performance and inefficiencies in dormitory walls by identifying thermal bridges, insulation gaps, and potential areas of energy loss that could not be fully captured from an aerial perspective.

Structure-from-Motion (SfM) photogrammetric 3D data generation, reliant on optical imagery, exhibits inherent limitations. These limitations can be substantially mitigated through post-processing methodologies employing referenced datasets. Alternatively, laser-scanning-assisted image acquisition offers a potential pathway to eliminate these photogrammetric limitations entirely [32].

For all Terrestrial Laser Scanning (TLS) operations, targets and scanning position registration are critical components for successful 3D modelling, as these aspects ensure the accuracy and comprehensiveness of the captured data, facilitating the creation of a detailed and precise 3D model of the scanned environment. Target registration involves placing artificial targets or recognising natural features in the scanning environment, which act as reference points during the data processing phase. These targets are used in the alignment and overlap process to bring together multiple scans with precision.

The strategic placement of the targets was considered, as they should be visible from at least two different scanning positions to ensure robust registration. The considered targets covered the entire scanned area of interest, being uniformly distributed across the site. For each asset, multiple scanning stations were considered to ensure that all the details were captured, resulting in between 6 and 11 scanning stations for each asset.

Figure 14 presents the scanning stations for the C8 student accommodation, as an example.

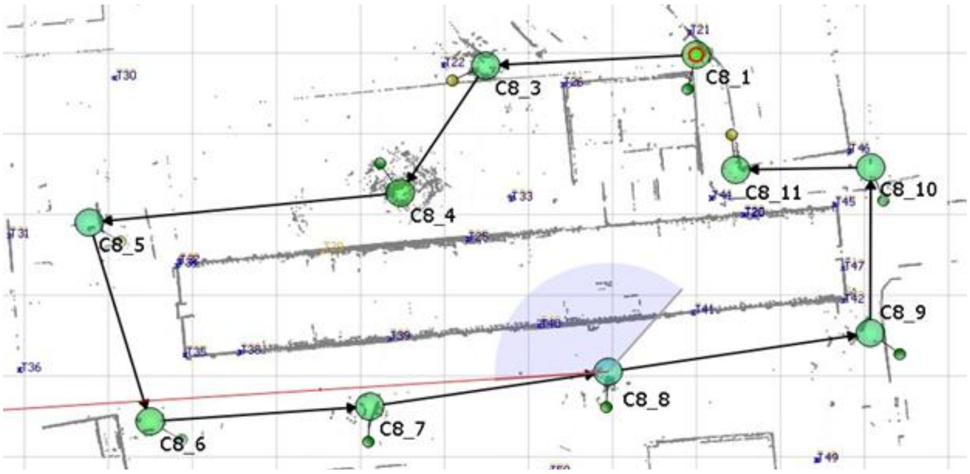


Figure 14. Scanning stations for C8 student dormitory building.

The scanning positions (C8_1...C8_11) are determined by the need to cover the entire area of interest comprehensively, while each position should offer a clear view of a significant portion of the asses, minimizing occlusions and the so-called shadow areas. Additionally, scans from different positions should have a consistent overlap (typically, 20–30%) between adjacent scans, to ensure that enough common features are captured.

To georeference the point clouds and enable their positioning into a unitary system, all fixed targets were surveyed using the total station. It is worth mentioning that, to ensure good alignment on all three dimensions X, Y, Z and the possibility of additional checks, at least three targets were surveyed for each scanning station.

Following this setup, the actual scanning process started. A clear image of the scanning process results using the TLS with the additional thermal camera is given by the following images.

Figure 15 shows the scanning results for C8 (north and east facades) and Figure 16 shows the integrated thermal information with TLS point cloud.

View of the dormitory building

Point cloud displayed after the grey scale reflection intensity view of the dormitory building

Thermography

Figure 15. View of C8 dormitory building.

Figure 16. Results for TLS thermal scan for C8 (north and east façade).

Table 1 presents the average value and the standard deviation for main building elements (i.e., walls, foundation, windows—open and closed).

The analysis of the data distinctly illustrates the significant influence of window status on thermal performance, specifically comparing scenarios with open and closed windows. Consistent with theoretical expectations, the findings indicate that the open windows on the east façade exhibit a considerably higher average temperature in comparison to their closed counterparts. This disparity underscores the pronounced thermal exchange that takes place when the windows are open, facilitating greater heat transfer between the interior and exterior environments. The observed increase in temperature with open windows can be attributed to direct solar gain, increased airflow, and the consequent convective heat transfer, which collectively amplify the thermal load within the space. These results emphasise the critical role of building envelope control in regulating indoor thermal conditions and the necessity of strategic window management to optimise energy efficiency and occupant comfort.

Table 1. Temperature values for C8 scanning.

Façade	Scanned Object	Average Value [°C]	Standard Deviation [°C]
North	Walls	8.5	0.79
	Windows (closed)	-	-
	Windows (open)	-	-
	Foundation	9.20	0.26
East	Walls	9.67	0.42
	Windows (closed)	12.43	0.67
	Windows (open)	21.27	1.10
	Foundation	11.27	0.45

This difference underscores the importance of thermally efficient windows and the role of windows in overall thermal performance. Properly sealed and insulated windows can markedly reduce energy loss, maintain more consistent internal temperatures, and contribute to the energy efficiency of a building.

Figure 17a presents the thermal results for the C6 building south façade, while Figure 17b presents the TLS thermal results of TLS for the C6 building east façade.

(**a**)

(**b**)

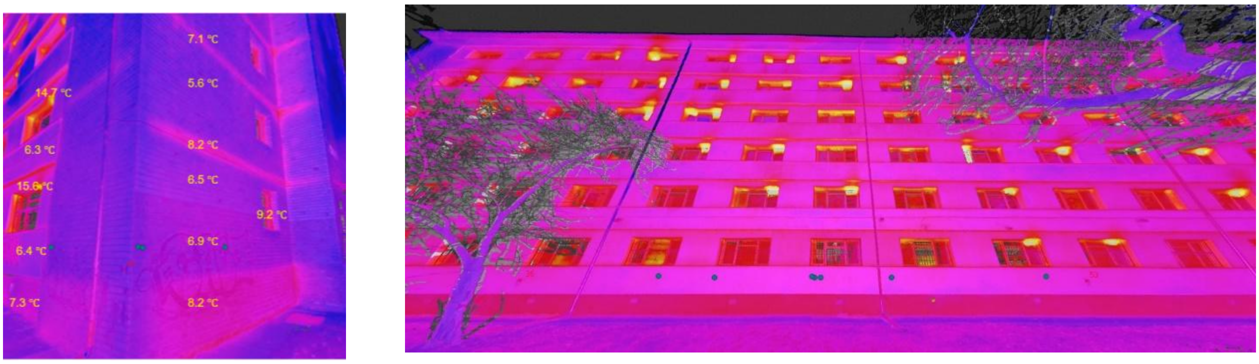
Figure 17. Integrating thermal information with TLS point cloud: C6 (**a**) south façade) and C6 (**b**) east façade).

Table 2 presents the average temperature value and the standard deviation for the main building elements (i.e., walls, foundation, windows—closed and inter-storey slab) for the west and north facades of the C6 building.

Table 2. Temperature values for C6 scanning.

Façade	Scanned Object	Average Value [°C]	Standard Deviation [°C]
South	Walls	4.57	0.31
	Windows (closed)	7.70	0.28
	Windows (open)	18.80	-
	Foundation	8.95	0.07
	Access door	11.30	1.27
	Technical room access	10.00	-
	Technical room window	21.10	-
East	Walls	3.13	0.25
	Windows (closed)	4.67	0.49
	Windows (open)	15.57	1.60
	Foundation	6.20	-

The results of the TLS thermal scan for the west façade of the C22 building clearly show the thermal losses occurring in an uninsulated wall, specifically focusing on critical areas at the foundation level and the inter-storey slab. The image (Figure 18) highlights the significant impact that a lack of insulation can have on a building's energy efficiency, as heat escapes through these critical areas, underscoring the potential for increased energy consumption and reduced interior comfort. The visualisation (Figure 19) serves as a compelling case for the importance of proper insulation, illustrating how thermal bridging at the foundation and inter-storey levels can lead to substantial energy losses.



(**a**) (**b**)

Figure 18. Integrating thermal information with TLS point cloud for C22: west (**a**) and north façade (**b**).

Table 3 presents the average temperature value and the standard deviation for the main building elements (i.e., walls, foundation, windows—closed and inter-storey slab) for the west and north facades of the C22 building.

Table 4 presents the average temperature value and the standard deviation for the main building elements (i.e., walls, foundation, windows—open and closed).

(**a**) (**b**)

Figure 19. Integrating thermal information with TLS point cloud for G24 north (**a**) and east façade (**b**).

Table 3. Temperature values for C22 scanning.

Façade	**Scanned Object**	**Average Value [°C]**	**Standard Deviation [°C]**
North	Walls	7.83	0.29
	Windows (closed)	10.47	0.65
	Windows (open)	22.87	1.77
	Foundation	9.37	0.15
West	Walls	5.77	0.57
	Windows (closed)	9.27	0.12
	Inter-storey slab	7.30	0.82
	Foundation	7.93	0.25

Table 4. Temperature values for G24 scanning.

Façade	**Scanned Object**	**Average Value [°C]**	**Standard Deviation [°C]**
North	Walls	8.30	0.40
	Windows (closed)	9.35	0.07
	Windows (open)	20.10	-
	Foundation	9.30	0.30
East	Walls	8.10	0.70
	Windows (closed)	10.63	0.78
	Windows (open)	19.83	0.59
	Foundation	9.63	0.12

Figure 20 illustrates the thermal losses of an insulating window by comparing two different scenarios: one with the window closed and the other with the window open. By analysing these images, one can appreciate the insulation window's role in maintaining energy efficiency within a building, highlighting the impact of simple actions like closing a window on a structure's overall thermal performance.

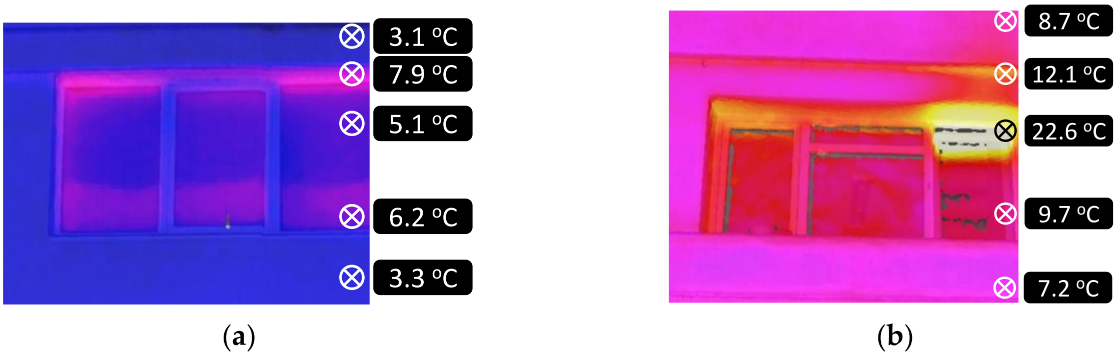


Figure 20. Thermal losses through thermal windows in closed (**a**) and open mode (**b**).

To obtain a colour scale from which heat losses emerge, the settings were made so as to capture temperatures between 0 and 24 degrees for dormitories 24 and 8, which were scanned at an ambient temperature with an average of 6 °C, and between 0 and 19° C when scanning dormitories 22 and 6, when the average ambient temperature was 2 °C. Therefore, even the smallest temperature differences, 1–3 °C, were captured.

Regarding a comprehensive analysis, this was conducted for the dormitory with the largest volumetric capacity, which also represents the most prevalent structural type within the campus.

4.5. BIM for Energy Conservation Measures

Using laser scanning, precise and detailed data about the structure of the buildings were obtained. Moreover, by adding information obtained from the field, the BIM model can then be developed to be later used not only as a digital representation of the construction, but also as a basis for the detailed analysis of structures, allowing the identification and precise quantification of existing deviations and deformations. This methodology provides a better understanding and objective interpretation of existing conditions, which is essential for planning future interventions.

Furthermore, BIM processes involve collaboration between the different disciplines involved in the project and emphasise the importance of using international standards to ensure interoperability of the data. The methodology also highlights the critical role of detailed planning and information management in the success of project development and implementation.

The article confirms that 3D scanning provides a solid foundation for BIM modelling and effective evaluation and planning of construction intervention projects, helps to adopt informed decisions, and optimises design processes. The proposed approach represents a step forward in the digitalisation of the construction sector and opens up new perspectives in the management and preservation of existing infrastructures. Our further research will focus on BIM modelling, the work and methodology presented here, creating the premises for that purpose.

A structural analysis of the buildings, as shown in Figure 21, can also be realised based on the information provided by the methodology presented.

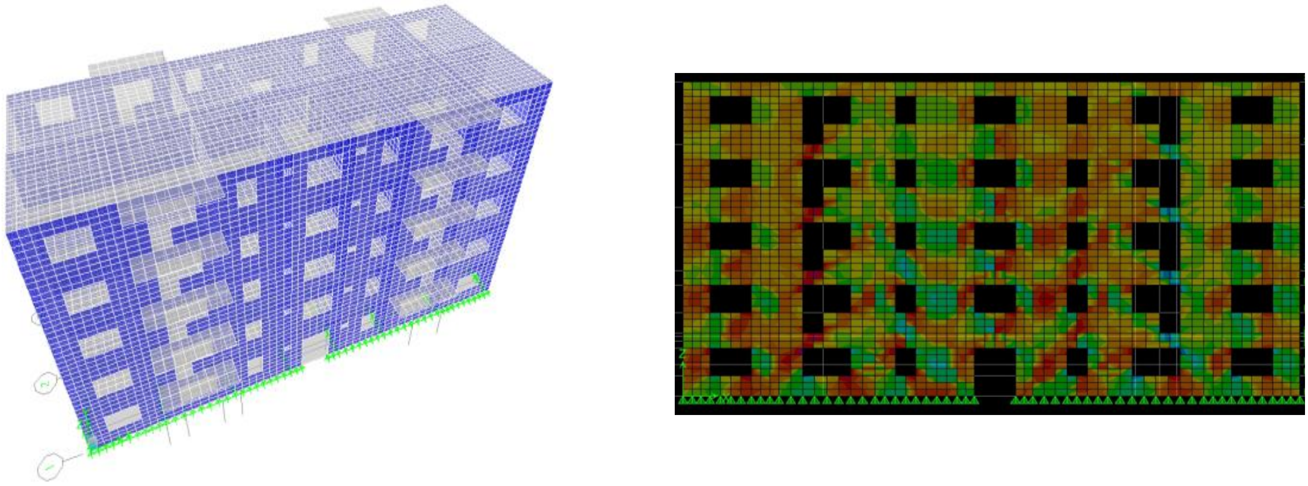

(**a**) (**b**)

Figure 21. Structural model of C8 dormitory: (**a**) 3D view of the mesh model using shell finite ele-ments; (**b**) Stress distribution on the main façade from seismic action.

5. Conclusions

The thermal performance assessment was enabled by a blend of cutting-edge technologies, including an advanced UAS with thermal cameras, a high-quality GNSS receiver, a powerful TLS with thermal camera, and a top-of-the-line total station. This evaluation provided a comprehensive view of the thermal performance and the potential for improvement in the structures of four dormitories (i.e., C6, C8, C22, and G24) from the Campus of Politehnica University Timisoara. This study is essential for further analysis and decision-making regarding the optimal solutions for energy efficiency and reducing the carbon footprint of buildings.

The integration of aerial and terrestrial surveys offered a comprehensive perspective, capturing thermal anomalies and inefficiencies from both macro- and micro-perspectives. The use of advanced equipment, such as UAS and TLS, enabled the acquisition of thermal data from all points of view, allowing for precise identification of areas requiring attention. The generated thermal maps will guide the intervention teams to specific locations, enabling more targeted and cost-effective interventions. Furthermore, the assessment provided valuable information on the energy efficiency of each assessed dormitory, highlighting opportunities to improve insulation and reduce energy consumption.

This detailed assessment was a critical step in understanding the energy performance of each building, allowing a roadmap definition for enhancing their thermal performance. It underscored the importance of technology-assisted inspections in the maintenance and energy management of building infrastructures.

The assessment provides clear benefits on multiple levels. It creates a pathway to define specific and targeted energy conservation measures, leading to significant cost savings and clear environmental benefits. Next, addressing the identified thermal inefficiencies will improve living conditions for students, ensuring better-regulated temperatures and reduced drafts. Proactively addressing thermal issues can even extend the lifespan of building materials and the overall lifespan of structures by preventing moisture accumulation and other degradation processes. Another important benefit is that this assessment can serve as a case study for the students themselves, offering real-world insights into the application of technology in building science and sustainability.

Even if advanced equipment was used for analysis, the accuracy of the thermal data was influenced by external environmental conditions. Additionally, certain areas were challenging to scan due to their location and limitations in the TLS range and angle of coverage. One additional limitation can be represented by the expertise required to interpret thermal data accurately, which requires specialised knowledge to transform raw data into actionable insights.

Further research will include texturing the model with thermal information. Through this process, energy efficiency maps can be realised at the community level, which provides support for the further development of the energy rehabilitation business. We consider repeating these thermal scans during the summer, when high temperatures over 40 ^{0}C are recorded, in order to determine the thermal radiation of the buildings and during the winter when the lowest temperatures are -5 °C to -10 °C in order to define a pattern for energy efficiency and integrate it into the life cycle assessment.

The proposed methodology sets the basis of an integrated rehabilitation, at neighbourhood levels, which should also include related facilities (photovoltaic panels, heat pumps, etc.) and creates the premises for efficient energy management at the macro level.

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Conflicts of Interest: The authors declare no conflict of interest.

List of Abbreviations

ALS	Aerial Laser Scanning
AIM	Asset Information Models
AIR	Asset Information Requirements
BIM	Building Information Model
EASA	European Union Aviation Safety Agency
ECM	Existing Conditions Model
EEA	European Economic Area
EPBD	Energy Performance of Buildings Directive
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LEED	Leadership in Energy and Environmental Design
LoD	Level of Detail
LiDAR	Light Detection and Ranging
NDT	Non-Destructive Testing
PIM	Project Information Models
PIR	Project Information Requirements
RTK	Real Time Kinematics
TIR	Thermal infrared

TLS	Terrestrial Laser Scanning
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USE-REC	University Students Engaging in Responsible and Sustainable Energy Consumption

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