VALIDATION OF ENERGY SIMULATION MODELS THROUGH COMPARISON WITH ACTUAL ENERGY CONSUMPTION IN BUILDINGS

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This paper examines the application of computer-based energy modeling and simulation tools in the analysis of building energy performance. The research is based on a comparative case study of two buildings, where detailed 3D models and energy simulations were developed using real data on construction systems, materials, heating, cooling and ventilation systems, as well as local climatic conditions.

The simulation results were compared with the actual energy consumption data for thermal and electrical energy on both monthly and annual levels. The analysis indicates a high level of agreement between simulated and measured values (over 90%), confirming the accuracy and reliability of the applied methodology. In addition to energy consumption, the simulations provide detailed insight into the thermal behavior of the buildings, including heat losses and gains, envelope performance, and CO_2 emissions.

The findings demonstrate that energy simulation tools represent an effective approach for analyzing, evaluating, and improving building energy performance, with significant potential for application in both research and engineering practice.

Keywords: energy simulation, building energy performance analysis, 3D modeling, energy consumption.

1. INTRODUCTION

Computer graphics and digital modeling technologies have become essential tools in contemporary architectural design, enabling faster project development, improved decisionmaking processes, and realistic visualization of architectural solutions. The continuous advancement of digital technologies has significantly transformed the architecture, engineering, and construction (AEC) industry, particularly through the introduction of Building Information Modeling (BIM). BIM provides comprehensive digital representations of buildings and facilitates data exchange throughout the entire building lifecycle, from conceptual design to operation and maintenance [1].

In addition to supporting the design process, BIM-based models serve as a foundation for advanced building performance analyses. However, BIM alone is not sufficient for evaluating the actual energy behavior of buildings under real operating conditions. Accurate assessment of energy performance requires the use of dynamic simulation tools capable of modeling heat transfer processes, energy consumption patterns, HVAC system operation, occupant behavior, and climatic influences. Software platforms such as DesignBuilder and EnergyPlus have therefore become widely used for predicting building energy performance and supporting energy-efficient design strategies.

Previous studies have demonstrated that building energy simulation tools can provide reliable estimates of energy demand and thermal performance. Nevertheless, differences between simulated and measured energy consumption are frequently reported due to uncertainties associated with material properties, occupancy schedules, equipment usage, climatic conditions, and system operation. Consequently, the validation of simulation models through comparison with actual energy consumption data remains an important research topic, particularly for improving the reliability of energy performance assessments.

The objective of this study is to evaluate the accuracy and applicability of building energy simulation models through a comparative analysis of simulated and measured energy consumption data. Two existing buildings with different architectural and construction characteristics were selected as case studies in order to assess the reliability of simulation results under varying building conditions. Detailed virtual models of both buildings were developed using DesignBuilder software with the EnergyPlus simulation engine. The modeling process included the definition of building geometry, construction materials, thermal envelope characteristics, HVAC systems, occupancy patterns, and local climatic conditions. The simulation results were subsequently compared with actual energy consumption data to evaluate the accuracy of the developed models and their applicability for energy-efficiency assessments and future building performance analyses..

2. METODOLOGY

This study applies a comparative simulation-based methodology for the evaluation and validation of building energy performance through the use of dynamic thermal simulations. The approach is based on the development of detailed digital models of two existing buildings and the comparison of simulated energy consumption with measured operational data. The methodological framework consists of the following steps: collection of architectural and technical documentation for both buildings, on-site verification of geometrical and construction characteristics, development of detailed 3D thermal models, definition of building envelope properties, internal loads, HVAC systems, and operational schedules, dynamic energy simulation, and comparison and validation of results against measured energy consumption data.

2.1 CASE STUDY BUILDINGS

Two existing buildings with different geometrical, structural, and functional characteristics were selected in order to evaluate the reliability of simulation models under different operational conditions. For each building, geometric data, construction details, and operational characteristics were collected from project documentation and field surveys. The buildings were modeled as separate thermal zones according to their functional layout, orientation, and usage patterns.

2.2 DEVELOPMENT OF SIMULATION MODELS

Three-dimensional models of both buildings were developed using DesignBuilder, while EnergyPlus was used as the simulation engine for dynamic thermal calculations. The following input data were defined for each building model: Building geometry and zoning configuration; Construction assemblies of external and internal envelope elements; Thermo-physical properties of materials (thermal conductivity, density, specific heat capacity, and U-values); Window systems, glazing properties, and shading elements; Air infiltration rates and ventilation assumptions; Internal heat gains (occupancy, lighting, and equipment loads); HVAC system configuration and operational schedules. Where available, real operational data were used to define realistic usage profiles in order to improve model accuracy.

2.3 CLIMATIC DATA

Weather data were obtained from a representative EnergyPlus Weather (EPW) file corresponding to the geographical location of the studied buildings. Hourly climatic parameters including outdoor temperature, solar radiation, humidity, and wind speed were used as input for the simulations.

2.4 SIMULATION AND VALIDATION PROCEDURE

Dynamic energy simulations were performed using EnergyPlus through the DesignBuilder interface. The simulations were conducted on an hourly basis over a full annual cycle. The validation of the developed models was performed by comparing simulated energy consumption with measured energy data obtained from utility bills and/or building monitoring records. The comparison focused on: annual heating energy consumption; Total building energy use; Seasonal variation of energy demand. Differences between simulated and measured results were analyzed in order to identify uncertainties related to occupancy behavior, system efficiency, material properties, and operational conditions.

This methodology enables assessment of model accuracy and provides a reliable basis for evaluating the applicability of building energy simulation tools in real operational conditions.

3. SIMULATIONS

3.1 SELECTION OF CASE STUDIES

The analysis of energy performance was conducted through two case studies selected as representative examples of modernist architecture in Skopje, characterized by complex spatial and functional configurations. The first building is the headquarters of the Macedonian Academy of Sciences and Arts (MASA), constructed in the 1970s, which represents a protected cultural heritage asset of the first category. The second building is the administrative building of the State Hydrometeorological Service in Skopje, also constructed in the same period and in a similar architectural style, representing a unique complex composition of multiple volumes and distinctive cylindrical towers. This building has also been proposed for protection as a cultural heritage asset of the second category.

Both buildings were constructed entirely in exposed concrete, without the application of thermal insulation, which is characteristic of the architectural practice of that period. These structural and material characteristics, combined with the ageing and degradation of materials over time, lead to pronounced issues related to energy efficiency, thermal comfort, and long-term sustainability. Consequently, they represent a relevant basis for conducting detailed energy simulations and analyzing their performance under real operational conditions. The buildings are shown in Fig. 1 and Fig. 2.

Figure 1. Case Study 1: Macedonian Academy of Sciences and Arts

Figure 2. Case Study 2: Hydrometeorological Institute

The selection of the two case study buildings was based on their representative characteristics within the local building stock and their relevance for energy performance assessment. Although the buildings differ in geometry, architectural configuration, construction period, and material composition, this variation was intentionally used to evaluate the robustness of building energy simulation models under different conditions. The main selection criterion was the availability of complete architectural documentation, construction data, and measured energy consumption records required for reliable model development and validation. The differences between the two buildings enable a comparative assessment of simulation accuracy across different building typologies, providing a broader validation of the modeling approach. The buildings are therefore not intended to be identical, but to serve as contrasting case studies for evaluating simulation performance under varying geometrical and thermal conditions. This approach improves the reliability of the results and enhances the applicability of the findings to a wider range of existing buildings.

3.2 GEOMETRY, LOCATION, ZONING, AND DESIGN TEMPERATURE

Case study 1 is a free-standing institutional structure located in a dense urban context and exposed to external conditions on all façades. The building is characterised by a relatively compact but thermally inefficient geometry dominated by large glazed surfaces and reinforced concrete volumes. The internal layout is divided into a high number of thermal zones exceeding 250 zones, where each room is defined as an individual thermal zone due to variations in occupancy, orientation, and internal gains. The building includes offices, laboratories, auditoriums, and service spaces distributed across multiple levels.

Case study 2 is a larger and more complex institutional facility with a multifunctional program and an atrium-based spatial organisation. The geometry is significantly more heterogeneous, including a main volume and a later administrative extension that introduces an internal courtyard configuration. The building is divided into approximately 257 thermal zones, reflecting its highly fragmented functional layout. Zones include administrative offices, libraries, archives, conference halls, exhibition spaces, and service areas, each with different occupancy schedules and internal loads.

For both buildings, design temperature conditions are defined based on local hourly climate data, with dynamic external temperature variation applied throughout the simulation period. The internal organization is addressed through detailed zoning, whereby each space is modelled as a separate thermal zone. This approach is derived from differences in function and usage patterns, which vary according to occupancy levels, equipment, lighting, orientation, and conditioning regimes. A specific design temperature is assigned to each zone, enabling a more accurate simulation of real operating conditions. The zoning approach is illustrated in Fig. 3 and Fig. 4.

Figure 3. Thermal Zones – Case Study 1

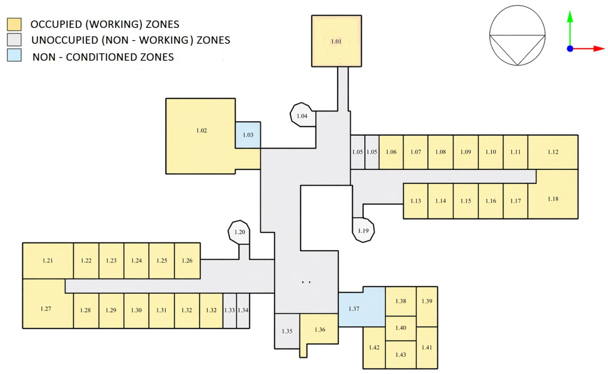

Figure 4. Thermal Zones – Case Study 2

Figures 3 and 4 illustrate the method of zoning the space into thermal zones, defined according to the functional use of the rooms. This approach is applied identically in both analysed buildings. Based on functional purpose, the following groups of thermal zones are distinguished:

Occupied (working) zones – spaces with continuous user presence, in which heating, cooling, and appropriate ventilation are provided in accordance with external climatic conditions (offices, laboratories, meeting rooms, galleries, auditoriums, etc.); Unoccupied zones – spaces not intended for permanent human occupancy, but which are heated during the heating season (corridors, hallways, etc.); Unheated / non-conditioned zones – spaces without permanent occupancy that are not subject to thermal conditioning, i.e., they are neither heated nor cooled (staircases, toilets, storage rooms, etc.). The zoning principle is consistently applied across all floors, including basement levels, and is identical for both buildings. Although in Figure 2 the zones are presented as groups with similar functions and thermal requirements, in the model they are considered as separate individual thermal zones. The design indoor temperature for occupied working zones (offices, halls, amphitheatres, etc.) is 21°C, while for unoccupied zones (corridors, toilets, and basement spaces) a temperature of 15°C is assumed. The number of users is significantly higher in occupied zones compared to unoccupied ones. Additionally, parameters such as orientation, spatial position, floor level, adjacency to other zones, and exposure to external influences vary for each zone and change dynamically during the simulation. The outdoor temperature also varies according to real climatic data, which are taken into account in the simulation process.

3.3 HEATING, COOLING, AND VENTILATION SYSTEMS

Case study 1 is equipped with a centralized hydronic HVAC system connected to district heating for space heating. Heat distribution is provided via fan-coil units installed in all conditioned spaces, while radiators are used in service zones such as corridors and toilets. Cooling is provided through a centralized chiller system with chilled water temperatures between 7–12°C. Mechanical ventilation is very limited and primarily restricted to sanitary spaces, resulting in dominant reliance on natural ventilation and infiltration. Due to poor envelope performance, the building frequently requires supplementary electric heating and split-unit air conditioning, particularly during winter and summer peak conditions.

Case study 2 has a more advanced but still partially inefficient HVAC configuration. Heating is also connected to a district heating system with secondary heat exchange delivering water at approximately 70–80°C. Cooling is provided through centralized chillers integrated with fan-coil systems. In addition, Building 2 includes mechanical ventilation with heat recovery in selected high-occupancy zones such as auditoriums, conference halls, libraries, archives, and exhibition spaces, with estimated heat recovery efficiency in the range of 50–70%. Remaining zones rely on natural ventilation and mechanical exhaust systems. Despite this more advanced configuration, the building still exhibits high energy demand due to envelope limitations and infiltration losses.

3.4 CONSTRUCTION AND ENVELOPE MATERIALS

Building 1 is constructed as a reinforced concrete frame structure with exposed concrete façades and extensive use of single-glazed aluminium curtain wall systems. The building has no continuous thermal insulation in the original construction. External walls exhibit very high thermal transmittance, with U-values ranging from approximately 1.73 W/m²K to 5.08 W/m²K, depending on wall typology. Roof structures include flat reinforced concrete slabs with limited insulation performance, with U-values between 0.44 W/m²K and 1.69 W/m²K. Ground-related slabs and intermediate floors show U-values in the range of 2.17–4.21 W/m²K, indicating significant heat transfer to unconditioned zones. Window systems are highly inefficient, with U-values up to 5.78 W/m²K, representing the weakest component of the envelope.

Building 2 is also based on reinforced concrete structural systems, but includes multiple construction phases. The original part of the building is largely uninsulated, while the later extension incorporates approximately 5 cm of internal thermal insulation. External wall U-values vary between 0.54 W/m²K and 4.68 W/m²K, depending on construction type and period. Roof assemblies show improved performance compared to Building 1, with U-values ranging from 0.28 W/m²K to 0.42 W/m²K, due to partial insulation layers. Ground floor and slab elements present U-values between 0.99 W/m²K and 1.98 W/m²K. Window systems include a combination of single and improved glazing, with U-values ranging from 2.0 W/m²K to 5.61 W/m²K, depending on the façade zone and construction phase.

.4. RESULTS

Based on the conducted modelling and simulation of the existing conditions for both buildings, a set of relevant output parameters was obtained, encompassing their energy and thermal performance. In this regard, the analysis includes the consumption of thermal and electrical energy (for heating, cooling, ventilation, lighting, and equipment), CO_2 emissions, as well as internal microclimatic conditions (temperature and relative humidity) across individual thermal zones. In addition, heat losses through the building envelope, infiltration, and ventilation were examined, along with the thermal characteristics of the construction elements expressed through their U-values.

From the obtained results, parameters relevant for model verification were extracted, which are comparable with the actual consumption of thermal and electrical energy. These were systematized and presented graphically in order to enable a comparative analysis with the measured data obtained from energy bills. In order to determine the accuracy and validity of the applied software model, comparative analyses were carried out between the actual energy consumption for heating, cooling, and operation—derived from monthly thermal and electrical energy bills over a one-year period—and the results of the simulated existing conditions obtained through a 3D model and energy simulation of both buildings. The analyses are graphically presented in Figures 5, 6, 7, and 8.

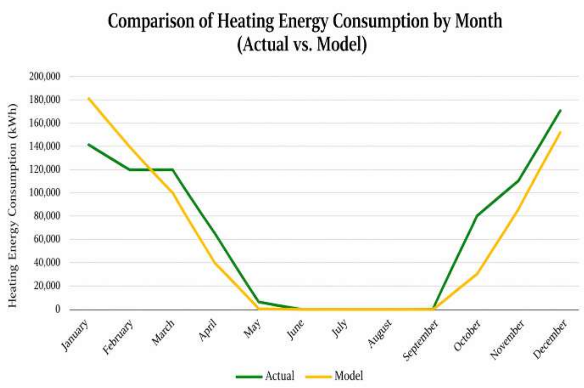

Figure 5. Heating energy consumption (comparison of utility bills and model results) – Case Study 1

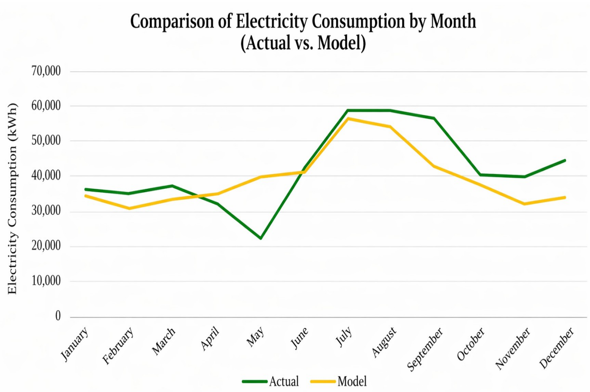

Figure 6. Electricity consumption (comparison of bills and model results) – Case Study 1

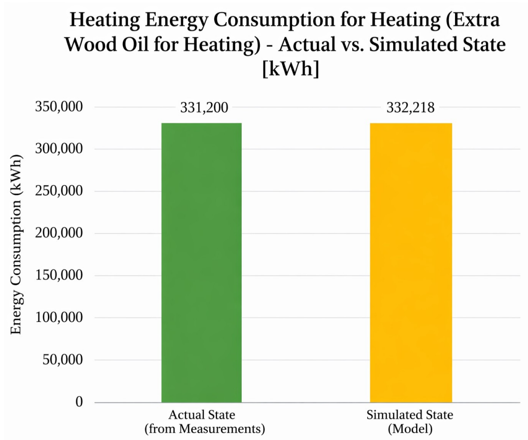

Figure 7. Heating energy consumption (comparison of utility bills and model results) – Case Study 2

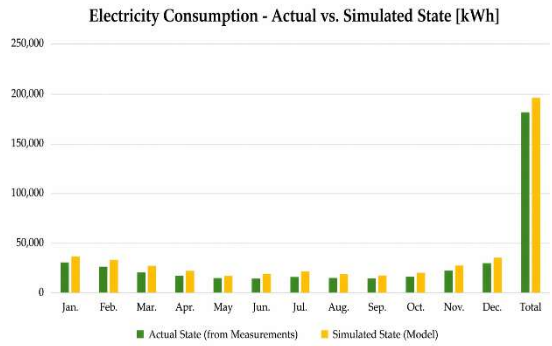

Figure 8. Electricity consumption (comparison of bills and model results) – Case Study 2

The obtained results indicate a high level of agreement between the actual and simulated values, confirming the reliability and applicability of the model. As shown in Figures 5 and 6, which present the comparison of thermal energy consumption, a correspondence exceeding 90% is observed at both the monthly and total levels, further validating the accuracy of the performed simulation.

5. CONCLUSION

The aim of this research is to highlight the role and significance of computer-based software tools in architecture and civil engineering, particularly in the domain of complex energy analyses and the prediction of building performance under real operating conditions. To this end, detailed 3D models were developed and energy simulations were conducted for the two analyzed buildings, based on comprehensive research, documentation, and systematization of relevant input data.

The modelling process involved the precise definition of geometry, materials, structural characteristics, heating, cooling, and ventilation systems, as well as local climatic conditions and the surrounding urban context. The application of advanced software tools enabled a realistic simulation of energy performance under dynamic (non-steady-state) conditions and the generation of detailed hourly results.

The simulation outputs were compared with actual data obtained from thermal and electrical energy consumption bills, revealing a high level of agreement (exceeding 90%) for both buildings. This strong correspondence confirms the accuracy, reliability, and practical applicability of the employed methodology and software tools.

In addition to energy consumption, the simulations provide detailed insight into the thermal behavior of the buildings, including heat losses and gains, the influence of the building envelope, and associated greenhouse gas emissions. Such an approach represents a solid foundation for further analyses and the development of improvement scenarios aimed at enhancing energy efficiency, sustainability, and overall building performance.

Based on the obtained results, it can be concluded that the application of computer-based simulations represents a robust and effective tool for analyzing and improving building energy performance, with significant potential for application in future research as well as in practical engineering and architectural interventions.

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