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Integrated Modeling and Simulation of Smart Building Energy Systems

Modelarea și simularea integrată a sistemelor de energie pentru clădiri inteligente

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Abstract. *This paper, entitled "Integrated Modeling and Simulation of Energy Systems for Smart Buildings", aims to obtain relevant results regarding energy consumption in a smart building and compare them with those of a less intelligent building with the same functional regime. A comparative analysis of different building models highlights the impact of each smart transformation measure. Using DesignBuilder simulations, the study confirms the efficiency of intelligent control solutions for building energy systems. The results provide practical value for optimizing energy consumption, reducing costs, and supporting sustainable design decisions.*

Key words: *smart buildings, energy systems, simulation, DesignBuilder, energy efficiency*

Rezumat. *articolul, intitulat „Modelarea și simularea integrată a sistemelor de energie pentru clădiri inteligente", urmărește obținerea de rezultate relevante privind consumurile de energie într-o clădire inteligentă și compararea acestora cu cele ale unei clădiri mai puțin inteligente, dar cu același regim funcțional. Analiza comparativă a diferitelor modele evidențiază impactul fiecărei măsuri de transformare inteligentă. Prin simulări în DesignBuilder, studiul reconfirmă eficiența soluțiilor inteligente de control pentru sistemele energetice din clădiri. Rezultatele oferă valoare practică în optimizarea consumurilor, reducerea costurilor și sprijinirea deciziilor de proiectare sustenabilă.*

Cuvinte cheie: *cuvinte reprezentative pentru articol*

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1. Introduction

In the current context of climate change, resource constraints, and increasing demands for energy efficiency, smart buildings emerge as a cornerstone of the transition towards a sustainable built environment. The concept of the smart building integrates advanced technologies for automation, control, and data analytics in order to optimize energy consumption, occupant comfort, and system maintenance.

European regulations, such as the “Fit for 55” package and the Energy Performance of Buildings Directive (EPBD), have reinforced the need for digitalization and automation in the building sector. These frameworks establish more stringent requirements for both existing and new buildings, with a clear objective of achieving nearly zero-energy buildings (nZEB) in the short term and zero-emission buildings in the future.

Smart buildings are defined by the integration of interconnected systems that enable the automated control of HVAC equipment, lighting, ventilation, and other subsystems, based on parameters such as occupancy patterns, indoor CO_2 concentration, daylight availability, or weather forecasts. The goal is to enhance operational efficiency and reduce the energy footprint without compromising indoor environmental quality.

This study aims to analyze the impact of implementing selected *smart building* measures on the energy consumption of a virtually modelled office building. Given the wide range of possible interventions, the research focuses on those measures that have the greatest potential to reduce energy use and can be effectively quantified and simulated using the DesignBuilder software [14].

To achieve this goal, the following objectives were pursued:

- To model an office building within a dynamic simulation environment (DesignBuilder), including a complete definition of the envelope, climate conditions, occupancy schedules, and usage profiles.
- To configure a baseline HVAC scheme with standard operation, serving as the reference for initial energy performance.
- To gradually implement smart building strategies aimed at optimizing consumption (e.g., intelligent lighting control, demand-controlled ventilation based on CO_2 levels, etc.).
- To compare the resulting energy consumption across scenarios in order to assess the individual and cumulative impact of each applied measure.
- To formulate conclusions regarding the effectiveness of these measures within the broader framework of modern building design, targeting reduced energy demand and alignment with nZEB requirements.

2. Methodology and Standards

The evaluation of building energy performance is a crucial step in designing and optimizing smart and low-energy buildings. Traditional static calculation methods cannot capture the dynamic interactions between building elements and external variables such as climate conditions or occupancy patterns. Therefore, dynamic energy simulations are essential tools, allowing detailed modeling of building systems over time, including weather effects, occupancy, operational schedules, and technical equipment characteristics.

In this study, simulations were performed using EnergyPlus via the DesignBuilder interface, providing an intuitive 3D modeling environment and efficient post-processing of results. The methodology ensures a rigorous, data-driven approach to assess the impact of smart building technologies on energy consumption and indoor comfort. Energy performance was evaluated in accordance with European standards, primarily EN ISO 52120-1:2022, which classifies automation systems into four performance levels (A–D) and defines correction factors for energy consumption. Additionally, the Smart Readiness Indicator (SRI) framework was considered to contextualize the building’s adaptive capabilities. While these standards provide theoretical benchmarks, the study relied on detailed dynamic simulations to accurately quantify the effect of each smart measure, integrating automated lighting, demand-controlled ventilation, and optimized HVAC scheduling directly within the model. This approach ensures realistic assessment of energy savings without relying solely on generalized correction factors.

3. Case Study and Virtual Building Model

3.1. General Description of the Modelled Building

The modelled building is primarily an office building with a height of basement + ground floor + 3 floors (B+G+3). The total usable area is 4,800 m², which will serve as the reference area for annual energy consumption calculations.
The building includes a catering area for food services and commercial and service spaces. Floors 1 through 3 primarily consist of open-plan office spaces, meeting rooms, individual offices, sanitary cores, and two server rooms located in the building core. The technical area for building systems is mainly on the rooftop terrace, with successive layers and bituminous exterior finish. Some technical equipment is installed outdoors in designated areas. The building entrance features a reception area spanning two levels (ground floor and first floor) with a free height of 4.59 m on the ground floor. The envelope is mostly glazed with some opaque sections. Upper floors have a height of 3.55 m, with a façade composed of The façade consists of an opaque parapet measuring 0.64 m, a glazed panel of 2.34 m, and an upper opaque element of 0.51 m that serves as a cover for the technical space and provides support for the glazed panel.

The building is located in an urban area. For energy simulations, the climate file for Bucharest from the ASHRAE IWEC2 database was used, providing Typical Meteorological Year (TMY) data for international energy calculations. [1], This includes:

- Dry and wet air temperature;
- Wind speed and direction;
- Solar radiation (modeled based on ASHRAE methods).

Fig. 3.1. Virtual Building Model used

3.2. Input Data and Operational Profiles

The building is divided into 27 unheated basement zones with negligible impact on energy use, while upper floors are zoned according to function, occupancy, and interaction with smart systems. The envelope (walls, roof, windows, doors) complies with MC–001/2022 and SR EN 12831-1, meeting NZEB recommendations. Glazed facades feature a solar factor g = 0.49 and visible transmittance VT = 0.65. Occupancy profiles, based on the UK NCM database, vary by time, day, and space type (offices, commercial, catering, server rooms) to support accurate energy estimations. Internal heat gains derive from people, lighting, and equipment. Indoor conditions follow SR EN 16798-1:2019 (IDA1) with 22 °C in winter and 24 °C in summer, circulation areas at 15 °C and sanitary areas at 18 °C in winter, and server rooms constant at 24 °C. HVAC operation is set at 6/12 °C for cooling and 60/40 °C for heating, with airtightness of $n_{50} \leq 1$ ach. Fresh airflows comply with I5/2022 for IDA 1 (36 m³/h·person and 3.6 m³/h·m²), dynamically adjusted via CO_2-controlled ventilation, representing a first smart readiness measure.

3.3. Initial HVAC Configuration (Conventional Building)

The cooling system uses a chiller and PICV valves for local control, with a VFD-equipped pump and bypass circuit to maintain minimum flow. The heating system is a boiler with a simplified hydraulic scheme. Ventilation is provided via AHU with heat recovery and heating/cooling coils. Fan coil units operate at 12 °C (cooling) and 35 °C (heating).

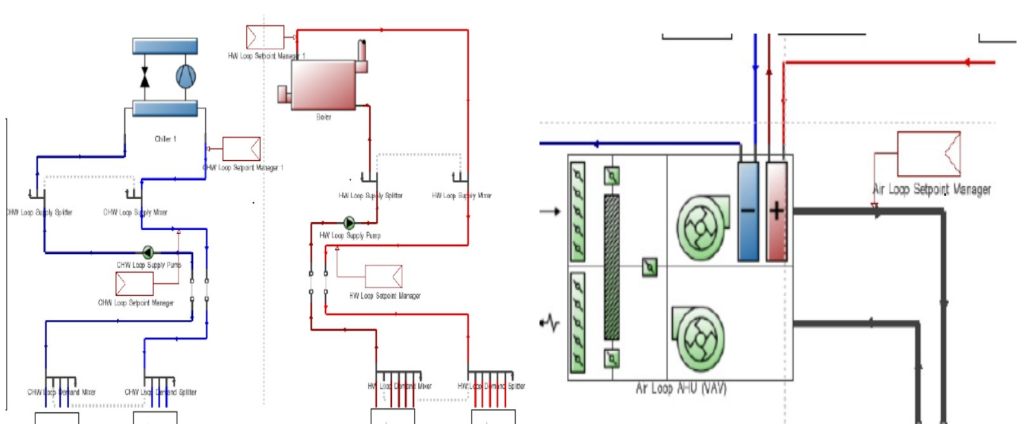

Fig. 3.2. Functional HVAC schemes

3.4 Simulation Scenarios and Implemented Smart Measures

To evaluate potential energy and operational optimization, several scenarios were simulated against the baseline configuration:

- **Automated lighting** , dynamic control based on natural light.
- **CO_2-based ventilation (DCV)** , adjusting fresh air supply based on indoor air quality.
- **Automated exterior blinds** , dynamic shading to reduce solar gains.
- **EC fan coils** , replacing conventional fans with electronically commutated high-efficiency fans.

These scenarios allow analysis of the individual and cumulative impact of each measure on energy consumption and indoor comfort.

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4.1. Simulation of the System Integrating Smart Lighting – V1

Smart Lighting represents a modern and integrated approach to building lighting, which intelligently leverages natural daylight and energy-efficient artificial lighting. This concept promotes optimal use of natural and artificial light to create a comfortable, healthy, and energy-sustainable indoor environment.

Natural light is essential for the physical and emotional well-being of people. The HCL (Human Centric Light) concept highlights the benefits of natural light for occupant health and indicates the need for artificial lighting systems that closely reproduce the natural light cycle. Daylight helps regulate the circadian rhythm, positively influencing sleep, energy levels, and concentration. [5]

Another advantage of the smart lighting system is increased energy efficiency, resulting in significant reductions in electricity consumption for lighting, as well as for cooling, since heat gains are significantly reduced. Other categories of energy consumption are not significantly or directly affected, but rather indirectly through adaptations of the building's control system.

Example: Because there is no longer as much heat gain in the room, the heating system will operate for longer periods, with fewer start-stop cycles, which the software is capable of simulating.

A typical smart lighting system consists of the following essential elements, which ensure automated and efficient control of indoor lighting:

- **LED luminaire**, the source of artificial light, with low consumption and fine adjustment of intensity and color temperature to adapt lighting to natural conditions and user preferences.
- **Ambient light sensors**, devices that continuously measure the natural light level in the room and transmit this data to the control unit to adjust artificial lighting accordingly.
- **Occupancy sensors**, detect the presence of people in the space and allow lights to be switched on, off, or automatically adjusted to avoid unnecessary energy consumption.
- **Central control unit (server)**, the brain of the system, which processes information from the sensors and commands the luminaires through

standardized communication protocols, such as DALI (Digital Addressable Lighting Interface).

- **Control panels and user interface** , allow manual setting of lighting scenarios, monitoring of energy consumption, and adjustment of system parameters according to specific needs.

For the smart lighting simulation in DesignBuilder, natural lighting simulation must be activated in "detailed" mode. The software can also account for adjacent buildings, trees, reflections, or any other elements that may influence natural lighting in our building.

After this setting is activated, it is necessary to select automatic control, illuminance, and the electric power at which luminaires can operate in the "Lighting" tab, as well as the control type and the working plane height for which illuminance must reach the value set .The control type can be linear (via DALI dimmer), stepwise, or linear to off. The linear option is selected.

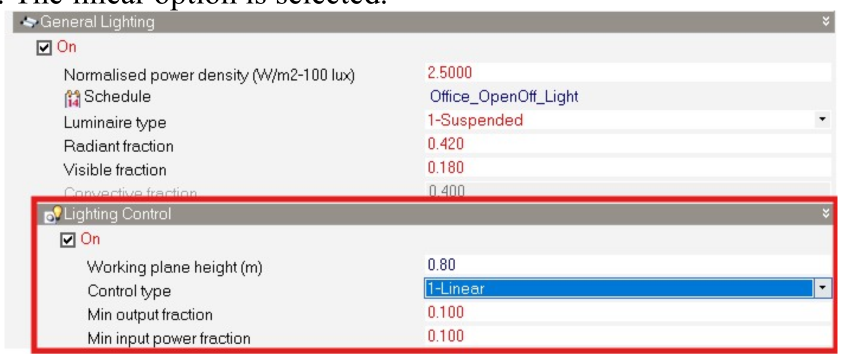

Figure 4.1. Presets for smart lighting control simulation in DesignBuilder

4.2. Simulation of the System with Demand-Controlled Ventilation – V2

Demand-Controlled Ventilation (DCV) is a modern energy-efficient strategy for buildings, adjusting fresh air supply according to actual occupancy. Unlike conventional systems operating at constant design airflow rates, DCV reduces airflow in partially occupied or unoccupied rooms while maintaining indoor air quality, particularly effective for offices, classrooms, and hotel rooms with variable occupancy [6].

4.2.1 Control Strategy

The system in DesignBuilder is modelled with the following elements:

- **Sensors:** CO_2 sensors measure indoor air concentration, while occupancy sensors detect presence.
- **Variable Air Volume (VAV) Dampers:** Modulate airflow to match real-time demand.
- **Fan Speed Control:** Variable Frequency Drives (VFD) adjust fan speed to maintain system pressure.
- **CO_2 Setpoint:** Indoor CO_2 is maintained 400 ppm above outdoor levels, based on NOAA measurements for Constanța.
- **Neutral AHU Role:** The Air Handling Unit (AHU) provides ventilation only, without heating or cooling the zones.

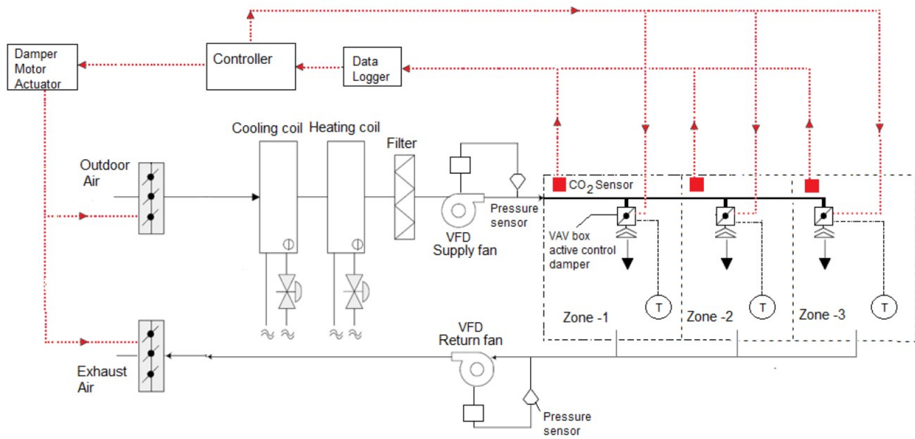

Figure 4.2. Functional scheme of the fresh air loop [7]

4.2.2. Simulation Setup in DesignBuilder

The simulation includes three categories of settings:

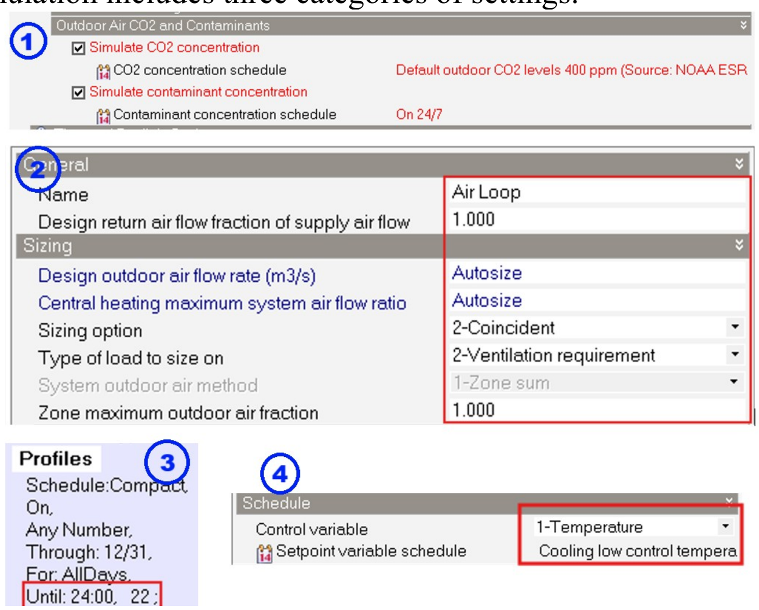

Figure 4.3. Site parameters setup in DesignBuilder

1. **Site Settings:** Outdoor CO_2 concentration, climate data, and location parameters. (constant outdoor CO_2 concentration of 400 ppm is assumed, based on NOAA measurements, considering this value appropriate for the purpose of the simulation). [8]
2. **Air Loop Settings:** Balanced supply and exhaust airflow, sizing according to zone demand, and neutral system load.
3. **Zone Groups Settings:** CO_2 setpoints, calculation of fresh air per zone, and system neutrality for heating/cooling.[3]
4. **Terminal Units (VAV Dampers):** Control airflow based on CO_2 and occupancy, adjusting schedules to each zone's demand.

4.2.3 Benefits of DCV

- Avoids over-ventilation while maintaining high indoor air quality.
- Reduces energy consumption for heating, cooling, and dehumidification.
- Allows real-time monitoring of occupancy and ventilation rates.
- Enables zone-specific ventilation and flexible adaptation to changes in space use.
- Provides operational data for maintenance, energy management, and safety analysis

4.3. Simulation of the System with Automated Solar Shading – V3

Solar radiation significantly affects both the energy performance and indoor comfort of office buildings. While natural light reduces artificial lighting demand and enhances occupant well-being, excessive solar gains may cause overheating, glare, and additional HVAC loads. [9]

4.3.1. Classification of Shading Systems

- **External:** brise-soleil, canopies, light shelves, external blinds, solar films.
- **Between-glass units:** louvers integrated in double glazing.
- **Internal:** textile or metalized blinds, opaque or semi-transparent shades.
- **Glazing-integrated:** reflective/absorptive glass, electrochromic glass.

Control types: manual, automated, or hybrid, depending on occupancy patterns and space function.

4.3.2 Simulation Setup

For the energy simulation, **automated external blinds** were selected due to their efficiency in limiting unwanted solar gains:

- **Summer:** fixed angle optimized to reduce solar gains without compromising daylight.
- **Winter:** fully retractable to maximize passive solar heating.

This configuration balances summer solar protection with winter passive heating, enhancing overall building energy performance.

4.4. Simulation of the System with EC Fan Coil Units – V4

Fan coil units (FCUs) equipped with Electronically Commutated (EC) brushless motors represent a significant upgrade in HVAC systems, offering improved energy efficiency, thermal comfort, and intelligent control compared to conventional AC motors. EC motors are DC motors with electronic commutation, eliminating carbon brushes and reducing friction, noise, and maintenance while increasing service life [10]

4.4.1 Advantages of EC Fan Coil Units

1. **Energy Savings:** Continuous and precise fan speed control allows a 45–50% reduction in energy consumption compared to traditional AC units.

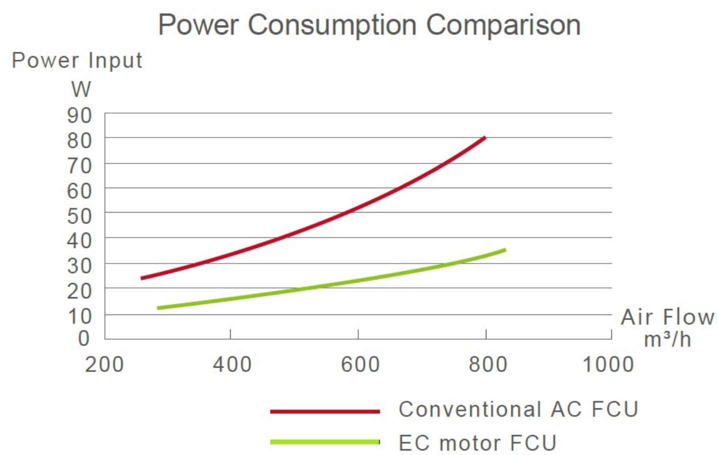

Fig. 4.4 – Electric power versus airflow for AC and EC motors. [10]

2. **Enhanced Thermal Comfort:** Proportional control via pulse-width modulation (PWM) ensures stable temperatures and humidity, minimizing thermal oscillations and discomfort.
3. **Quiet Operation:** Brushless operation, aerodynamic fan design, high-quality bearings, and acoustic insulation reduce noise, particularly at low to medium speeds.
4. **Flexible and Intelligent Control:** Compatible with both stand-alone and BMS-integrated systems, allowing individual unit control, zone-based operation, and real-time performance optimization [10]

4.4.2. Simulation Setup

In DesignBuilder, EC FCUs were modeled with the **"variable fan" option**, enabling precise modulation of both airflow and thermal agent flow for each zone.

5. Analysis of Results and Energy Consumption Comparison

5.1. Smart Lighting (V1)

The implementation of the smart lighting system had a significant impact on the building's energy consumption, affecting lighting as well as cooling and heating loads. A comparison between the reference scenario (V0) and the optimized scenario (V1) shows a notable reduction in energy use for lighting and cooling, while heating experiences a slight increase due to reduced internal heat gains.

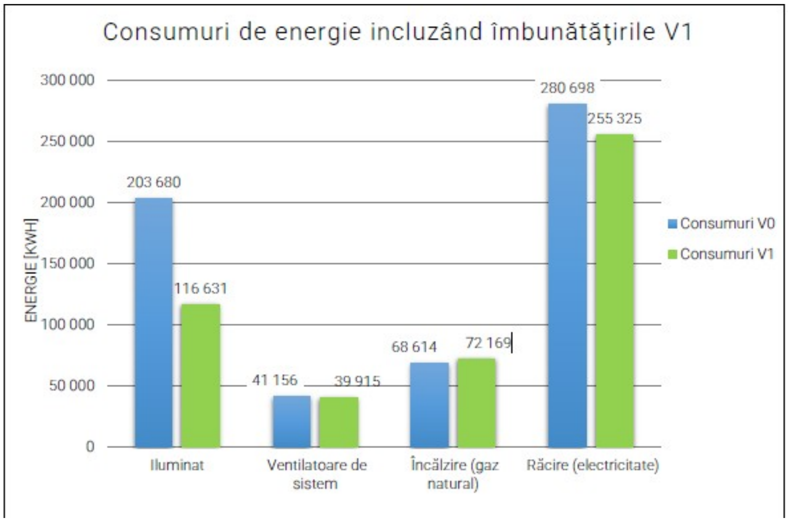

Figure 5.1 : Annual Energy Consumption for Lighting, Cooling, and Heating

Analyzing the share of each component in the cooling load indicates an indirect positive effect of the automated lighting system: lighting-related heat gains decrease significantly, while contributions from equipment, solar gains, and human presence remain relatively constant.

Overall, the smart lighting system achieves a net annual energy saving of approximately 12.7%, highlighting the efficiency of this simple and easily implementable measure in office buildings.

5.2. Demand-Controlled Ventilation (V2)

In this stage (V2), the system was enhanced by implementing Demand-Controlled Ventilation (DCV) over the previously optimized configuration with automated lighting (V1). The primary goal of DCV is to adjust the supply of fresh air based on occupancy levels and CO_2 concentration, reducing the energy consumption of fans and the heating load for outdoor air during the cold season.

The impact on cooling loads was minimal. Although a lower fresh air flow might be expected to reduce cooling demand, simulations show that the heat contribution from incoming air is mitigated by the heat recovery unit in the Air Handling Unit (AHU). Consequently, its share in the total cooling load remains negligible.

Similarly, latent loads at the fan coil units did not increase significantly. This indicates that the reduced fresh air in V2 did not adversely affect indoor humidity compared to V1, and thus did not increase the latent cooling requirement

Overall, compared to V1, implementing DCV in V2 resulted in an additional **2.8% reduction in total energy consumption**, mainly due to decreased fan energy and lower heating demand for the fresh air supply. The effect on cooling requirements remains marginal, thanks to the efficiency of the heat recovery system and the limited contribution of fresh air to total cooling loads.

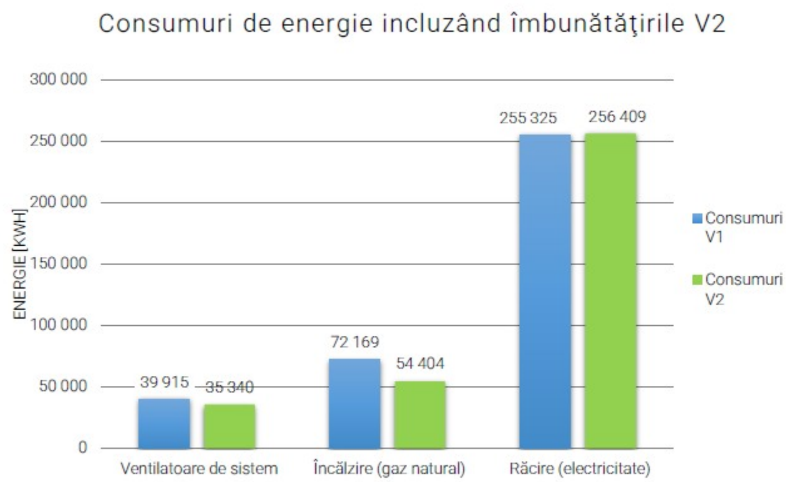

Figure 5.2. Energy consumption changes integrating demand-controlled ventilation

5.3. Automated Solar Shading (V3)

In this stage (V3), the system was enhanced through the integration of automated solar shading devices designed to reduce incident solar radiation on glazed surfaces. This optimization leads to a notable reduction in cooling energy demand, while slightly increasing artificial lighting consumption due to the lower availability of natural daylight indoors.[9]

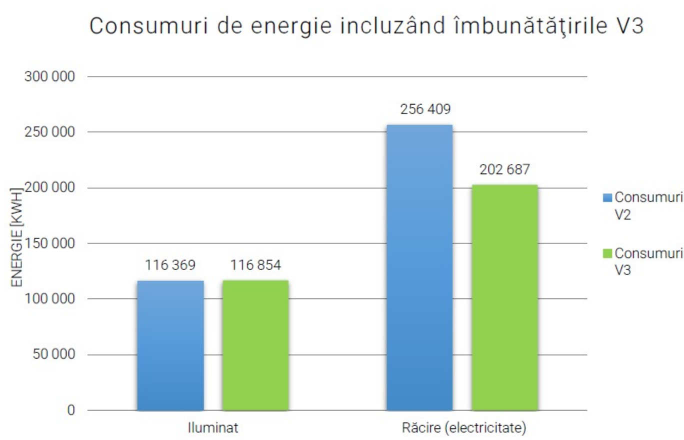

Figure 5.3. Energy consumption changes integrating Automated Solar shading

The energy performance of this configuration presents the consumption profiles obtained for scenarios V2 and V3.

A detailed breakdown of the cooling load is shown, where the share of solar gains through glazing decreases from 50% to 38% of the total cooling load. This confirms the effectiveness of automated shading in limiting solar heat input.

The overall annual energy balance indicates that the reduction in cooling demand compensates for the minor increase in lighting energy. The net effect of the measure is a total annual energy saving of approximately **8%**.

5.4. EC Fan Motors for Fan Coil Units (V4)

The final optimization stage (V4) involved replacing conventional fan coil unit (FCU) fans with Electronically Commutated (EC) motors, enabling continuous modulation of airflow to match thermal loads. This measure reduces electricity consumption for fans while providing improved thermal comfort through more stable adherence to setpoint temperatures.

The results show a marked decrease in fan energy use, offset by slight increases in heating and cooling demand due to reduced heat recovery efficiency and finer control of indoor temperature. Thermal conditions in occupied zones became significantly more stable, with reduced deviations from the setpoint.

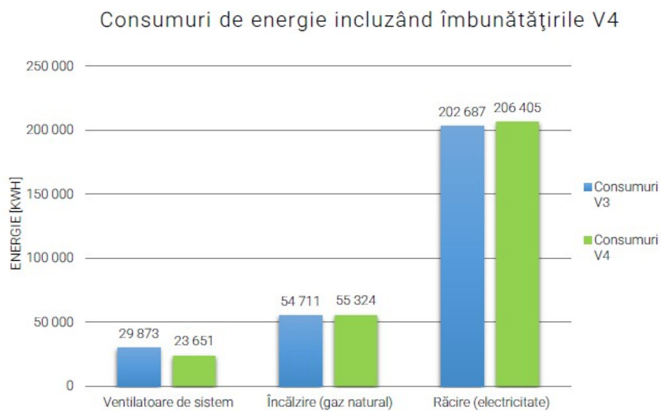

Figure 5.4. Energy consumption by end-use after integrating EC fan motors in FCUs

Daily operation analysis further highlights the enhanced precision of EC motors: during cooling, setpoint proximity was maintained with minor increases in energy demand, while in heating, energy use decreased locally at FCUs but required greater input from the central system to compensate for lower exhaust air temperature.

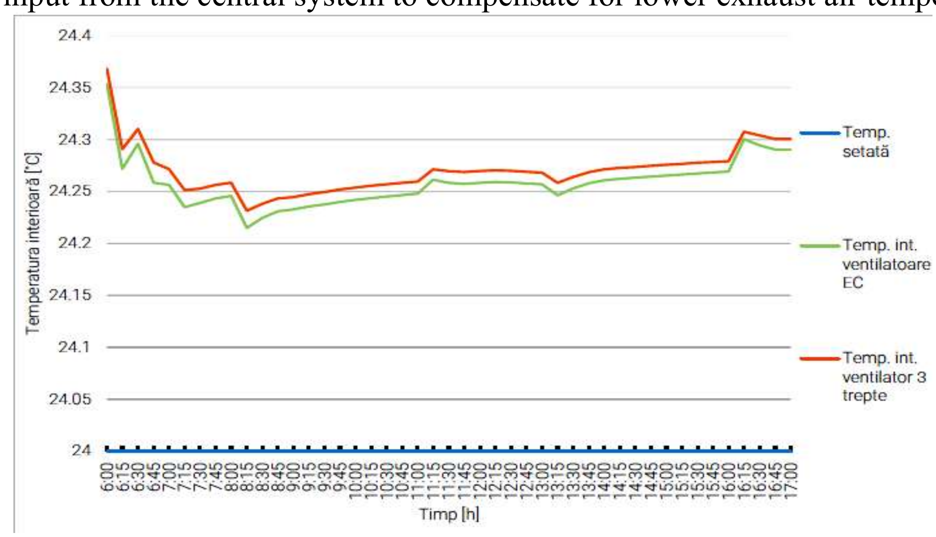

Figure 5.5. Indoor temperature variation during a summer day: comparison between conventional and EC fan motors

On an annual basis, the energy savings achieved were modest, 679,415 kWh/year compared to 677,523 kWh/year (≈0.22%). Nevertheless, EC motors provide qualitative advantages, including reduced noise, higher comfort stability, and seamless integration into smart building platforms. When aggregated with previous measures, the hierarchy of contributions to total savings becomes clear: intelligent lighting (≈12.7%), automated solar shading (≈6.7%), demand-controlled ventilation (≈2.5%), and EC fan motors (≈0.2%). The combined effect demonstrates the added value of layered optimization strategies in achieving superior energy efficiency

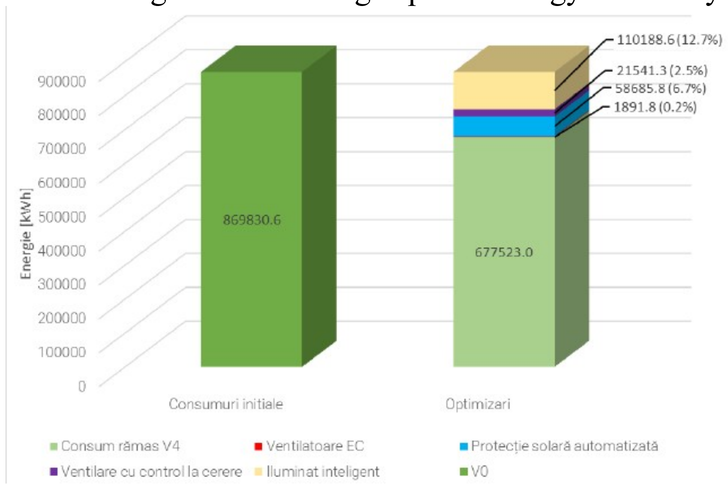

Figure 5.6. Cumulative impact of all optimization measures (V0–V4) on total building energy used

5.5. Payback Time Analysis for Smart Lighting [13]

The analysis is based on reference data from the Northwest Energy Efficiency Alliance (NEEA, 2020), with international costs converted from USD/ft² into RON/m². The estimated cost of a conventional system is 55 RON/m², while the smart lighting system reaches 82 RON/m², representing a difference of about 49%, or an additional 27 RON/m².

For the modeled building with a usable area of 4,800 m², the total additional investment required for implementing smart lighting is approximately 131,100 RON. Considering an average electricity price of 1.19 RON/kWh, the annual operating cost of the conventional system is estimated at 242,379.6 RON, compared to 139,054.5 RON for the smart system. The resulting annual savings of around 103,325 RON lead to a payback period of only 1.27 years when considering the additional investment compared to a conventional solution, or 3.82 years when accounting for the total cost of the smart lighting system. These results confirm the strong economic feasibility of smart lighting and support its integration in both new projects and major renovations, particularly in the current context of energy efficiency requirements.

5.6. Smart Readiness Indicator (SRI) Evaluation

The Smart Readiness Indicator (SRI) [15] is a European assessment tool developed under the revised Energy Performance of Buildings Directive (EPBD) to quantify the level of building digitalization and automation. Its objective is to measure the building's ability to adapt operation for the benefit of occupants, energy efficiency, and interaction with surrounding energy networks. The evaluation in this dissertation was performed using the official European platform https://srienact-tool.eu

Two scenarios were analyzed: the baseline building (V0), equipped with conventional systems and no BMS, and the improved building (Vfinal), with all proposed smart solutions implemented. The results show a significant increase in SRI across most dimensions. Energy efficiency improved from 22.39% to 57%, comfort from 20.13% to 59.75%, health and accessibility from 22.22% to 61.11%, and predictive maintenance from 0% to 26.62%. Even communication with occupants rose from 3.19% to 19.31%, while flexibility and storage grew from 2.6% to 19.09%.

The only dimension with limited progress is the Grid component, increasing from 2.6% to 19%, reflecting the current lack of standardized methodologies and infrastructure for grid integration. Although these functionalities primarily aim at cost optimization (dynamic tariffs, demand response) rather than direct building energy efficiency.

Overall, the SRI evaluation demonstrates a major improvement in smart readiness after implementing the simulated measures. Despite the modest contribution of grid interaction, the indicator provides an essential complementary perspective to energy analysis, emphasizing adaptability, digital interaction, and systemic efficiency in smart buildings

5.7. Alternative Measures for Energy Optimization

An effective measure for reducing cooling loads is the integration of an adiabatic humidifier on the outdoor air stream before the heat recovery unit (CIBSE, 2016). For an AHU sized at 30,000 m³/h (outdoor air 35.3 °C, 35% RH; indoor air 24 °C, 50% RH), the cooling coil demand decreased from 142 kW (without humidification) to 83 kW (with adiabatic pre-cooling), representing a 41.5% reduction. Simultaneously, heat recovery increased from 89 kW to 139 kW. This demonstrates the significant potential of adiabatic pre-cooling in lowering cooling energy consumption. Water use can be optimized by reusing condensate collected from the building. [11] . In fan-coil based cooling systems, design temperatures (7/12 °C or 8/14 °C) are often oversized for transitional seasons. Raising the supply temperature (e.g., from 7 °C to 10 °C) increases return temperature proportionally (12 °C to 15 °C), reduces latent load, and improves the chiller's efficiency due to higher evaporator operating temperatures. This strategy reduces electricity consumption and lowers dehumidification demand in fan-coils. TES systems decouple cooling production from demand by storing chilled water or ice during off-peak hours, when chillers operate at higher EER due to lower ambient temperatures (ASHRAE, 2020). During daytime, stored cooling is released, reducing peak electrical demand and enabling the use of smaller, more efficient chillers. Benefits include lower operating costs, deferred capital investment, and reduced stress on the electrical grid, making TES a sustainable and economically attractive solution. [12]

6. Conclusion

This study investigated the impact of implementing smart solutions in office buildings on overall energy performance. Using a detailed virtual model in DesignBuilder, simulated with EnergyPlus, four practical measures were evaluated for their demonstrated energy-saving potential: smart lighting, demand-controlled ventilation (DCV), automated shading, and EC fans in fan-coils.

The simulations revealed a total energy reduction of approximately **22%**, with the largest contributions from smart lighting (**12.7%**) and automated solar protection (**6.7%**). The cumulative effect of all applied measures decreased annual energy consumption from **869,830 kWh/year** to **677,523 kWh/year**, lowering the specific energy demand from **181 kWh/m²/year** to **141 kWh/m²/year**, approaching near-zero energy building (nZEB) standards.

Additional measures, such as indirect adiabatic cooling, chilled water reset, and thermal energy storage, were identified as further opportunities for optimization, either through advanced technologies or by enhancing the interaction of existing systems.

Beyond energy savings, the analyzed solutions enhance indoor comfort, reduce operational noise (notably from EC fans), and improve environmental controllability, which are critical aspects for modern buildings.

For the highest-impact measure—smart lighting—a payback analysis based on real cost data indicated a payback period of 1.27 years relative to additional investment over conventional systems, or 3.82 years relative to total system cost, demonstrating strong economic feasibility.

The Smart Readiness Indicator (SRI) assessment further highlighted the building's digital and automated capabilities. The overall SRI increased markedly from 9.3% (initial state) to 35.5% (optimized state), with the energy efficiency component improving from 22.39% to 57.11%. This confirms the ability of smart technologies to enhance not only automation but also operational efficiency and cost reduction.

In conclusion, dynamic simulations clearly demonstrate that smart building technologies can significantly reduce energy consumption, improve occupant comfort, and enhance sustainability. The results validate the technical and economic rationale for implementing these solutions, while the inclusion of SRI provides a comprehensive evaluation framework that captures both automation levels and the building's capacity to interact dynamically with external energy networks.

7. Acknowledgments

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