Dynamic BIM-Based Simulation for Optimizing Ventilated Facades: Enhancing Architectural Design for Energy Efficiency

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Abstract

The trend of recent years is the use of a building information model (BIM) in the early design stages. This procedure positively affects the entire life cycle of a building, especially its construction and operation, during which the largest percentage of financial and energy resources are spent. The consumption rate of these resources is directly influenced by the architectural design of the building, from shape solutions to structural and material characteristics of passive systems. One of them is a multilayered external envelope with a ventilated gap, which reduces heat gains during the summer and better accumulates heat from solar radiation during the winter. The fact is that the internal climate in the gap is different from the external environment and is influenced mainly by the external temperature, air flow speed, sunlight intensity, material on the external and internal facade and shading from surrounding buildings. The aim of the work is to develop a simulation tool that will lead to a more efficient design of the shape of the building envelope with a ventilated gap. The tool will simulate the impact of solar radiation on the facade at a certain day and hour of the year, shading from surrounding buildings and materials on the external surface and their influence on the temperature course in the ventilated gap. This simulation will run dynamically on the background of the architectural design and will support the decision-making process. This could subsequently lead to savings in the total energy consumed for heating and cooling the building.

Keywords: *BIM, ventilated façade, thermodynamic analysis*

1. Introduction

The building envelope plays a key role in ensuring energy efficiency, thermal comfort, and the long-term durability of buildings. Among available strategies, ventilated façade systems are increasingly applied due to their ability to balance heat gains and losses through a controlled air cavity. These systems contribute to improved thermal and hygrothermal performance, especially when designed in relation to solar exposure and orientation.

At the same time, the adoption of Building Information Modeling (BIM) has fundamentally transformed the design and operation of buildings. BIM enables performance-based design approaches, allowing for data-driven decision-making even in early design phases. Its integration with environmental simulation tools supports a more accurate assessment of the building envelope's behavior under dynamic climatic conditions.

This study explores the intersection of BIM, parametric modeling, and façade performance, with a particular focus on optimizing ventilated cavities for energy efficiency in architectural design.

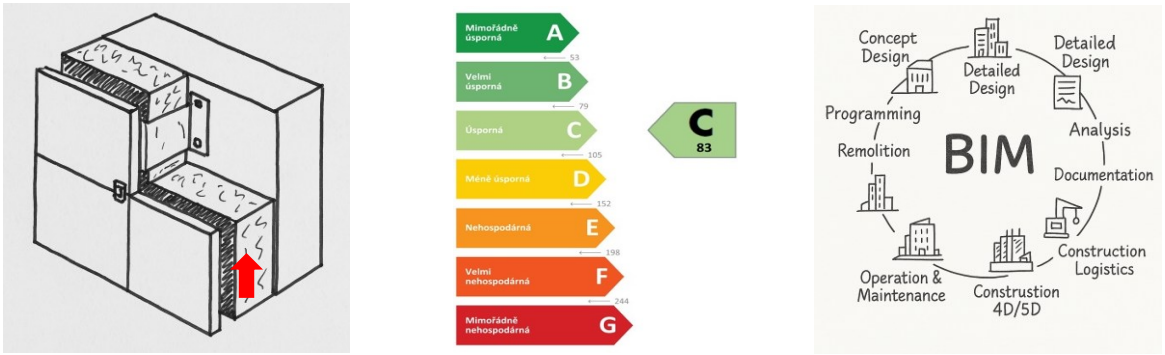

Fig. 1. Figure of the three thematic strands running through the research - double-skin façade with ventilated gap, building energy efficiency and BIM (source: author's own processing)

1.1 Ventilated façade

Ventilated façade systems represent the contemporary standard for building envelope design, ensuring a favorable thermal and hygrothermal performance of the construction. This multilayered envelope typically consists of five primary components:

- The inner load-bearing structure, which forms part of the building's vertical structural system. It may be either an infill wall or an integral element of the structural framework.
- The thermal insulation layer, whose thickness is mainly determined by regulatory requirements, particularly Czech Standard ČSN 73 0540 – Thermal Protection of Buildings.

- The supporting structure for the external cladding, which is a separate anchoring system composed of steel, stainless steel, or aluminum subframes, anchors, and clips designed to resist mechanical loads and secure the external cladding.
- The ventilated air cavity, typically 20–60 mm thick and connected to the external environment. This cavity is a critical element of the system. Through the stack effect, air circulates within the cavity, enabling essential building physics phenomena.
- The external cladding, which comes in various materials and fastening systems.

In common design practice, ventilated façade assemblies are often designed based on the empirical experience of the architect or engineer, while still complying with current regulations concerning thermal, acoustic, fire safety, mechanical resistance, and structural stability. Additionally, economic efficiency is considered to minimize investment costs. This approach is generally successful, producing constructions that meet legal requirements while remaining cost-effective.

Between design and execution, the contractor plays a key role, often adapting the system to fit familiar construction techniques or preferred components. The contractor typically submits shop drawings (if required) or outlines implementation principles in a Method Statement, frequently accompanied by simplified schematic details. Deeper analysis of the proposed assembly is rarely conducted due to time constraints and is virtually absent from standard design practice [1]. This article proposes a more detailed design procedure that may lead to optimized outcomes.

Advantages of ventilated façade systems:

- Favorable thermal and hygrothermal performance of the building envelope
- Thermal stability (mitigation of heat gains and losses)
- Improved acoustic properties compared to contact or lightweight façade systems
- Long service life
- Potential for use of cladding materials with high vapor diffusion resistance
- Disadvantages of ventilated façade systems:
- Higher direct costs compared to contact façade systems
- Requirement for skilled installation

From a performance perspective, the design - and more importantly, the execution - of the ventilated cavity plays a vital role in the overall durability of the façade system. This layer maintains a favorable microclimate within the system. For the façade to function properly, uninterrupted airflow must be ensured. As air in the ventilated cavity warms due to heat from the external cladding, it rises along the height of the façade...

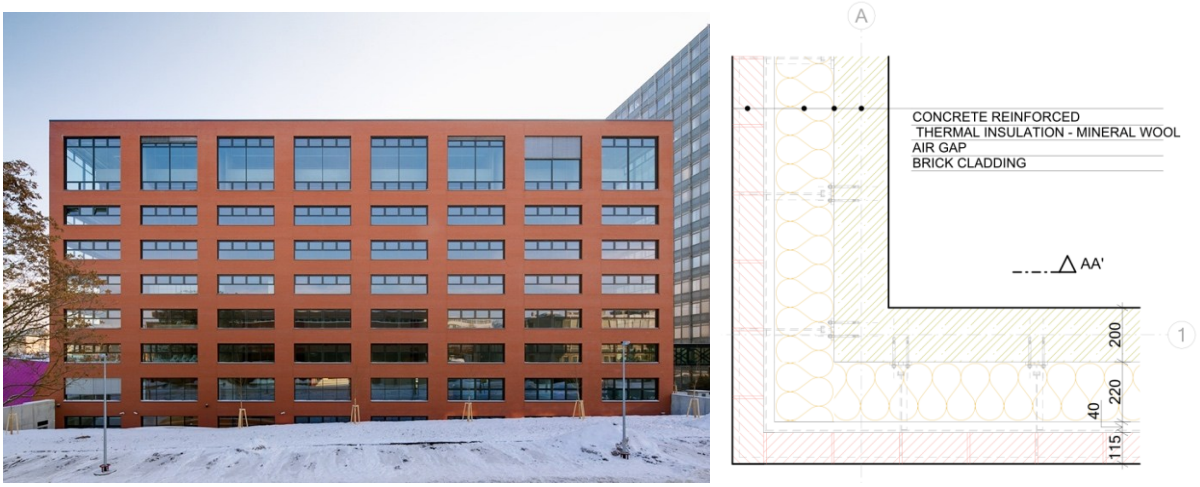

Fig. 2. Figure of the Faculty of Architecture (photo: archiweb.cz, accesed March 29, 2025) and a schematic composition of the façade structure (author's drawing)

1.2. BIM

BIM is not merely 3D modeling. It represents a fundamentally different approach to thinking and utilizing computational tools, leading to optimization in the design and operation of buildings. The role of BIM models is to create an organized database that encompasses both graphical and non-graphical information. A simple comparison can be drawn between an information model and a traditional drawing of a window in a wall. A CAD drawing represents the window as a set of lines, which carry no embedded data—at most a graphical symbol, which constitutes unstructured information. In contrast, an information model is composed of individual model instances, each carrying various types and quantities of data. Visible on the figure 2 below. These data can be easily structured into databases, enabling significantly improved control over the project.

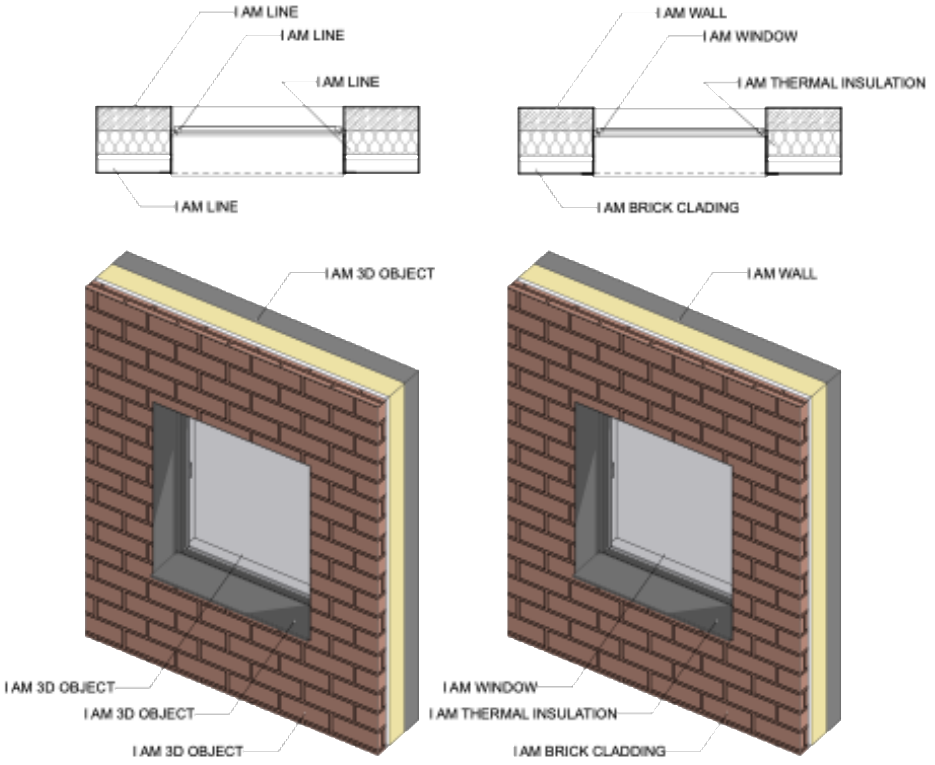

Fig. 3. Difference between information model and 3D or 2D model (author's drawing)

A wide range of software tools exists to support information modeling, each with different applications. Furthermore, there are various contractual frameworks that define the structure of individual models and sub-models, as well as several established (though often unwritten) best practices. However, the true strength of information modeling lies in the final letter of the BIM acronym: Management. One of the core tools in this regard is the Common Data Environment (CDE)—a network-accessible space available 24/7 to all stakeholders in the construction and investment process. Access and data organization rights are assigned based on user roles, ensuring that all participants always have access to up-to-date information, reducing duplication, and enhancing the transparency and control of information flow.

In the context of Building Information Modeling, traditional construction documentation—as known in standard practice—becomes merely a secondary output of the model. It is increasingly likely that, soon, such drawings will serve only as a supplement to the model, which will become the principal reference for all stakeholders.

Key advantages of BIM include:

- Control – BIM enhances control over documentation and communication through the shared data environment. System transparency leads to more efficient data and time management.
- Coordination – It allows for proactive issue resolution and facilitates more effective interdisciplinary coordination across project disciplines.
- Accuracy and quality – BIM enable the creation of a precise and detailed digital representation of the building, including all construction elements, systems, materials, and other components. This improves planning and execution, leading to higher quality outcomes.
- Greater efficiency – BIM supports faster and more effective planning, design, construction, and facility management. This contributes to cost reduction, shortened construction timelines, and improved quality of work.
- Collaboration – BIM enables architects, engineers, contractors, and building owners to collaborate within a unified digital model. This improves communication, reduces the risk of errors, and enhances project coordination.
- Better facility and systems management – BIM provides building owners with access to a comprehensive digital model containing all relevant building information. This facilitates efficient building operation and maintenance, ultimately reducing operational costs.

Key disadvantages of BIM include:

- High costs – BIM implementation can be costly, requiring specialized software and trained personnel. This may render it financially unfeasible for smaller projects.
- Complexity – BIM demands a high level of technical expertise and proficiency, which can pose challenges for some project participants, particularly small firms and contractors.
- Need for collaboration – Successful BIM implementation requires close cooperation among all stakeholders. Without effective coordination, this can result in delays and complications.
- Compatibility – BIM models are often created using different software platforms, which may lead to compatibility issues. This can result in data loss, both graphical and non-graphical.

2. Current state of knowledge

The methodological approach began with a literature review conducted via the SCOPUS online database, one of the most prominent peer-reviewed platforms in the academic community.

A quantified data analysis from the Scopus database focused on publications related to the topic of Building Information Modeling (with "BIM" used as the primary search keyword). Several aspects were examined to provide a comprehensive overview of current scientific trends and key areas of focus within this domain.

The analysis indicates that BIM represents a crucial tool for the modernization of the construction industry [1]. A notable trend is the integration of BIM with sustainable technologies and digital innovations, as evidenced by the increasing inclusion of topics such as energy efficiency, automation, and building management. Keywords and leading authors highlight the interdisciplinary nature of the field, connecting technical, environmental, and managerial perspectives. These findings served as a foundation for the research, for example by identifying and targeting underexplored areas. The results also reinforce the significance of BIM as a tool for promoting sustainable development in the construction sector.

The next step involved narrowing the dataset using Boolean operators to include only articles related to the construction sector and closely associated disciplines. Specifically, the selected subject areas included Engineering, Computer Science, Social Sciences, Environmental Science, Energy, Business, Management and Accounting, Decision Sciences, and Materials Science. Subsequently, the articles were sorted by citation count, and the top 50 most cited publications were selected for further analysis.

An analysis of these publications was conducted to identify the key areas currently at the forefront of research in construction and modern technologies. The most frequently occurring terms included data, barriers, buildings, management, digitalization, BIM (Building Information Modeling), Digital Twins, and construction. These terms reflect the main trajectories of scientific discourse, with the strongest emphasis placed on digital transformation and innovation within the field of civil engineering [2, 3, 8, 9, 11, 12].

The selected publications predominantly focus on overcoming barriers to the implementation of modern technologies and exploring strategies for effectively managing processes in the construction sector through digital tools [10]. A substantial portion of the analyzed texts consists of studies examining the application of BIM as a key instrument for managing construction projects, emphasizing its benefits in terms of sustainability, cost reduction, and enhanced stakeholder communication and large amount of simulations which lead to various types of optimization [4, 13, 14, 15].

Another recurrent topic is the concept of Digital Twins, which enable the simulation and analysis of real-world assets within digital environments, thereby contributing to the optimization of building operation and planning. Themes related to data management and organization underscore the critical importance of effective information handling, which constitutes a foundational element in the realization of digital projects.

The results of the quantitative analysis indicate that digitalization is a central theme in research and development within the construction domain. Publications frequently highlight the need for process standardization and for addressing both technical and organizational challenges.

The quantitative analysis of data from the Scopus database continued with a more refined focus. This phase of the analysis targeted publications related to the topic of ventilated façades (using "ventilated" and "facade" as the primary search keywords). Several aspects were examined to provide a comprehensive overview of current scientific trends and key areas of focus within this field.

Key findings in the field of ventilated façades highlight concepts of sustainable development, energy performance, and advanced architectural design, reflecting current trends and requirements for the construction of energy-efficient buildings. A major challenge in this area lies in optimizing the thermal performance of buildings, which involves minimizing heat losses through appropriately designed façade structures and materials.

Ventilated envelopes play a crucial role in regulating the indoor microclimate and reducing the demand for heating and cooling [16]. At the same time, there is an increasing emphasis on enhancing energy efficiency through the integration of technologies such as photovoltaic panels, double-skin façades, and natural ventilation systems, all of which synergistically contribute to achieving low-energy building performance [5].

A significant component of research in this domain involves the application of advanced technological solutions and modeling tools, including numerical models and simulations, which allow for the prediction of the performance of ventilated façades and their interactions with climatic conditions. These approaches encompass the study of thermal flow, heat transfer, and air dynamics within ventilated cavities, thereby enhancing design effectiveness and system functionality.

Equally important is the integration of environmentally friendly materials and principles of sustainable design, enabling the use of recyclable and ecological resources while promoting long-term durability and adaptability of buildings. Another vital research area includes advanced cooling methods, such as night cooling technologies and phase change materials [6]. These techniques enable the storage and release of thermal energy, reducing reliance on external energy sources and contributing to greater building efficiency.

Façade components—such as surface layers, joints, and cavities - play a key role in optimizing functional properties. These elements combine aesthetic and performance parameters, supporting long-term sustainability and improved building performance. To validate research models, both numerical and experimental methods are employed, including simulations of turbulence and radiative dynamics. These models support more accurate predictions and enable a deeper understanding of the energy savings achieved through the implementation of innovative technologies [17,18,19]. The research also underscores the importance of an interdisciplinary approach that integrates architectural expression, environmental sciences, and engineering. This synergy facilitates comprehensive solutions to sustainability challenges in the built environment.

However, identifying the limitations and challenges of current technologies - particularly under varying climatic conditions - is essential for future development. Further research should focus on the long-term reliability and return on investment of such systems, as well as the potential for broader implementation.

Ventilated façades thus represent a key element of contemporary architecture aimed at sustainability and technological innovation. Their continued research and application contribute not only to improved energy efficiency in buildings but also to the achievement of global sustainable development goals.

3. Objectives

The primary objective of this research is to develop a dynamic simulation workflow that supports early-stage design decisions for ventilated façade systems. The simulation calculates cavity air temperatures based on hourly climatic data and evaluates the thermal impact of solar radiation, façade geometry, orientation, and material properties.

A key outcome is a weighted temperature metric that enables objective comparison of different design variants. The simulation framework is intended to be flexible, applicable to low-detail BIM models, and adaptable throughout the design process. Ultimately, the goal is to support performance-driven design decisions that improve the energy efficiency of the building envelope.

4. Methodology

4.1 Provide climatic input data

For the design and assessment of building structures, the key factors are air temperature and humidity, wind direction and speed, and solar radiation, with extreme values determining the reliability of structures and average values determining the energy demand for heating. Meteorological data describe the current state of the atmosphere characterized by quantities such as temperature, humidity, wind, and precipitation, while climate data express the long-term average of these quantities for a given location.

For accurate modeling of boundary conditions of building structures, a reference climate year is used, defined according to ČSN EN ISO 15927-4. The reference climate year is compiled on the basis of long-term measurements and analyses, which allow the selection of representative climate parameters according to a precisely defined methodology. This approach provides users with comprehensive data necessary for the technical assessment of building structures in their real conditions.

The climate data set is based on the Climate.OneBuilding.org platform, which is a specialized online climate data source designed primarily for the needs of energy and environmental analyses of buildings. It provides access to a wide range of reference climate sets, which include data usable for simulations of buildings and technical systems. The database contains climate information from more than 2,900 locations around the world, compiled according to methodologies that comply with international standards.

Data are available in various formats (e.g. TMY, EPW, IWEC), which provide information on hourly variations of key meteorological variables, such as air temperature, relative humidity, wind speed and direction, solar radiation or precipitation. These data enable accurate modeling of the energy performance of buildings and technical systems, optimization of building designs and assessment of their environmental impacts.

4.2 Provide model information data

The level of development (LOD) of the information model does not fundamentally limit the capacity for proposed simulation. Simulations related to ventilated façade systems can be conducted independently of model detail, allowing for analyses to be performed on models ranging from LOD 100, which includes only basic massing and volumetric representation, to LOD 350, where elements are defined with higher geometric accuracy and associated data. This flexibility ensures that simulation workflows can be integrated into various stages of the design process without requiring fully detailed BIM models from the outset.

However, a critical prerequisite for meaningful simulation outcomes is the correct identification of interior and exterior conditions within the model. Model elements must carry sufficient semantic information to distinguish whether they are exposed to internal or external environments. This distinction is essential for thermal performance simulations, airflow analysis within ventilated cavities, and the evaluation of façade behaviour under varying climatic conditions. Models that lack this spatial and relational clarity may yield inaccurate or incomplete simulation results.

In addition to geometric information, the model must be enriched with non-graphical data that is relevant to ventilated façade simulations. These data parameters include material properties (e.g., thermal conductivity, density, vapor diffusion resistance), system layer compositions, cavity dimensions, cladding characteristics, and information about connections to structural or anchoring systems. This set of attributes must conform to a consistent data standard to ensure compatibility with proposed simulation and maintain interoperability across software platforms.

The integration of such data is essential for enabling the parametric control and performance evaluation of the façade system within BIM-based simulation environments. By embedding this information directly into the model, we can leverage real-time feedback and simulation results to inform design decisions, ultimately contributing to more efficient building envelopes. Establishing a structured, simulation-ready data standard is therefore a key step toward optimizing workflows for ventilated façade analysis within the broader context of digital design and building performance assessment.

4.3 Design a computational model

For design optimization and simulation, the study utilizes Rhinoceros in combination with the Grasshopper plugin—a visual programming environment embedded within Rhinoceros. Grasshopper is designed for parametric modeling and allows users to create complex 3D models and algorithmic design workflows without the need to write conventional programming code. It operates on a node-based interface, enabling intuitive programming through graphic elements, which makes it particularly accessible to architects and engineers. The Live Connection between Archicad and Rhino/Grasshopper facilitates seamless interoperability between design and analysis, simplifying the iterative modification of the model based on simulation results.

An additional tool used in this research is Ladybug, an open-source plugin for the Grasshopper platform, focused on environmental data analysis and the simulation of factors that influence building design. Ladybug is part of the broader Ladybug Tools suite, which offers advanced features for simulating energy performance, daylighting, and other environmental aspects of building design. Integrated into the parametric modeling workflow within Rhinoceros 3D, Ladybug enables designers to visualize and analyze climate-related data directly within their modeling environment, thereby supporting informed and sustainability-oriented design decisions [7].

The simulation developed for this research calculates the air temperature within the ventilated cavity of a façade system. The temperature is computed based on the methodology and equations defined in the Czech technical standard ČSN 73 0540 – 4 (Thermal protection of Buildings - Calculations methods). In order to account for the effect of solar radiation on the temperature rise in the cavity, the following formula is applied:

$$\mathbf{T_{eq}} = \mathbf{T_e} + \frac{\mathbf{I} + \boldsymbol{\alpha}}{\mathbf{H_e}} \qquad \mathbf{T} = \frac{U_v \times T_{ai} + U_z \times T_{eq}}{U_v + U_z}$$

Where:

T_e	ambient outdoor temperature [°C]
T_{eq}	radiation-corrected external temperature [°C]
T	temperature in the ventilated cavity [°C]
T_{ai}	interioer temperature [°C]
I	incident solar radiation [W/m²]
A	surface absorption coefficient [-]
H_e	external heat transfer coefficient [W/m²K]
U_z	unit of the thermal transmittance from cavity to exterior [W/m²K]
U_v	unit of the thermal transmittance from cavity to interior [W/m²K]

This approach enables a dynamic evaluation of the thermal environment within the cavity, considering both climatic inputs and surface material properties.

The global horizontal solar radiation data were converted into incident radiation on façade surfaces using the Ladybug Tools plugin within the Grasshopper environment. This transformation accounts for the specific orientation and inclination of each façade segment relative to the sun path throughout the year. To ensure accurate results, it is crucial that the geometry of the façade is defined with correctly oriented surface vectors, as these vectors determine the directionality of each plane. Inconsistent or reversed vector orientations can lead to substantial inaccuracies in solar radiation mapping.

In addition to solar angle calculations, the simulation also incorporates self-shading effects, which can significantly reduce the amount of solar radiation received by parts of the façade. These shading effects were computed using the MeshShadow component from Ladybug, which analyzes the occlusion of sunlight caused by the building's own geometry. This enables a more realistic evaluation of solar gains, particularly in the case of articulated or deeply modulated façade designs. The combination of solar position data, orientation-aware radiation mapping, and geometric shading analysis provides a robust foundation for simulating the thermal behavior of ventilated cavities.

4.4 Design an evaluation system

The simulation model generates a structured dataset describing the thermal behavior of the ventilated cavity across defined façade segments. For each segment, the model calculates the air temperature inside the cavity based on hourly climatic data throughout the simulation period. Additionally, it determines the average cavity temperature during hours when solar radiation is present, providing insight into the thermal impact of solar exposure. The model also records the cumulative duration of solar radiation for each façade segment, expressed in hours.

In addition to numerical results, the simulation outputs graphical representations of the cavity air temperature development over time for each façade segment, facilitating visual comparison of thermal performance. The model also includes an analysis of the façade's surface composition, calculating both the absolute area (in square meters) and the relative share (in percentage) of each segment. This spatial analysis supports a better understanding of thermal behavior in relation to façade geometry and orientation.

To enable the evaluation of the building envelope as a whole, the model calculates a weighted average of the cavity air temperature across all façade segments. This approach accounts for the varying sizes of the individual segments by weighting the temperature of each one according to its surface area. As a result, larger segments contribute proportionally more to the final value, reflecting their greater influence on the overall thermal performance of the ventilated cavity system. The resulting weighted temperature offers a single, representative indicator that summarizes the cavity's thermal behavior at the scale of the entire building envelope. This metric serves as a comparative benchmark for assessing different design variants and identifying those with more favorable thermal characteristics under given climatic conditions.

The weighted temperature is calculated as follows:

$$\mathbf{T_{weighted}} = \frac{\sum(\boldsymbol{A_i} \times \boldsymbol{T_i})}{\sum \boldsymbol{A_i}}$$

Where:

$T_{weighted}$	area-weighted average cavity temperature [°C],
A_i	surface area of façade segment i [m²],
T_i	cavity temperature corresponding to segment i [°C].

4.5 Model Limitations and Simplifications

Several simplifying assumptions were made in the simulation model in order to maintain computational efficiency and focus on core variables. Firstly, transient variations in the outdoor environment—such as cloud cover, wind gusts, and other short-term atmospheric phenomena—were not explicitly modelled. These effects introduce high-frequency variability that falls outside the intended scope of this study. Secondly, the influence of surrounding built structures was not considered. The current simulation assumes an unobstructed site, while the impact of external shading from nearby buildings will be the subject of future research.

Furthermore, the thermal phase shift of the façade material—i.e., the time delay between surface heating and heat transfer—was neglected due to the primary focus on air temperature dynamics rather than material-specific thermal storage. The absorptivity and reflectivity of the surrounding environment were also not accounted for, as these parameters require detailed spectral and contextual input that is beyond the resolution of the current model. Lastly, aerodynamic effects within the ventilated cavity, including turbulent flow and pressure-driven variations, were simplified to idealized assumptions. While these phenomena can influence convective heat transfer, their modeling requires advanced CFD approaches, which are outside the scope of this study.

5. Results

Let us consider the design variant. The input model data represents a generalized building envelope corresponding to the intended construction project. At this early stage, the model is characterized by low geometric detail, with only the building volume and site location clearly defined. In this context, the simulation serves as a decision-making tool for optimizing the placement of the building on the site, particularly in relation to its orientation toward cardinal directions.

For instance, if the building is positioned as illustrated below, the ventilated cavity benefits from positive solar heat gains during the winter period (October to March). Under these conditions, the area-weighted average temperature within the cavity during operational hours reaches 6.5 °C. If the same building were rotated by –15°, the weighted temperature would decrease by 0.05 °C, which can be interpreted as a slightly less favorable option at this stage of the design process. For the simulation, a commonly used cavity depth of 40 mm was applied, along with a typical façade cladding material consisting of fiber cement panels.

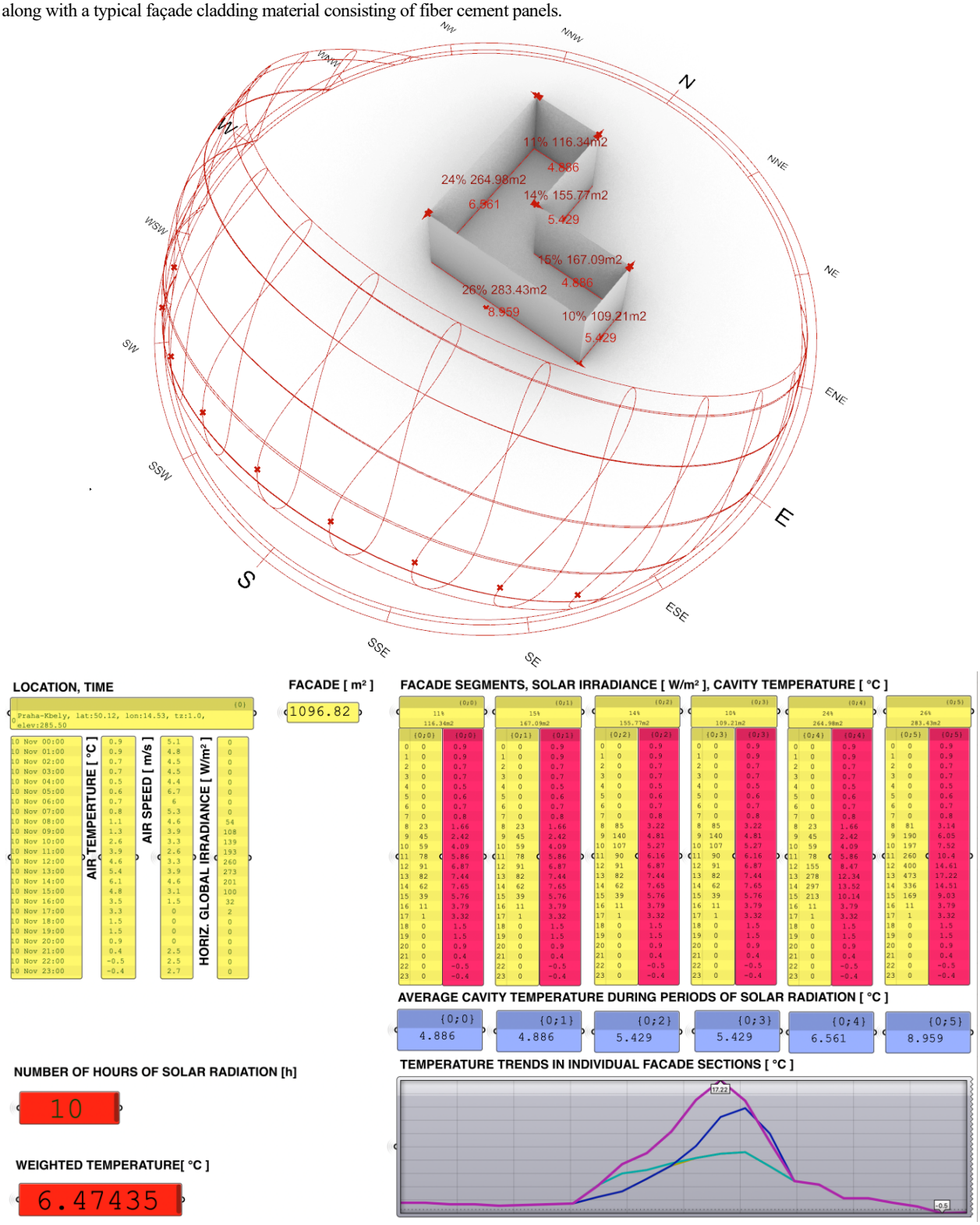

Fig. 4. Results for generalised geometry in Grasshopper and Rhino interface, geometry iss fully conected with ArchiCad via LiveConnection (author's proposal)

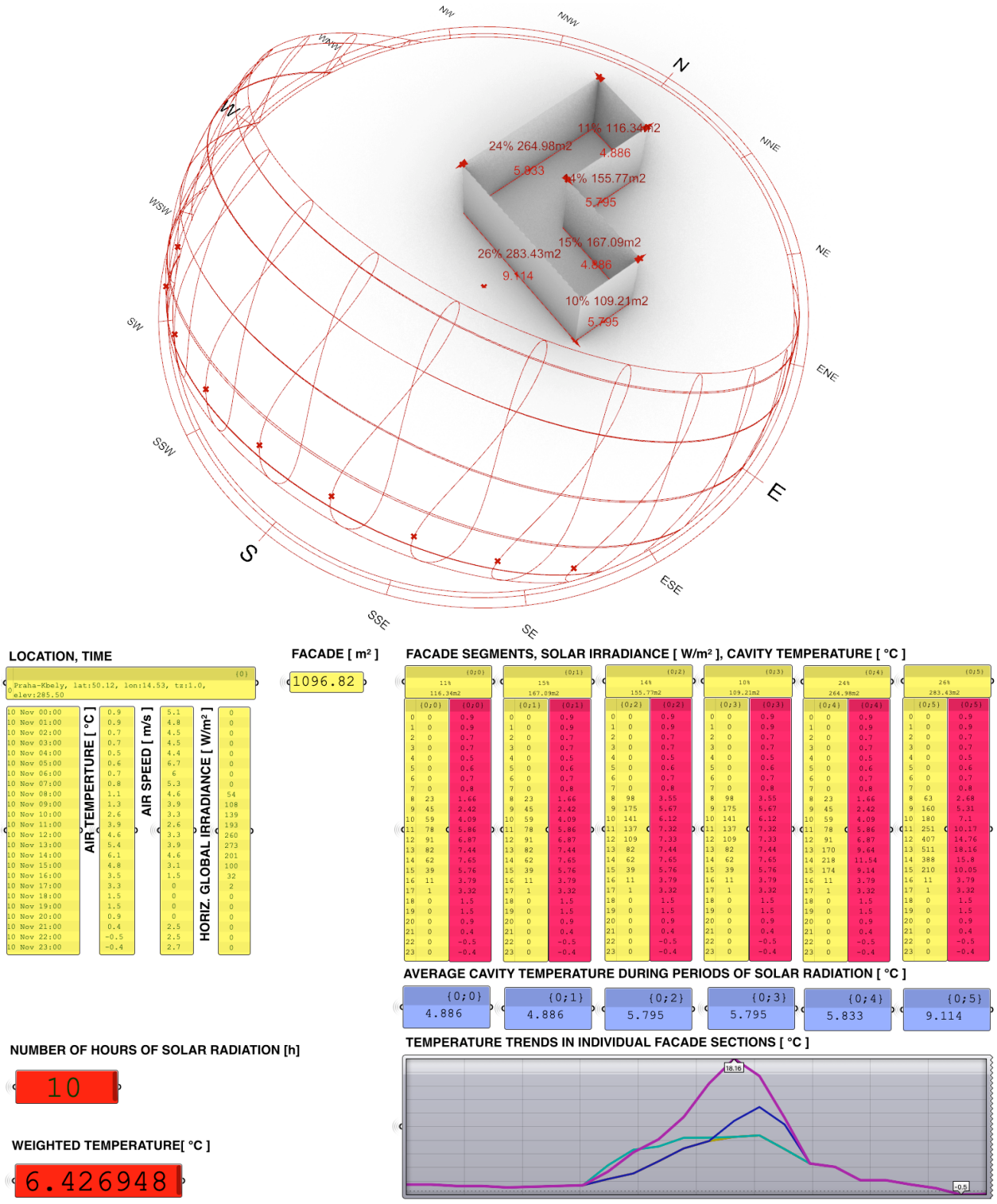

Fig. 5. Results for the same geometry but with –15°, rotation around z axis (author's proposal)

The potential applications of this simulation approach are numerous and can be further expanded throughout the design process. These include, for example, testing different cladding materials, incorporating more detailed geometric representations, evaluating multiple volumetric massing options, or refining boundary conditions based on site-specific constraints. As the design develops, the simulation framework can flexibly adapt to increasing model complexity and provide valuable feedback for performance-driven decision-making.

6. Conclusion

This article presents a computational approach for analyzing the thermal behavior of ventilated façade cavities based on geometric segmentation and climatic data inputs. The simulation model, developed within the Grasshopper environment using Ladybug Tools, enables dynamic evaluation of cavity air temperatures across distinct façade segments, incorporating solar radiation, orientation, and self-shading effects. The methodology provides not only detailed local results, such as average and peak temperatures during periods of solar exposure, but also a global performance indicator in the form of an area-weighted cavity temperature. This allows for objective comparison between different façade design variants under consistent boundary conditions.

The proposed workflow demonstrates the potential of parametric modeling and environmental analysis tools for early-stage architectural decision-making. Despite several simplifications—such as the omission of surrounding built context, phase shift of materials, or detailed airflow modeling—the results offer valuable insights into how façade geometry and orientation influence thermal performance. Future research will focus on incorporating additional factors such as urban shading, detailed material behavior, and convective dynamics within the cavity to further enhance the precision and applicability of the model in real-world scenarios.

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