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2025

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ÚSTAVU KONŠTRUKCIÍ V ARCHITEKTÚRE A INŽINIERSKYCH STAVIEB FAD STU V BRATISLAVE
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PROGRAM

09:00 - ÚVOD
09:10 - 10:45 - PREZENTÁCIA VÝSKUMNEJ ČINNOSTI DOKTORANDOV (BLOK 1)
10:45 - 11:00 - COFFE BREAK
11:00 - 12:30 - PREZENTÁCIA VÝSKUMNEJ ČINNOSTI DOKTORANDOV (BLOK 2)
12:45 - 13:30 - OBED (ALŽBETKA)
14:00 - 15:00 - KOMENTOVANÁ PREHLIADKA MODERNIZOVANEJ SNG (VAJANSKÉHO NÁBREŽIE)

*program je predbežný, jeho zmena je vyhradená

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VÝSTUP

ŠPECIÁLNE VYDANIE MLADEJ VEDY - PREZENTUJÚCI ÚČASTNÍCI ODOVZDAJÚ ODBORNÉ ČLÁNKY NA RECENZIU V TERMÍNE DO 31.5.2025

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RESEARCH ON DOUBLE-SKIN TRANSPARENT FACADES: A CONCEPT OF MODULAR ADAPTIVE FACADE UTILIZING RENEWABLE ENERGY SOURCES

VÝSKUM DVOJITÝCH TRANSPARENTNÝCH FASÁD: KONCEPT MODULÁRNEJ ADAPTÍVNEJ FASÁDY VYUŽÍVAJÚCEJ OBNOVITEĽNÉ ZDROJE ENERGIE

Alžbeta Danková, Michal Šveda[1]

Alžbeta Danková pôsobí ako interná doktorandka na Stavebnej fakulte Slovenskej technickej univerzity v Bratislave. Vo svojom výskume sa venuje problematike dvojitých transparentných fasád využívajúcich obnoviteľné zdroje energie – ich návrhu, simulovaniu a experimentálnemu overeniu. Michal Šveda pôsobí ako interný doktorand na Stavebnej fakulte Slovenskej technickej univerzity v Bratislave. Vo svojej výskumnej činnosti sa zaoberá analýzou fyzikálnych vlastností dvojitých transparentných fasád a ich integráciou s obnoviteľnými zdrojmi energie v kontexte energetickej efektívnosti budov.

Alžbeta Danková works as an internal doctoral student at the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava. Her research focuses on the issue of double-skin transparent facades utilizing renewable energy sources – their design, simulation, and experimental verification. Michal Šveda is a PhD student at the Faculty of Civil Engineering, Slovak University of Technology in Bratislava. His research focuses on analyzing the physical properties of double-skin façades and their integration with renewable energy sources in the context of building energy efficiency.

Abstract
This research project introduces an innovative approach to modular, adaptive double-skin transparent facades (DSF), specifically engineered for modern intelligent buildings. These DSFs are designed to seamlessly integrate advanced renewable energy sources, including a high-efficiency solar energy system that contributes to the facade's overall energy performance, and novel ejector cooling systems for thermal regulation, directly into their structure. The core objective is to develop a robust and functional DSF prototype that efficiently harnesses solar radiation for both passive heating (via an integrated recuperation

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unit) and active cooling (using compact ejector machines). Our methodology involves rigorous analysis and simulation of energy uses with advanced computational tools to ensure optimal performance, alongside comprehensive assessments of energy efficiency and daylighting. This holistic approach aims to create a prototype ready for extensive validation through controlled laboratory experiments and real-world climatic conditions in experimental facility Twin Rooms.
Key words: double skin facade, renewable energy, office buildings

Abstrakt

Tento výskumný projekt predstavuje inovatívny prístup k modulárnym, adaptívnym dvojitým transparentným fasádam (DSF), špeciálne navrhnutým pre moderné inteligentné budovy. Tieto DSF sú navrhnuté tak, aby bezproblémovo integrovali pokročilé systémy pre obnoviteľné zdroje energie, vrátane vysokoúčinného solárneho energetického systému, ktorý prispieva k celkovej energetickej výkonnosti fasády, a inovatívnych ejektorových chladiacich systémov na tepelnú reguláciu, priamo do svojej štruktúry. Hlavným cieľom je vyvinúť pevný a funkčný prototyp DSF, ktorý efektívne využíva slnečné žiarenie na pasívne vykurovanie v zimnom období (prostredníctvom integrovanej rekuperačnej jednotky) a aktívne chladenie v letnom období (pomocou kompaktných ejektorových strojov). Naša metodológia zahŕňa dôkladnú analýzu a simuláciu energetickej spotreby pomocou pokročilých výpočtových nástrojov na zabezpečenie optimálneho výkonu, spolu s komplexným posúdením energetickej účinnosti a denného osvetlenia. Tento komplexný prístup má za cieľ vytvoriť prototyp pripravený na rozsiahlu validáciu prostredníctvom kontrolovaných laboratórnych experimentov a reálnych klimatických podmienok v experimentálnom zariadení Twin Rooms.
Kľúčové slová: dvojitá transparentná fasáda, obnoviteľné zdroje energie, administratívne budovy

Introduction

In the current global context, driven by increasing efforts to reduce energy consumption and minimize the environmental impact of buildings, adaptive facades are emerging as a pivotal element in contemporary architecture and construction. These dynamic systems, capable of intelligently responding to fluctuating external conditions, offer effective solutions for optimizing indoor environments and significantly reducing energy demand [1, 2, 3, 4]. Their inherent flexibility and adaptability to changing requirements generate substantial operational cost savings related to building thermoregulation and lighting. However, the widespread implementation of such systems simultaneously presents complex challenges in their design and the precise evaluation of their performance [3, 4, 5].

Reducing a building's energy demand critically depends on its facade. This outer envelope serves as a vital interface between indoor and outdoor conditions. Accordingly, the construction industry has recently seen significant progress in developing novel facade materials, elements, and components aimed at optimizing energy efficiency, improving user comfort, and promoting environmental sustainability. This investigation explores the conceptualization, design, and prospective implementation of modular adaptive facade systems. A core innovative aspect of this research lies in the seamless integration of diverse renewable energy technologies directly within the facade structure. This integration directly contributes to the advancement of intelligent building solutions and sustainable architectural practices. Our methodology encompasses comprehensive design and development phases, rigorous numerical calculations, advanced simulations, and thorough experimental validation to ensure the optimal performance and practical applicability of these cutting-edge facade systems.

Research on double-skin transparent facades

At the Department of Building Structures, advanced double-skin transparent facades (DSF) have been the subject of intensive, long-term research. To comprehensively understand the behavior of DSFs and their effectiveness in reducing building energy demand, it is essential to combine numerical simulations with in situ experimental verification. It was precisely for this purpose that the specialized experimental facility, Twin Rooms, was developed (Fig.1) [6].

Fig. 1 – Within the Twin Rooms first experimental setup, a conventional, single-skin facade is installed on the left, matching the geometric and physical characteristics of the inner wall of the double-skin system. Conversely, an innovative double-skin transparent facade is positioned on the right
Source: authors

This experimental facility, designed for the detailed analysis of facade fragments, is located within the Central Laboratories campus of the Slovak University of Technology in Bratislava (Trnávka district). A key advantage of the Twin Rooms facility is its ability to provide a precisely regulated, yet realistic, simulation environment for interior spaces (unoccupied). The primary functional objective of these test cells is the exact determination of thermophysical characteristics (such as heat transfer coefficient, thermal resistance, surface temperatures, and temperature fields) and the quantification of energy flows passing through the tested facade elements. These measurements are performed in response to varying external climatic conditions [6].

The technological infrastructure of the Twin Rooms facility is configured to ensure controllable, stable, homogeneous, and reproducible indoor temperature regimes within two independent measuring cells and a compensation space. This unique configuration allows for the simultaneous execution of measurements for thermal balances, integral and local heat fluxes, as well as surface temperatures on two investigated constructions. These constructions are installed in the measuring apertures and exposed to non-stationary external climatic influences, ensuring high validity of the acquired data [6].

Over the past few weeks, an intensive comparative analysis of the energy performance of two prototype facade systems has been conducted (Fig.1). The investigation focused on an innovative modular double-skin transparent facade (DSF) featuring a natural ventilated cavity and multi-stage solar energy utilization. A conventional single-skin transparent facade, with geometric and physical parameters identical to the inner layer of the DSF, served as the established reference sample.

This prolonged testing aimed to quantify precisely the energy benefits attributable to the double-skin facade. Specifically, the research examined its efficacy in reducing thermal gains during summer, facilitated by the transformation of short-wave solar radiation into long-wave thermal radiation within the DSF's cavity and its subsequent, aerodynamically optimized dissipation to the external environment. Concurrently, the study assessed the minimization of thermal losses in winter, achieved through the pre-heating of air within the DSF's cavity for an integrated ventilation recuperation unit. Furthermore, the efficiency of renewable electricity generation via integrated photovoltaic technology, positioned within the facade's spandrel section, was comprehensively evaluated under authentic climatic conditions. Based on the detailed data acquired from these experiments, an innovative design for a novel double-skin transparent facade (DSF) has been formulated. This design incorporates optimized thermophysical properties and integrates adaptive elements that facilitate the photothermal conversion of solar radiation into thermal energy via integrated solar collectors. Subsequently, this thermal energy is transformed into cooling through an ejector cooling machine strategically integrated into the facade's spandrel section, specifically for summer operation. As of April 2025, the fabrication and preparation of this new prototype have commenced. Extensive experimental validation within the "Twin Rooms" facility is scheduled for the upcoming summer period to rigorously verify its projected benefits and to optimize its operational characteristics under controlled conditions.

New modular adaptive facade

The geometry of the newly proposed double-skin transparent facade (DSF) is based on the dimensions of an existing single-skin transparent facade located at the experimental facility within the Central Laboratories of the Faculty of Civil Engineering, Slovak University of Technology in Bratislava – Trnávka. The inner skin of this new facade is identical to the existing single-skin facade, consisting of two windows with an integrated sash. These windows are glazed with AGC Glass Thermobel TG Top insulating triple glazing, which offers high performance metrics including a heat transfer coefficient (U_g = 0.6 W/(m^2.K)), a total solar energy transmittance (g = 53%), a light transmittance (T_L =75%), and an airborne sound insulation index (R_w = 35 dB). The upper opaque spandrel section of the inner facade element is enclosed by galvanized steel sheeting, behind which a mineral wool thermal insulation infill (75 kg/m^3) is placed.

The fundamental concept behind this novel design is a modular double-skin transparent facade (Fig.2) capable of dynamically responding to and adapting to fluctuating external climatic conditions without negatively impacting the quality of the building's internal environment. This innovative adaptive facade concept features a modular and atypical geometric configuration, with the outer facade skin structurally and geometrically optimized to achieve an ideal solar collector tilt angle of α=40° (for a flat-plate solar collector oriented towards the south) [6].

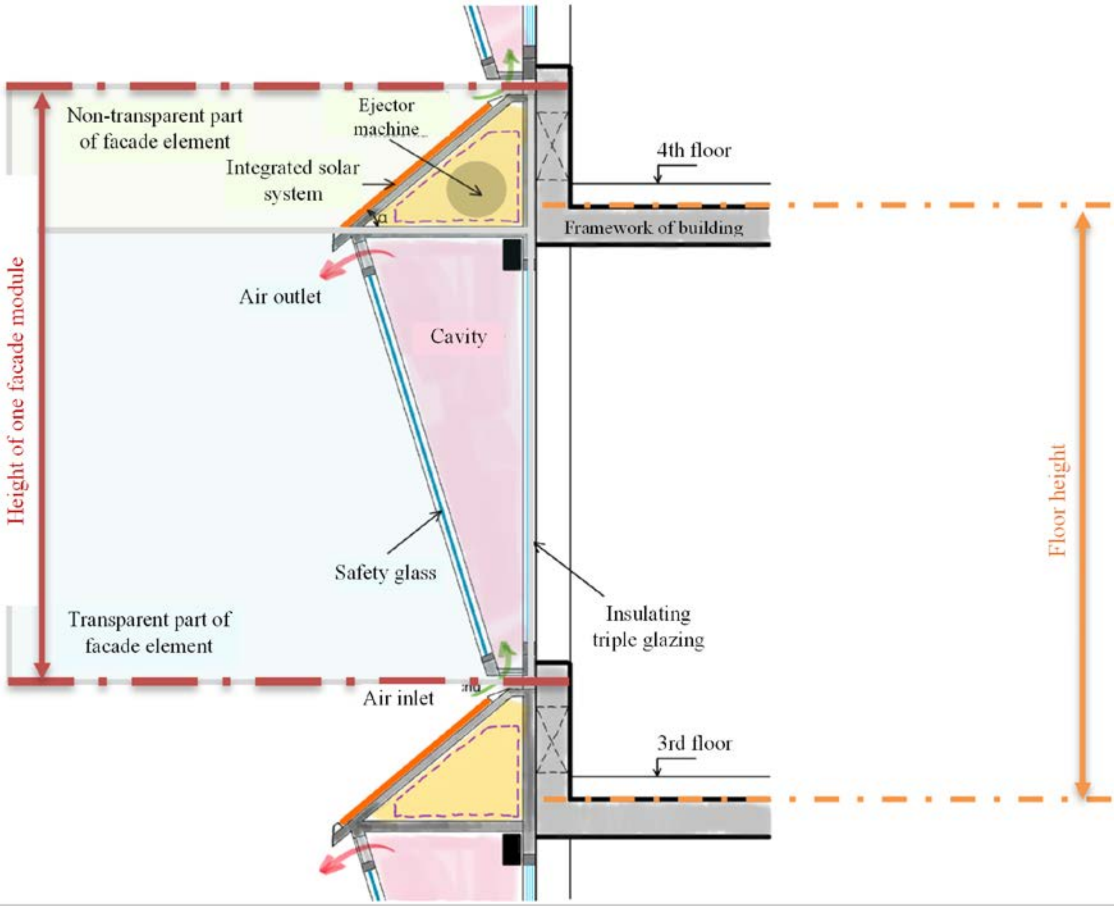

Fig. 2 – Scheme of newly designed double-skin transparent façade
Source: authors

Renewable energy sources: solar radiation utilization

Solar energy, a pervasive and inherently renewable resource, is increasingly recognized as a cornerstone for enhancing the energy performance and mitigating the environmental footprint of the built environment. Its multifaceted integration within architectural systems enables diverse pathways for energy harvesting and management [7]. Beyond direct electrical generation through photovoltaic conversion, solar radiation facilitates thermodynamic processes for both active and passive thermal regulation, including space heating, daylighting optimization, and solar-driven cooling cycles [8]. Such judicious utilization of solar insolation is fundamental to achieving net-zero energy building standards and advancing sustainable urban development paradigms [9].

Our new double-skin transparent facade is designed to strategically utilize the energy of solar radiation in several distinct ways. This includes the transformation of short-wave solar radiation into long-wave thermal radiation within the physical cavity of the double-skin transparent facade, which positively reduces energy flows into the building core, specifically by decreasing thermal load from solar radiation in the summer and eliminating heat losses in the winter period. Additionally, temperature-conditioned air from the physical cavity of the double-skin facade can be utilized during the winter for a facade recuperation unit integrated into the facade element, thereby positively impacting the reduction of heating demand. Furthermore, solar energy can be used via the photothermal conversion from solar collectors, serving as a heat source for an ejector cooling system [10] for direct cooling of the building's interior spaces.

Computational facade testing – reference building

The reference administrative building design is based on the parameters of the double-transparent facade. The typical floor plan is developed in two variants: one featuring three distinct reference offices (Fig.3), and another with an open-space office layout. The open-space variant corresponds in size to three of the reference offices. The width of a single reference office is specifically designed to accommodate three facade modules. Each individual reference office measures 6.8 meters by 6.3 meters, resulting in an area of 42.84 square meters and utilizing three facade modules. The open-space office, by contrast, measures 20.6 meters by 6.3 meters, covering an area of 129.78 square meters and integrating nine facade modules. Furthermore, the building is conceptualized in two height configurations: the primary variant consists of seven above-ground stories, while an additional variant with fifteen above-ground stories was developed specifically for comprehensive fire safety assessment and for daylight availability.

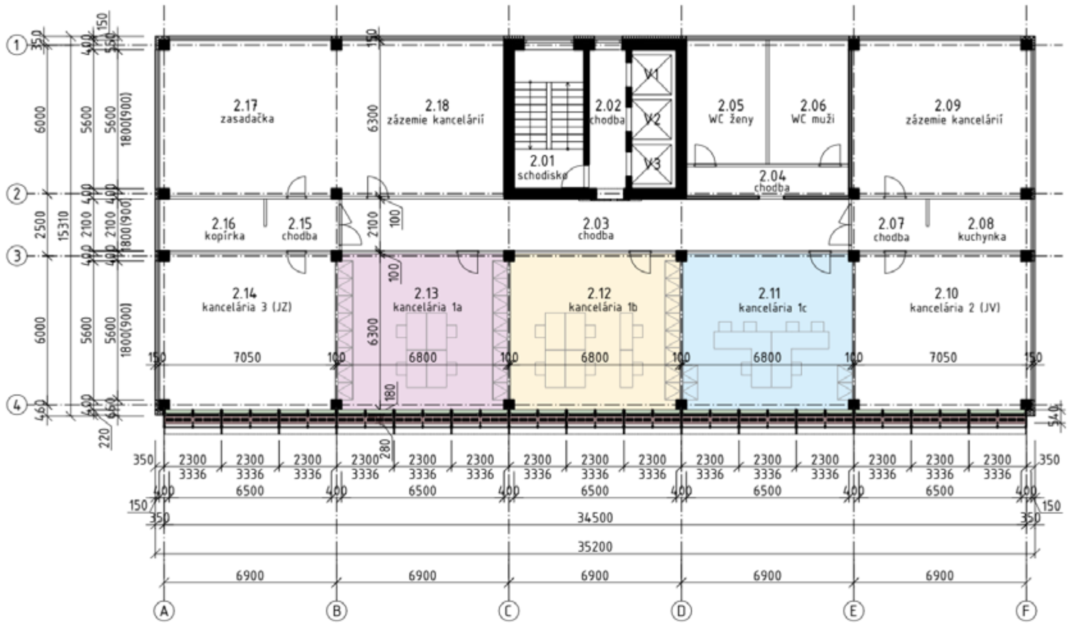

Fig. 3 – Reference building – floor plan with three distinct reference offices
Source: authors

Computational facade testing – energy performance

We conducted a study utilizing dynamic simulation methods to assess the energy performance of an administrative building featuring a newly designed double-transparent facade. Our primary objective was to quantitatively evaluate the facade's influence on the internal thermal environment, specifically addressing heating and cooling demands, and to determine the impact of exterior shading elements on energy efficiency and thermal comfort.

The reference building model (Fig.4), featuring a modular adaptive facade, was simulated using the DesignBuilder energy simulation program (EnergyPlus v. 9.4) [11, 12]. As previously discussed, the facade's outer shell is specifically designed to optimize the tilt angle for a flat plate solar collector, oriented south, at 40 degrees. We analyzed two main configurations of the building: one with three reference offices and another with an open-space office, both configured with and without exterior shading. The seven-story building model, with its double-transparent facade oriented south, was subjected to dynamic energy simulations. Simulations incorporated hourly climatic data for Bratislava from a typical meteorological year (TMR) and standardized input values for administrative buildings, as per Slovak decrees, including thermal properties of the envelope and operational schedules. A simplified HVAC system, relying solely on infiltration without mechanical ventilation, was used for the basic calculations. Operating hours were defined from 7:00 to 16:30 on weekdays, determining the operational schedules for various internal gains [13, 14, 15, 16, 17].

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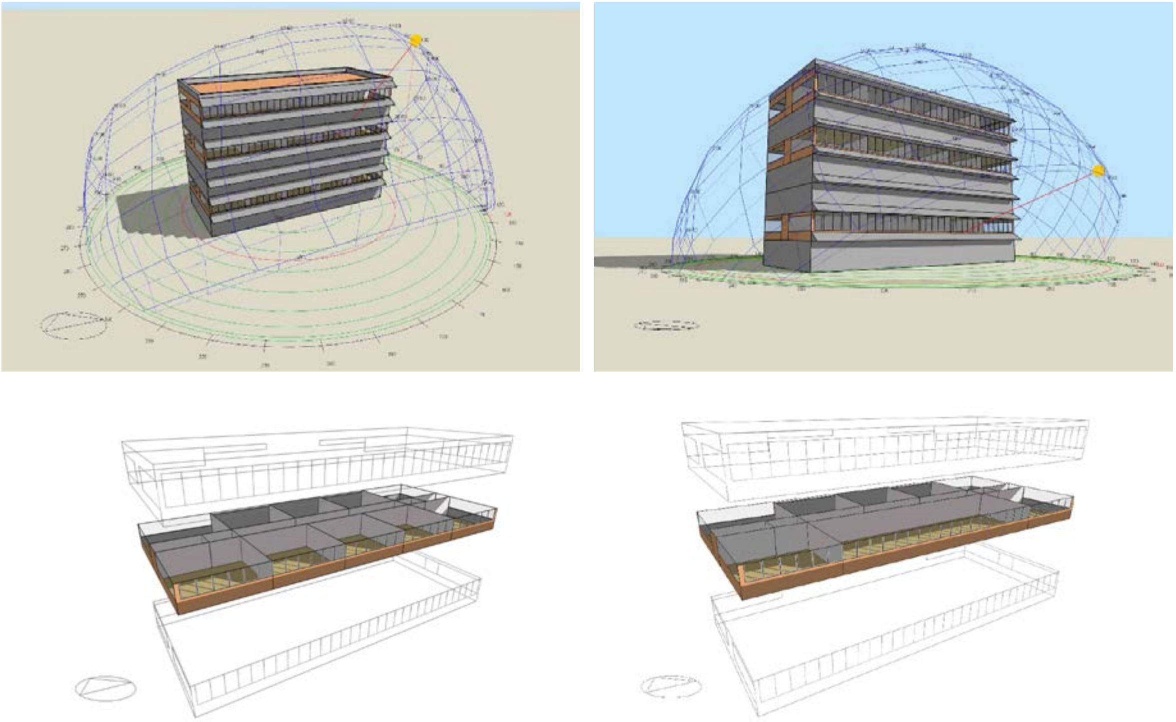

Fig. 4 – 3D simulation model
Source: authors

Our simulation results indicated that exterior shading elements, such as horizontal blinds (with a solar reflectance of 0.20, an absorptance of 0.80, and a transmittance of 0.00), significantly reduce cooling loads. These blinds activate automatically when solar radiation on the window reaches 200 W/m². For instance, a 24% reduction in cooling capacity was observed when exterior shading was implemented. Conversely, heating demand remained unchanged by shading, as solar gains are not considered in heating design calculations. These findings underscore the facade's role as a significant passive shading element, particularly due to its 1.3-meter cantilever design. The analysis further highlighted the substantial contribution of solar radiation to total heat gains during summer, which is beneficially utilized by the integrated solar collector for the ejector cooling circuit. The more heat supplied to this circuit, the greater the cooling output for the interior spaces. We emphasize the critical importance of accurate input data for reliable energy performance predictions in buildings with adaptive facades. Future research endeavors should focus on developing robust methodologies for acquiring and processing detailed input data specific to adaptive facades, alongside validating these models with real-world operational data. This comprehensive approach will foster a deeper understanding of the dynamic characteristics of such systems and their overarching impact on building energy efficiency. This study provides valuable insights for the design and optimization of energy-efficient buildings incorporating such innovative facade systems.

Computational facade testing – daylight availability

We investigated the impact of a newly designed experimental double-skin transparent façade (DSF) on the indoor environment of an administrative building, specifically focusing on daylight availability. Our aim was to evaluate how this façade influences natural lighting conditions within typical office spaces. For simulation purposes, we modeled the proposed DSF on the south-facing side of a representative administrative building. Side-lit offices on three distinct floors (1st, 10th, and 15th) were chosen for evaluation, receiving light exclusively through the studied façade.

The innovative façade features a modular design with a basic module size of 2300×3360 mm, constructed from an aluminium system. The outer shell is specifically configured to accommodate a south-facing solar collector at an optimal 40-degree tilt, and includes a 1.5-meter cantilever above windows. The inner façade incorporates insulating triple glazing, while the overall structure is designed with thermal breaks and controlled drainage.

We utilized Rhino 7 for geometric modeling and ClimateStudio [18, 19, 20], specifically the Daylight Availability module, for calculations. A detailed light technical assessment was conducted to evaluate the impact of the cantilevered facade, particularly in the parapet section of the element, on the daylight factor. According to STN 73 0580-1, offices are categorized under visual activity class IV, which mandates a minimum daylight factor of 1.5 to ensure adequate natural illumination [22, 23]. Beyond the standard daylight factor, our evaluation incorporated advanced metrics such as Annual Sunlight Exposure (ASE), Spatial Daylight Autonomy (sDA), and Average Illuminance from Daylight, aligned with LEED v4 Daylight Option 1 [21]. Simulation parameters included 100 passes, 64 samples per pass, and 6 ambient bounces. External shading within the façade's cavity was not considered in this specific phase of the simulation.

Our results indicated that for critical central offices, the daylight factor met minimum requirements up to approximately half of the room's depth (Fig.5). The range of daylight factor values observed in a typical office varied from 0.9% to 4.7%. Dynamic simulations showed that all evaluated rooms generally met the criteria for spatial daylight autonomy, receiving over 300 lux of daylight for at least 50% of annual operating hours. We found minimal differences in daylight availability across the selected floors (1st, 10th, and 15th) when no external obstacles were present. However, the presence of external obstructions would significantly reduce daylight penetration on lower floors due to reduced sky visibility. These simulation results are crucial for verifying the design performance and guiding the further development of the final façade module.

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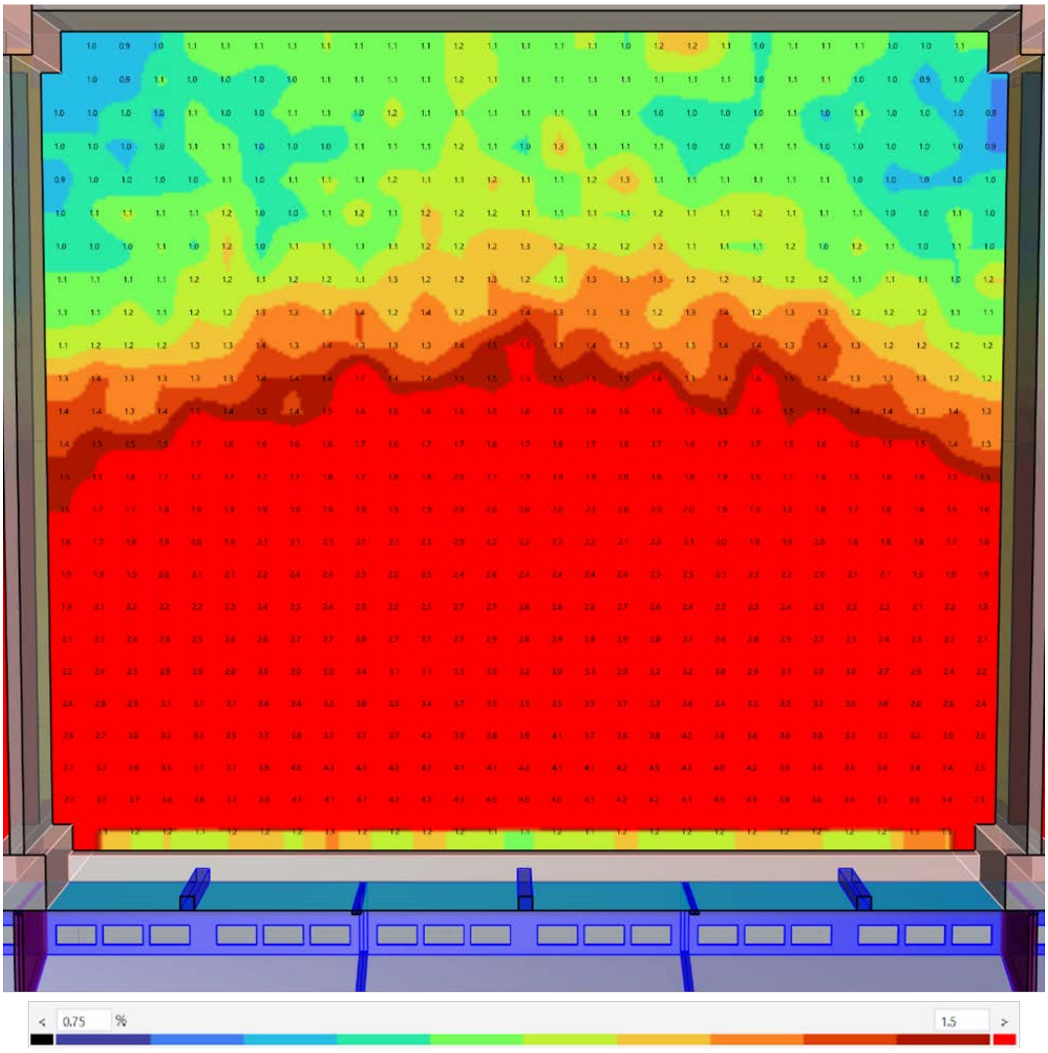

Fig. 5 – Daylight factor results – Office on the 1st floor
Source: authors

Prototype development and experimental facility setup

Current modifications are being implemented at the experimental facility Twin Rooms. These ongoing adjustments are crucial steps in progressively preparing the facility for the rigorous experimental verification of the novel double-skin transparent facade. A prototype of this novel double-skin transparent facade has been fabricated and is being integrated into the Twin Rooms facility for experimental validation, precisely adhering to the design specifications. Prior to fabrication and installation, we projected a precise 3D model encompassing all components, ensuring accurate adherence to the design specifications (Fig.6). Preparation is currently proceeding at an accelerated pace, with the primary supporting structure for the facade already having undergone precise positioning and installation on-site (June 2025 – Fig.7). Concurrently, all requisite components, including specialized solar collectors and the associated instrumentation essential for the facade's operational assessment and comprehensive data acquisition, have been fully prepared. We project the completion of these installation and setup procedures by July 2025. This timeline has been strategically established to facilitate the initiation of extensive measurement campaigns throughout the

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ensuing summer period, thereby enabling the collection of critical performance data under representative seasonal conditions.

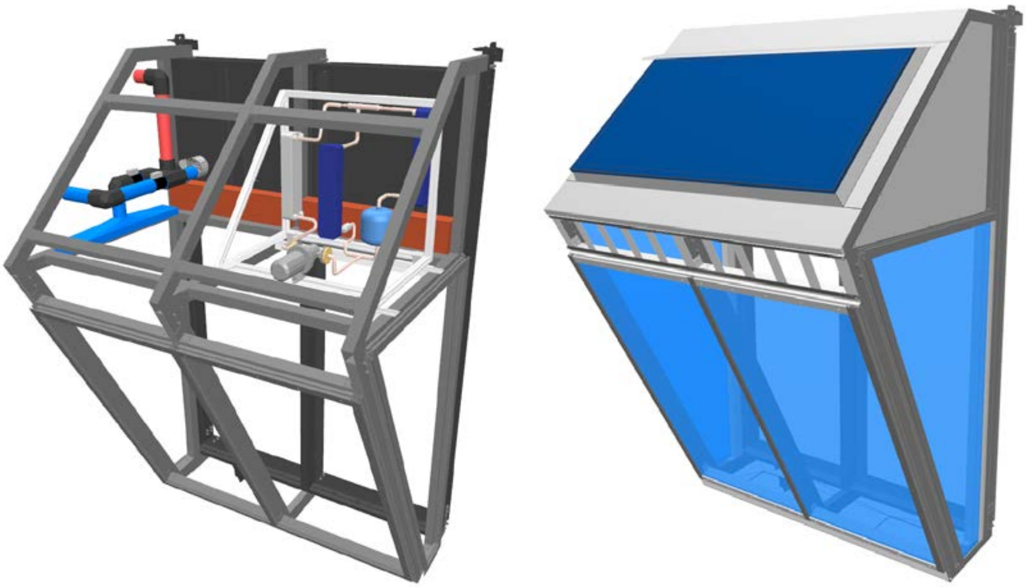

Fig. 6 – 3D model of new double-skin transparent façade
Source: authors

Fig. 7 – Experimental facility Twin Rooms in June 2025. The new facade is positioned on the left side, while the original double-transparent facade is situated on the right side
Source: authors

Conclusion

This research comprehensively investigates modular, adaptive double-skin transparent facades (DSF) for intelligent building applications, focusing on the integration of renewable energy

sources for thermal regulation and optimized daylighting. Our methodological approach combines advanced numerical simulations with comprehensive experimental verification. Simulation outcomes demonstrate a significant reduction in cooling loads attributable to exterior shading elements, with a recorded 24% decrease in cooling capacity, whereas heating demand in design calculations remained largely unaffected by such shading. The facade also functions as a substantial passive shading element, and its integrated solar collector effectively contributes to the ejector cooling circuit by utilizing solar gains. Furthermore, daylight availability simulations confirm that evaluated office spaces generally meet the criteria for spatial daylight autonomy; however, external obstructions are shown to reduce daylight penetration on lower floors. A prototype of this novel DSF has been precisely fabricated and is currently undergoing integration into the experimental TwinRooms facility for extensive validation. Installation and setup procedures are projected for completion by July 2025, facilitating the commencement of comprehensive measurement campaigns throughout the ensuing summer period to acquire critical performance data under representative seasonal conditions. This study underscores the paramount importance of accurate input data for reliable energy performance predictions and provides fundamental insights for the design optimization of energy-efficient buildings incorporating advanced facade systems.

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