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Research Article

Building Thermal, Lighting, and Acoustics Modeling

Example-based dynamic façade design using the façade daylighting performance improvement (FDPI) indicator

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Abstract

It remains challenging to conduct an efficient dynamic façade design. In this article authors try to address this issue introducing the façade daylighting performance improvement (FDPI) indicator aimed to evaluate the performance of a dynamic (adaptive) façade from its daylighting performance point of view. To illustrate the FDPI application the authors introduced the preliminary dynamic façade concept for an office building located in Tel Aviv (Hot-summer Mediterranean Climate Csa) with further shape modification based on the daylighting performance analysis compared to the three alternatives representative of different typologies of dynamic façades. Al Bahr, One Ocean and The University of Southern Denmark façade systems were simulated under the same weather and building conditions of the preliminary dynamic façade concept and were considered as a benchmark for the study. The final dynamic façade concept elaborated by the authors in the preliminary comparative workflow showed noticeable daylight performance improvement with respect to the case studies comparative scenarios. The FDPI metric allowed to estimate a daylighting performance improvement of 43% of the final dynamic façade concept over the case study dynamic façade that showed the best performance in the daylighting simulations.

Keywords

dynamic façade
adaptive façade
daylight performance
performance evaluation
façade daylighting performance Improvement

Article History

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1 Introduction

The sustainability of buildings is influenced by three challenging factors: user well-being and IEQ, reduction of building energy consumption and neutralization of building-related environmental impacts (Attia 2018a, 2018b). Natural light provides positive psychological and mental effects on building occupants (ASRAE 2006; Michael and Heracleous 2017; Hosseini et al. 2019a). The studies that discuss the lighting conditions in office buildings show strong relationships between the illuminance at eye level and the health parameters (Al Horr et al. 2016): the daylight influences the productivity (Alrubaih et al. 2013), health conditions (Beute and de Kort 2014) and job satisfaction of employees (Edwards and Torcellini 2002). Additionally, the available daylight as a renewable source can reduce artificial lighting using direct sunlight and diffusing light from the sky and ambient environment (Hviid et al. 2008). Furthermore, enhancing useful daylight of interior space, as much as possible, has been considered as a significant aim of architects, building engineers and designers. However, adjusting the levels of the daylight penetration is a challenging work that is accomplished by the investigation of the features of daylight that influence the occupants' visual comfort (Hosseini et al. 2018), since daylight can also cause visual discomfort through glare and distraction (Alrubaih et al. 2013). The visual efficiency of the daylight depends on how it is delivered, and it is recommended to balance the level of the direct sunlight in areas in which visual activities are required (Ne'Eman 1974).

Building façade systems play an important role in the daylight regulations and associated with it IEQ and visual comfort of occupants.

The design and implementation of new types of building envelopes, that are interactive, adaptive, and responsive, may lead to an improvement of the building daylighting performance (Rafsanjani et al. 2015; Baranova et al. 2018; Zemitis and Terekh 2018) and respectively improve building's

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List of symbols

ASE	annual sunlight exposure, the percent of an analysis area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year
CBDM	climate-based daylight metrics
DA	daylight autonomy, the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone
DA_500	DA with a set minimum illuminance of 500 lx
DGP	daylight glare probability
FDPI	façade daylighting performance improvement
IEQ	indoor environmental quality
LENI	lighting energy numerical indicator
sDA	spatial daylight autonomy, the percent of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year
UDI	useful daylight illuminance, the annual occurrence of daylight levels across the task area that is considered useful for occupants
UDI-a	UDI-autonomous
UDI-e	UDI-exceeded

sustainability. The integration of passive and active design technologies in the building envelope is gaining attention from the research and development community (Cuce and Riffat 2015). The dynamic façades or adaptive façades, as defined by the European COST Action TU1403 (Adaptive Façades Network (2014–2018)) (2014), have a profound effect on achieving the three performance requirements in terms of occupant's satisfaction, energy saving, and environmental impact neutralization. Dynamic façades are building envelopes that are able to adapt to changing boundary conditions in the form of short-term weather fluctuations, diurnal cycles, or seasonal patterns (Knaack et al. 2015; Attia et al. 2018; Loonen 2018). Dynamic shading system provides potentially continuous adjustment according to the variations of the local climate conditions (e.g. sun position during the day), which could be impractical to be done by users in case of a static shading implementation (Rafsanjani et al. 2015). The use of dynamic shading systems might be efficient in terms of regulation of the daylight penetration inside the building envelope and, therefore, regulation of the visual comfort of occupants (Freewan 2014; EN 12665-2011 2011). One of the most ambitious challenges for designers is to keep the balance between the daylight harvesting maximization on one hand, and magnitude of discomfort glare on the other hand (Bellia et al. 2008). Dynamic façade systems offer numerous benefits as these can be applied to allow for winter sun or to block direct summer sun. Therefore, it is of value to dynamic façade both to prevent and control undesirable daylight and solar radiation, keeping the daylight intensity in comfort levels (Kirimtat et al. 2016).

However, being such an interesting and promising technology for regulation of daylight harvesting, associated indoor comfort and, as a result, lowering building's energy demand for artificial lighting, the literature analysis showed that there are still several open challenges and questions.

Several technical solutions related to dynamic façades can be acquired in the market (Loonen et al. 2013; Attia et al. 2018), but their performance evaluation is limited (Favoino et al. 2014). A benchmark performance and simple universal computational methodology of daylighting performance evaluation of dynamic façades that could be used by designers on the early stage of building design is an open research question. It remains challenging to assess the performance of such façades in early design stage, leading to difficulties for their efficient design (Favoino et al. 2014; Jin and Overend 2014; Rafsanjani et al. 2015; Loonen et al. 2017; Taveres-Cachat et al. 2021). Moreover, the lack of consistent performance evaluation criteria seriously hinders dynamic façades widespread use and market penetration (Attia et al. 2016).

Several important studies that discuss the issues of the dynamic façade performance assessment in terms of daylight performance propose different methods of performance evaluation and quantification. In the study (Le-Thanh et al. 2021) the authors discuss the daylighting performance evaluation of the dynamic façade (inspired by the Origami art) in baseline climatic conditions. The authors present the simulation-based method that uses the Leed v4 certification (U.S. Green Building Council 2019) as the benchmark performance evaluation, taking into consideration such CBDM as sDA (IES 2012) and ASE (Kim and Clayton 2020). Using the proposed methodology, the authors were able to design an optimal in daylight performance dynamic façade system. However, the used methodology has a limitation – a high computation cost due to the need to perform communication steps between the number of used tools via transferred files. Additionally, the authors point out that the developed façade solutions might not be feasible to construct since the applied materials and actuation mechanisms were not investigated.

Kim and Clayton (2020) presented a multi-objective optimization (MOO) framework and a parametric behaviour map that aim to support a decision-making process in adaptive façade design. The authors focused on such design criteria as minimizing cooling loads and maximizing daylighting conditions with the use of the proposed methodology. Two dynamic façades were tested with various operation scenarios to reach the optimal operation scenario that provides optimal performance in a given climatic conditions. However, the main limitation of the proposed methodology is that it is focused on the operation profile of the already chosen dynamic façade design and does not include the shape finding issue. Additionally, the methodology incur high computational costs (took 4 days to test each model).

Another important study on the matter (Hosseini et al. 2019b) discusses the advantages of the 3-dimensional dynamic façade over 2-dimensional in the specific climatic conditions. The authors provide a comprehensive review of the existing static and dynamic shading solutions with the analysis of the type of dynamic shading movements. The authors use the simulation approach to find out that implementation of the 3D dynamic façade shape change showed better results in daylight performance in comparison to 2D dynamic façade shape change. To conduct a performance estimation the authors used such CBDM as DA (Li 2010), UDI (Nabil and Mardaljevic 2005) and DGP (Wienold and Christoffersen 2006). However, the authors compare only specific 3D and 2D geometries with specific motion properties of dynamic façades in the simulation without deriving universal methodology to actually evaluate daylight performance of the dynamic façade.

Overall, the performance evaluation of dynamic façade systems has been investigated by many scholars. In addition to the mentioned studies, Kasinalis et al. (2014) developed a framework based on a genetic algorithm (GA) to analyze and quantify the energy and daylighting performance of dynamic façades. Attia et al. (2018) proposed an evaluation structure that includes key performance indicators, proposing an evaluation of the necessity, performance criteria, and technical qualitative characteristics of dynamic façade systems. Battisti et al. (2019) developed a life cycle assessment tool to evaluate the sustainability of the initial stages of dynamic façade technology. Yitmen et al. (2022) proposed an analytical network process model to determine the evaluation criteria for dynamic façades in complex commercial buildings. An adaptive evaluation framework for dynamic façades was proposed in Sadegh et al. (2022), emphasizing the combination of top-down and bottom-up approaches to evaluate kinetic façades.

A common limitation of the above-mentioned studies is that the dynamic façade performance evaluation criteria are inconsistent and lack quantification (Zhang et al. 2022).

The authors propose the dynamic façade design methodology that would ensure a simple and straight-forward dynamic façade design at the early design stage without high computational costs. It is based on the façade daylighting performance indicator (FDPI). Being a part of the FDPI comparative workflow, FDPI allows to consider several parameters in the dynamic façade performance evaluation and provides quantitative performance estimation results in comparative terms. FDPI could be efficiently used in a preliminary design stage.

In this research, authors illustrate the use of the FDPI-workflow in the process of the dynamic façade design that would ensure the occupants comfort inside the building. In order to do so, the authors established several baseline conditions and simulation assumptions, such as climatic conditions, building description (office building) and daylighting zone definition. The authors selected several existing efficient dynamic façade solutions representatives of different typologies of dynamic façades and introduced the preliminary dynamic façade concept the motion properties of which merges the types of movement of the analysed existing façades. The preliminary dynamic façade concept was further compared to the selected existing ones in terms of façade daylight performance. By changing the dynamic façade's shape, the authors were able to achieve better results in its performance from daylight availability and, therefore, visual comfort points of view. The performance evaluation criteria is the daylighting (or visual) performance of the dynamic façades was analysed using commonly used dynamic metrics – UDI, DA and DGP that constitute the FDPI.

Apart from process challenges in the design phase, that includes difficulties in performance quantification and façade's performance evaluation (Wienold and Christoffersen 2006; Struk et al. 2009; Kassem and Mitchell 2015; Attia et al. 2018; Zhang et al. 2022), there are other types of barriers influencing the adoption of dynamic façade technologies. One of which is related to the feasibility and implementation of the analytical dynamic façade model (Attia et al. 2018). With the well-being of occupants (El-Arnaouty et al. 2020) being the ultimate goal of performance evaluation (Attia et al. 2019), other factors, such as dynamic façade durability, feasibility, mechanical properties of the applied materials need to be balanced. Therefore, the transitions from dynamic façade's analytical model to physical model, that is one of the existing challenges in the dynamic façade design, is also considered a part of the FDPI-workflow.

It is important to mention, that in this research only daylighting performance as the performance evaluation part of the workflow was taken into consideration, focusing on the aspect that influence the occupants' comfort. The salient feature of the dynamic façade is the variability of its responses to indoor visual comfort conditions and outdoor climate changes; however, many variables such as climate factors and occupant requirements exist, and integrating multiple variables for performance evaluation is challenging (Favoino et al. 2014; Alexander 2016; Kuru et al. 2022). Pilechiha et al. (2020) pointed out that the comprehensive building façade design has to include simultaneous evaluation of such factors as daylighting efficiency (Uribe et al. 2017) in terms of visual comfort, and energy performance. These factors are a function of such exterior dynamic façade components as external shading (Manzan and Padovan 2015). These interdependent factors have not been simultaneously considered in the building design (Pilechiha et al. 2020). Multiple design criteria might as well be considered in the methodology simultaneously since FDPI is a universal parameter that in comparative terms allows to evaluate the performance improvement of the façade under investigation including the parameters that are of interest of the designer.

From the analysed literature, a comprehensive analysis of the daylight availability in the office spaces may lead to significant advantages in energy savings. Since approximately 30%–50% of the total commercial building electricity demand is used for artificial lighting (Yang et al. 2021) with significant variation from one building to another (Krarti 2016), and taking into account that lighting energy savings regarding daylight harvesting vary from 20% to 87% (Yu and Su 2015), the addition of the energy savings aspect to the FDPI might be beneficial. Since daylight penetration solely is not enough to lead energy savings automatically, unless it is linked to shading and lighting control strategies (Akimov et al. 2021a), the dynamic façade systems may play an important role in the daylighting and artificial lighting systems regulation (Rafsanjani et al. 2015).

The simultaneous evaluation of the parameters that consider energy performance, daylight gain, and visual comfort (sDA, ASE, parameters that evaluate the glazed façade performance from energy-efficiency point of view) has been examined within a multi-objective framework for the office building windows system design in the study (Pilechiha et al. 2020). Aiming to minimize energy usage while maximizing received daylight and quality of the view, using the approach that allowed the simultaneous evaluation of the mentioned parameters, the authors were able to conduct an optimization of the windows system in a specific building using this framework. The research showed that approach that includes the simultaneous evaluation of daylighting and energy performance parameters is beneficial in the windows design, though the research did not take into consideration the shading system design (neither static, nor dynamic).

Similarly, to make a multi-objective framework for the dynamic façade design, the methodology proposed in this research can be extended by the parameter that accounts for the artificial lighting energy demand evaluation. The inclusion of the LENI (Akimov et al. 2021a) in the FDPI methodology is an efficient way of creating universal parameter that would be useful for detailed dynamic façade analysis from both daylighting performance and energy-efficiency points of view. The LENI inclusion would not bring any conflict to the FDPI-based daylighting performance evaluation since the basic LENI calculation, proposed by the European Normative EN15193-1:2017 (2017) includes the daylight availability estimation in the zone under evaluation. The mentioned aspect is as well discussed in the research.

Overall, the FDPI-workflow is a simple dynamic façade design methodology that allows to consider multiple design criteria, such as the dynamic façade daylighting performance estimation, the shape finding approach and transition from analytical to physical model (as illustrated in this research). This methodology can be used at the early-stage design of the dynamic façade since does not incur high computational costs.

2 Materials and Methods

2.1 The FDPI-workflow definition

The dynamic façade design is a cross-disciplinary multi-objective design process, in which the façade designer should balance the optimal trade-offs between the performance indicators by adopting an appropriate combination of various façade design variables, such as façade-intrinsic variables (dynamic façade's shape and design, shading materials) and façade-extrinsic variables (such as building location, layout, orientation, usage and other) (Jin and Overend 2014). The aim of the FDPI-workflow is to make a dynamic façade design at the early stage of the design process efficient from the performance of the dynamic façade ("daylighting performance" as the focus of this research) and the feasibility of the designed dynamic façade points of view.

The basis of the FDPI-workflow is the comparative analysis of the designed dynamic façade's daylighting performance to the daylighting performance of the existing proved to be efficient dynamic façade solutions, representatives of different dynamic façade typologies, evaluated in the same baseline conditions. This analysis allows the designer to understand which typology and its specific geometrical property influences the dynamic façade's performance.

The designed dynamic façade (at the first design iteration called "initial dynamic façade") performance in the specific baseline conditions is compared to the chosen for the analysis existing façades' performance in the same baseline conditions. The specific dynamic façade properties (geometry, materials, translucency of the shading unit, etc.), that constitute the dynamic façade typology, are taken into the consideration in the dynamic façade performance evaluation in the specific baseline conditions. The "shape finding" of the desired dynamic façade (the last design iteration that shows the best performance results in the comparative analysis) is based on the indication of the analyzed dynamic façades properties that influence the façade's performance improvement with their further adoption to the design.

The transition from the analytical dynamic façade model to the physical dynamic façade model is done by adopting an actuation mechanism, façade's materials to the analytical model and integrating the dynamic façade into the curtain wall bearing structure. This process may as well lead to a dynamic façade's shape optimization. The designed dynamic façade has to obtain not only desirable daylighting properties, but also mechanical, structural and durability properties, have executable design that would allow to provide acceptable maintenance.

The FDPI-workflow definition is present in Figure 1.

2.2 Choice of the baseline conditions: Simulation assumptions

The baseline building used for the comparative analysis is an office building with daily (weekdays) operating hours from 8 a.m. to 6 p.m. The building consists of 5 floors, 4 m in height each (measuring from the floor level to the ceiling level). To make an evaluation of the daylight availability inside the building space, the authors picked one representative room of the building under consideration. This room is hereafter referred to as "daylighting zone" (or DZ). Figure 2 illustrates the geometry of the building and the DZ location.

Since the visual transmittance parameter change reduces proportionally an amount of daylight inside the building space, the authors modelled a raw building carcass opening meaning that no windows were modelled in the envelope. This was done to estimate a daylight availability inside the DZ and to have an idea of the maximum daylight potential

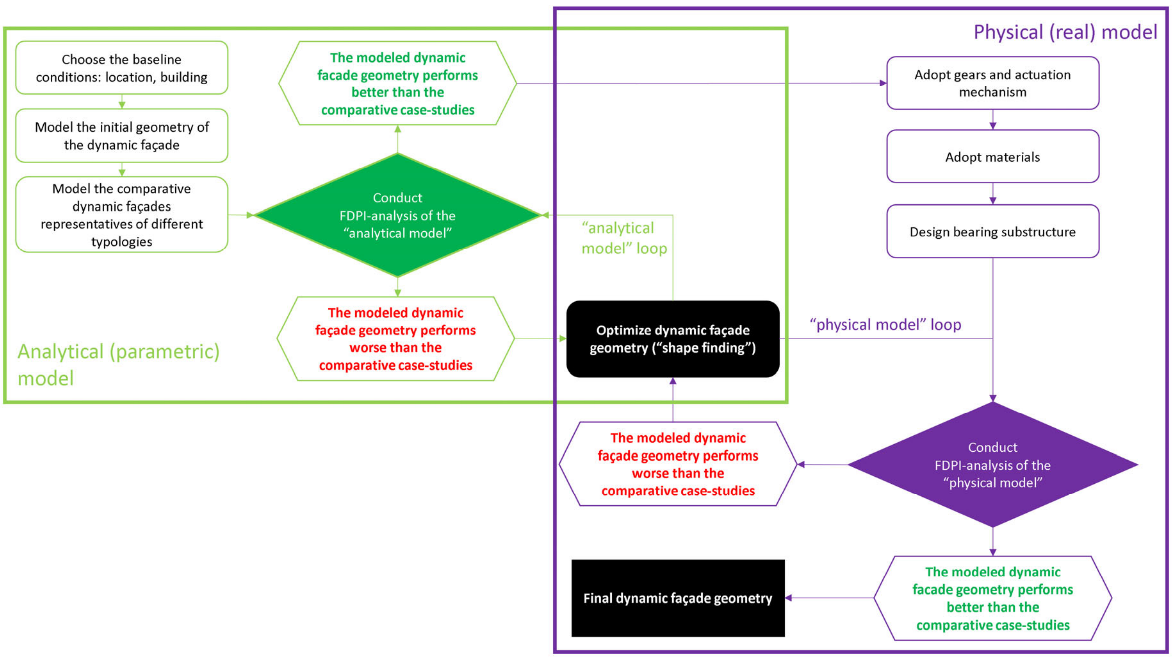


Fig. 1 The FDPI-workflow definition

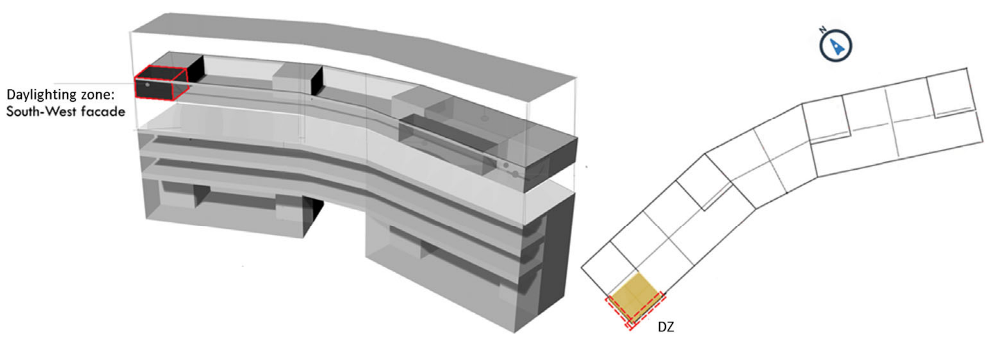


Fig. 2 The baseline building: building's shape and orientation and DZ location

related to each system. This assumption would omit every parameter related to glazing angular properties, leaving only dynamic façade's properties impact on the daylight availability inside the DZ.

The performance of shading systems (including dynamic façades) depends heavily on the climatic conditions, and for hot climates, the dynamic façade systems are usually set to control the transmitted solar radiation (Ruck et al. 2000). The study by Hosseini et al. (2019a) demonstrates that the dynamic façades may greatly improve visual comfort levels in hot and dry climates. To make a dynamic façade design and conduct the comparative analysis the authors decided to choose climatic conditions with high solar gains levels throughout the year. For this reason, a hot-summer Mediterranean climate (Csa according to Koppen climates classification (Peel et al. 2007)), that is characterized by dry summers with high solar gains and a great impact of solar radiation on the ambient visual comfort conditions, was chosen as the baseline climate for the analysis. Specifically, the Mediterranean Sea facing office district in Tel Aviv, Israel (latitude: 32°05', longitude: 34°48') was chosen as the baseline building site.

Test points for daylight availability estimation were generated on the work plane situated at 0.8 m height above the floor level of the DZ (EN 15193-1:2017 2017). The work plane was split into a grid with 0.5 by 0.5 m spacing. Table 1 summarizes the DZ properties.

2.3 Existing dynamic façade systems selected for the comparative analysis ("Case Studies")

Dynamic façade is a complex mechanical system in which a certain kind of motions like displacing, sliding, expanding, folding or transforming, ensure variable geometries and mobility of the system (Tabadkani et al. 2021). These façades require efficient-tuning to outdoor boundary conditions and actuation force to generate movement (Sharaidin 2014).

The dynamic façade systems might play an essential role in the building's appearance while providing improved insulation across a window or other types of openings due to their modular construction. The design emphasis on various building structures has maintained pressure on the industry to continue creating unique coverings for architectural openings. As some successful examples: Al Bahr (Attia 2018c), The University of Southern Denmark façade (Fakourian and Asefi 2019) and One Ocean (Knippers et al. 2013) are among the most recognizable efficient dynamic façade solutions where the performance of the façade can be managed with high spatiotemporal resolution by separately addressable modules (Tabadkani et al. 2019).

Having different types of movement ("in plane", "out of plane" and combination of "in plane" and "out of plane" with respect to the envelope plane types of movement) of separately addressable modules, providing either vertical or horizontal shading, proved to be efficient executed dynamic façade solutions (Tabadkani et al. 2019), Al Bahr (Attia 2018c), The University of Southern Denmark façade (Fakourian and Asefi 2019; Sood and Patil 2021) and One Ocean (Knippers et al. 2013) were modeled as representatives of different typologies of the realized dynamic façades (henceforth referred to as "Case Studies") for the sake of comparative analysis as the step of the FDPI-workflow. These façades were adopted to the baseline building under the baseline climatic conditions.

In accordance with the available literature the authors reconstructed the geometry of each façade, retaining the original type of movement and geometrical features. Although to keep the analysis simple that would not require high computational costs and would be feasible to conduct in the preliminary design phase some simplifications were introduced:

- The systems were modelled fully opaque;
- No operation profile was modelled.

Table 2 summarizes the Case Studies geometrical and motion properties.

2.4 The initial (preliminary) dynamic façade concept

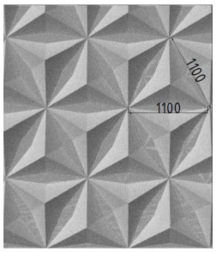
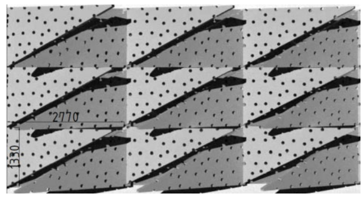
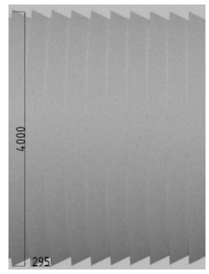
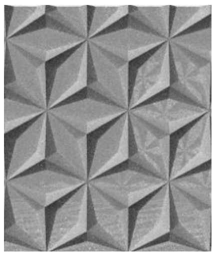
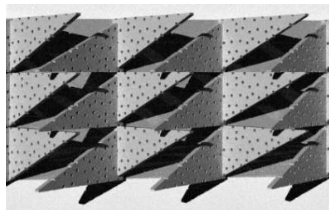
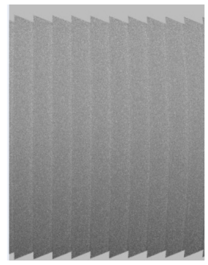
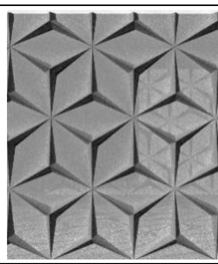
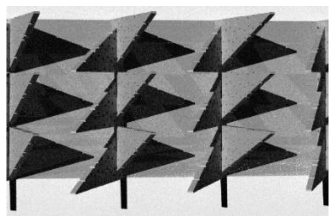
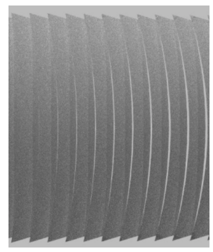
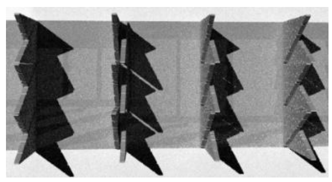
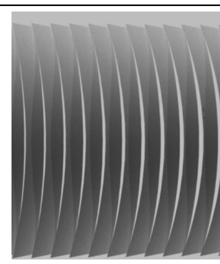
Designing a complex system that is capable of dynamically control internal visual (and thermal) conditions by balancing daylighting levels inside the internal environment requires comprehensive analysis, that includes appearance of a façade, it's durability, capability of modulating amounts of incoming solar radiation, type of movement and the control strategies. In most of the cases, the theoretical design solutions obtained by following solely the daylighting (and/or energy performance analysis) are impossible to develop and construct in real life conditions due to complexity of shapes and movement types (Mahmoud and Elghazi 2016).

The design of a dynamic façade has to satisfy a criterion of feasibility of its construction. That is why the preliminary dynamic façade design that authors have introduced to the

Table 1 DZ properties

Façade exposure	DZ dimensions [m]	Number of sensor points	Floor surface reflectance (ρ_F)	Walls surface reflectance (ρ_W)	Ceiling surface reflectance (ρ_C)
South-west	6 × 6.5	156	0.2	0.5	0.8

Table 2 The summary of the Case Studies' geometrical and motion properties

	Case Study 1: Al Bahr	Case Study 2: The University of Southern Denmark façade	Case Study 3: One Ocean Pavilion Expo
Degree of opening: 25%			
Degree of opening: 50%			
Degree of opening: 75%			
Degree of opening: 100%			
Geometry of shading units	Equilateral triangular units: 1.1 m side length, no perforation	Right triangular units: legs: 1.33 m × 2.77 m; Perforation holes: 80 mm in diameter every 0.3 m	Vertically placed louvers, dimensions: 4.00 m × 0.29 m, no perforation
Motion properties: type of movement	In plane movement with respect to the envelope plane	Out of plane rotation with respect to the envelope plane	In plane movement (upper and lower part) and out (central part) of plane rotation with respect to the envelope plane
Type of shading	Vertical and horizontal	Vertical and horizontal	Vertical
Original orientation of the façade with applied shading	All, except north	South and north-east	South-east

study was based on the idea of merging such technical features as motion properties, geometrical shape and the ability to transmit light of the dynamic façade case studies: simple actuation pattern, in and out of plane movement, the use of the available materials with known properties, perforation/transmittance application. The designed façade was further evaluated using the proposed FDPI metric.

Additionally, as it is concluded in Tabadkani et al. (2021), an innovative solution to develop new generations of non-conventional dynamic façade is foldable structures to implement three-dimensional changes over the façade, particularly to counterbalance solar radiation, daylight and view out. Using bending and folding techniques are not only applicable to perform complex adaptive geometries, but also reversible deformations.

The case studies dynamic façades technical features and actuation patterns (described in Section 2.3) as well as the implementation of the concept of "foldable structure" with "rotation" and "folding" types of movements (two types of motion that have been more widely used in high-rise building practice in recent years) (Shi et al. 2020) can be found in the already existing engineering solution known as "Klemen's Torggler Door" (http://www.torggler.co.at/). It consists of 4 triangles connected with each other by piano hinges and a rotating hinge in the middle of the unit. The actuation structure is based on a plane rotation of top and bottom triangles and an out of the plane movement of central triangles, shown in Figure 3. With this type of movement it is possible to control the opening and closing of the dynamic façade.

The illustration of possible degrees of opening of such concept applied as the dynamic façade is present in Figure 4. The degree of opening of this particular façade concept is assumed as the relative offset (displacement) value of the central rotary hinge with respect to the edge of the curtain wall mullion.

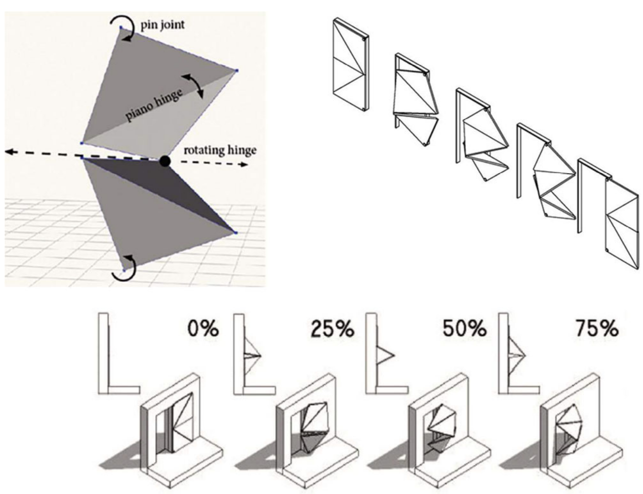


Fig. 3 Klemen's Torggler Door type of movement (Klemens Torggler 2014)

Based on this actuation pattern, the authors were able to develop 3 different initial dynamic façade configurations, changing the size of the shading unit, the distance between the envelope plane and the dynamic façade (offset) and material properties. Further, all these configurations were tested in terms of daylighting performance to select the best in performance scenario and compare it to the case studies dynamic façades. The initial dynamic façade configurations are described in Table 3 and are shown in Figure 5.

2.5 Metrics used to evaluate dynamic façade daylight performance

The metrics used in this study to evaluate the daylighting performance are dynamic, intending to provide a comprehensive annual overview rather than focusing on a specific point in time situations. Hourly results are summarized according to the established daylighting metrics of UDI (useful daylight illuminance), DA (daylight autonomy), and daylighting glare probability (DGP).

UDI proposed by Nabil and Mardaljevic (2005, 2006), is a dynamic daylight performance metric based on the work plane illuminances. UDI is defined as the annual occurrence of daylight levels across the task area that is considered useful for occupants. Based on different sources (Li et al. 2006; Tzempelikos and Shen 2013; Tian et al. 2021) the daylight illuminance in the range of 100–3000 lx is considered to be effective within buildings of various use and various activities held on the working plane. For office buildings in particular this range is considered to be effective from 100 lx to 2000 lx: i.e. it is neither too dark (<100 lx) nor too bright (>2000 lx) on the working plane (Reinhart et al. 2006). The suggested range for office buildings is founded on reported occupant preferences in daylit offices (Nabil and Mardaljevic 2005). Based on the upper and lower thresholds of 2000 lx and 100 lx, UDI results in three metrics, i.e. the percentages of the occupied times of the year when the UDI was achieved (100–2000 lx) – this domain is also called UDI-a, fell-short (<100 lx), or was exceeded (> 2000 lx) – this domain is also called UDI-e. The last bin is meant to detect the likely appearance of thermal discomfort and glare – visual discomfort (Reinhart et al. 2006; González and Fiorito 2015).

Table 3 The initial dynamic façade configurations description

CONF.#	1	2	3
Title	Default	Default 1 m offset	Half-dimension
Description	4 m × 2 m size of the shading device unit made of fully opaque material, fully covering the whole floor height on the span between two mullions (2 m distance), placed on the distance of 20 cm from the envelope outer plane	Same as CONF1, but placed on the distance of 1 m from the envelope outer plane	Same as CONF1, but the size of each unit is 2 m × 1 m, placed one under the other to fully cover the whole floor height on the span between two mullions (1 m distance)

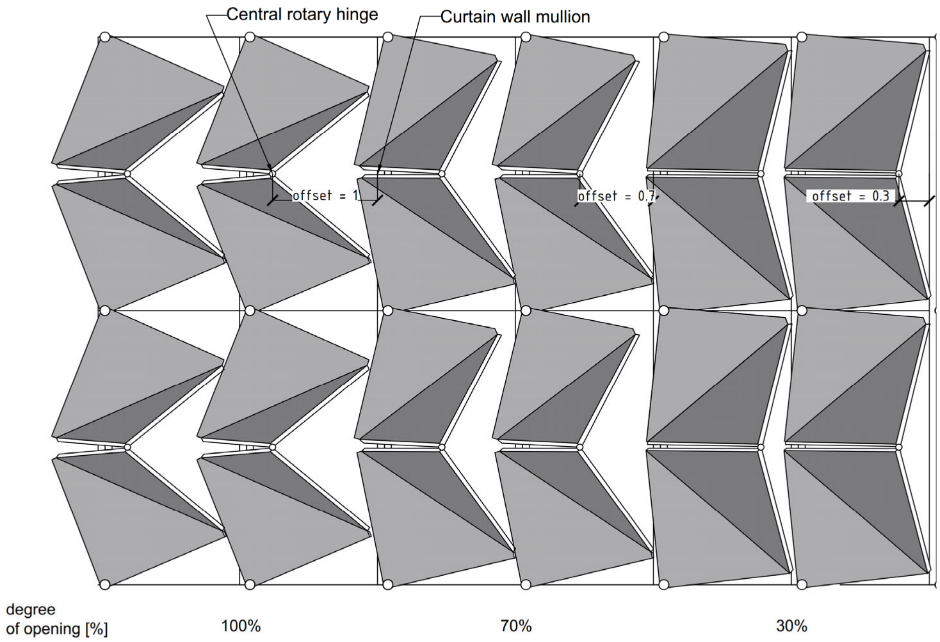


Fig. 4 The illustration of possible degrees of opening of Torggler Door concept applied as the dynamic façade

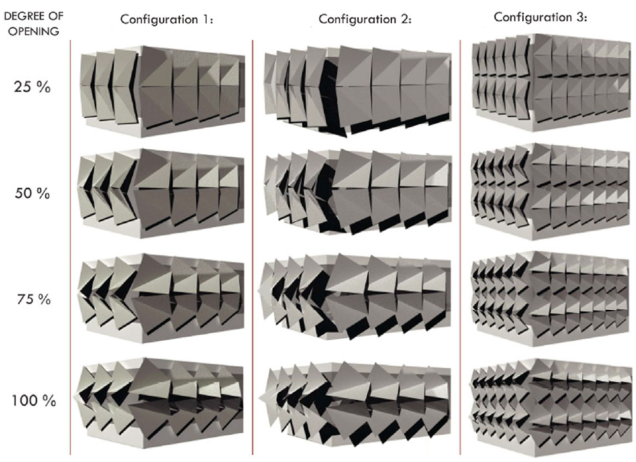


Fig. 5 The initial dynamic façade concept configurations illustration

The aim of UDI metrics is to maximize the occurrence of UDI-a range.

Therefore, considering an office building as the baseline building, the authors set the desired UDI in a range from 100 lx to 2000 lx.

DA measures the annual frequency of targeting a specified illuminance value only exploiting daylight and is highly promoted in currently used daylight evaluation standards (Li 2010). It is represented as a percentage of annual daytime hours that a given point in space is above a specified illumination level. This metric uses work plane illuminance as an indicator of whether there is a sufficient daylight in a space so that an occupant can work by daylight alone. The publications (Reinhart and Walkenhorst 2001; Reinhart et al. 2006) redefined DA-metric as the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. In later publications (Reinhart 2002; Reinhart and Andersen 2006), the concept of DA was further refined by combining it with a manual blind control model that predicts the status of movable shading devices at all-time steps in the year.

Considering DA metric, required minimum illuminance levels for different space types can be directly taken from reference documents such as (IESNA 2000). For this particular research, the choice of the threshold value of DA metric was related to the comfortable illuminance level on the working plane for office workers. The research by Akimov et al. (2021a) defines that the comfortable illuminance level on the working plane set for an office building is 500 lx. Therefore, the authors set a DA with a threshold of 500 lx (DA_500).

However, more daylight is accompanied by increased solar gains and possible visual discomfort (glare). Glare is defined as the contrast lowering effect within a visual field due to the presence of bright light sources (Galatioto and Beccali 2016). DGP (Chaloeytoy et al. 2020) is the most recent index used to evaluate glare from daylight, and it was extracted by experimental data in private office spaces involving human test subjects. DGP is considered as the main climate-based daylight metric for assessing daylight quality (Cantin and Dubois 2011) and establishing adaptive zones (Jakubiec and Reinhart 2012). As it is discussed in Hosseini et al. (2019b) the highest levels of DGP occur during winter solstice in Csa climate. Therefore, in this research the glare was analyzed on 21st of December when the sun position is the lowest in the sky, promoting the highest probability of glare in the chosen location (Northern hemisphere, latitude 32°5’).

2.6 Software used for the algorithm-aided (parametric) dynamic façade design development and its performance evaluation

To evaluate UDI, DA and DGP on the working plane in the DZ the Radiance-based software DAYSIM (2013) was used. DAYSIM is a daylighting analysis software program that performs climate-based annual daylight simulations, including the calculation of annual daylight metrics, and makes it possible to estimate the daylight availability through the daylighting metrics. Grasshopper (https://www.grasshopper3d.com), a graphical algorithm editor integrated with the 3D modelling tools of Rhino (https://www.rhino3d.com.), alongside with Rhino was used to set up the parametrical model, create the dynamic façades geometries and the mesh for the test-points on the working plane in the DZ.

The Grasshopper’s plug-ins Honeybee and Ladybug (https://www.ladybug.tools) were used to connect Grasshopper to DAYSIM (2013) and OpenStudio (https://www.openstudio.net) for building daylighting simulations.

2.7 The FDPI introduction

To estimate the performance improvement of the dynamic façade solution in comparative terms, the authors propose the metric called façade daylighting performance improvement (FDPI). This indicator aims to provide an information in percentage of “how one dynamic façade solution (called “modified configuration”) performs better (or worse) than the one it is compared to (called “reference configuration”)” from daylighting performance point of view (UDI, DA and DGP estimation). Since the sole calculation of the UDI, DA and DGP is rather difficult to analyze because of large array of resulting graphical data (that is further illustrated in Section 3), the FDPI combines these indicators and allows to simplify the post-processing of the results decreasing the list of evaluated parameters to one comprehensive number. The combination of these parameters in FDPI gives an idea of the daylight availability effectiveness empathizing both the effective daylight levels (DA, UDI-a) and exceeding daylight levels (UDI-e, DGP). The FDPI can be extended by other parameters that are of interest of the designed (for example, LENI, which is discussed in Section 2.8) being a part of the comparative FDPI-workflow and providing result in relative numbers.

The FDPI metric is calculated as follows from Eq. (1):

$$\mathrm{FDPI}=\sum \mathrm{FDPI}_{n\%} \quad (1)$$

where: $\mathrm{FDPI}_{n\%}$ is the façade daylighting performance improvement in a certain degree of façade’s opening, which can be calculated as follows from Eq. (2):

$$\mathrm{FDPI}_{n\%}=\left[\left(\frac{\mathrm{UDI}_{a,n\%}}{\mathrm{UDI}_{\mathrm{r},n\%}}-1\right)+\left(\frac{\mathrm{DA}_{a,n\%}}{\mathrm{DA}_{\mathrm{r},n\%}}-1\right)+\left(1-\frac{\mathrm{DGP}_{a,n\%}}{\mathrm{DGP}_{\mathrm{r},n\%}}\right)\right]\times 100[\%] \quad (2)$$

where: $\left(\frac{\mathrm{UDI}_{a,n\%}}{\mathrm{UDI}_{\mathrm{r},n\%}}-1\right)$ is the ratio showing the overall UDI improvement of the a-th modified configuration with n-% degree of façade’s opening ($\mathrm{UDI}_{a,n\%}$) over the reference configuration with the same n-% degree of façade’s opening ($\mathrm{UDI}_{\mathrm{r},n\%}$); $\left(\frac{\mathrm{DA}_{a,n\%}}{\mathrm{DA}_{\mathrm{r},n\%}}-1\right)$ is the ratio showing the overall DA improvement of the a-th modified configuration with n-% degree of façade’s opening ($\mathrm{DA}_{\mathrm{a},n\%}$) over the reference configuration with the same n-% degree of façade’s opening ($\mathrm{DA}_{\mathrm{r},n\%}$); $\left(1-\frac{\mathrm{DGP}_{a,n\%}}{\mathrm{DGP}_{\mathrm{r},n\%}}\right)$ is the ratio showing the overall DGP improvement of the a-th modified configuration with n-% degree of façade’s opening ($\mathrm{DGP}_{a,n\%}$) over the reference configuration with the same n-% degree of façade’s opening ($\mathrm{DGP}_{\mathrm{r},n\%}$) at the specified point of the testing DZ (where glare probability is analyzed).

It is required to establish the reference dynamic façade (“reference configuration”), the daylighting performance of which is compared to the daylighting performance of dynamic façade in question (“modified configuration”).

Since the FDPI is based on the daylighting parameters that come from the hourly annual-based daylighting information (annual weather data), the approach allows to analyze several distinctive discreate dynamic façade opening positions significantly simplifying the dynamic façade performance evaluation matrix. While $\mathrm{FDPI}_{n\%}$ denotes the daylighting performance difference of evaluated dynamic façades in certain degree of opening throughout the year, the final FDPI sums up $\mathrm{FDPI}_{n\%}$ for n evaluated opening positions and shows the overall dynamic façade performance difference on the annual basis. This means that accuracy of the FDPI results depends on the number of opening positions analyzed.

Additionally, as it is illustrated in Section 2.8 the FDPI can be extended by adding LENI estimation to the dynamic façade evaluation matrix. The addition to the dynamic façade performance evaluation matrix (FDPI-workflow) of the LENI provides additional information of the façade’s performance evaluation from lighting energy efficiency point of view. As it is discussed in Section 1, the dynamic façade has a profound effect on achieving the three performance requirements in terms of occupant's satisfaction, energy saving, and environmental impact neutralization. Therefore, addition of the LENI to the FDPI-workflow would allow to estimate another basic dynamic façade performance requirement – artificial lighting energy savings achieved by using the dynamic façade.

2.8 The LENI inclusion to the FDPI

In order to include the artificial lighting energy saving estimation to the dynamic façade performance evaluation, the authors propose to add the LENI parameter to the FDPI calculation (modifying the Eq. (2)).

The LENI quantifies the annual energy consumption for lighting per square meter of treated floor area and is typically expressed in kWh/(m^2·yr) (EN 15193-1:2017 2017). The detailed calculation method proposed by EN 15193-1:2017 (2017) can be applied for energy certification related to lighting energy consumption of buildings.

The LENI itself is in the direct dependence with the daylight illuminance met on the working or "task" plane (CEN/TR 2017). The main parameter constituting the LENI is the estimated lighting energy $W_{L,t}$ required to provide a zone of the building with adequate illumination. As it is defined by EN 15193-1:2017 (2017) and Akimov et al. (2021a) $W_{L,t}$, among other factors, depends on the daylight dependency factor F_D that, being a function of building location and geometry along with openings geometry, obstructions presence, shading device presence/absence and glazing properties, denotes the daylight availability in the zone under evaluation.

As it is set in the experiment from Akimov et al. (2021a), the artificial light is turned on only when the mean illuminance met on the task plain is below 500 lx. This means that LENI is in the direct dependence with DA_500 (which indicates the percentage of the occupied hours of the year when an illuminance of 500 lx is met by daylight alone). Since the FDPI-workflow present in this study includes the evaluation of DA_500, and since the higher percentage of DA_500 occupation of the task plane, considering other parameters that constitute the FDPI stay unaltered, results in higher FDPI results, the addition of the LENI parameter to the FDPI calculation would correlate with the results achieved in this study.

Introducing the LENI estimation to the FDPI, Eq. (2) would take the following form (Eq. (3)):

$$\mathrm{FDPI}_{n\%} = \left[\left(\frac{\mathrm{UDI}_{a,n\%}}{\mathrm{UDI}_{\mathrm{r},n\%}} - 1\right) + \left(\frac{\mathrm{DA}_{a,n\%}}{\mathrm{DA}_{\mathrm{r},n\%}} - 1\right) + \left(1 - \frac{\mathrm{DGP}_{a,n\%}}{\mathrm{DGP}_{\mathrm{r},n\%}}\right) + \left(1 - \frac{\mathrm{LENI}_{a,n\%}}{\mathrm{LENI}_{\mathrm{r},n\%}}\right)\right] \times 100[\%] \quad (3)$$

where $\left(1 - \frac{\mathrm{LENI}_{a,n\%}}{\mathrm{LENI}_{\mathrm{r},n\%}}\right)$ is the ratio showing the overall LENI improvement of the a-th modified configuration with n-% degree of façade's opening ($\mathrm{LENI}_{a,n\%}$) over the reference configuration with the same n-% degree of façade's opening ($\mathrm{LENI}_{\mathrm{r},n\%}$).

The results present in Section 3 do not include the LENI estimation, which is of interest for the further research.

3 Results and discussion

Adopting all the baseline conditions and simulation assumptions to the analysis, the authors were able to acquire case studies dynamic façades' and the initial dynamic façade configurations' daylighting performance results. Further, following the FDPI analysis the authors were able to change the initial dynamic façade shape to achieve an improvement in the daylighting performance results. The actual improvement was further indicated by the FDPI. For the sake of simplification of the dynamic façade performance evaluation matrix, the FDPI was calculated for 3 distinctive degrees of opening (25%, 50% and 75%) of the dynamic façades.

3.1 Daylighting performance of the case studies: results and discussion

Figure 6 summarizes the results of the daylight availability performance of the case study façades in the DZ with all the simulation assumptions and the baseline conditions discussed in Section 2.

As it can be observed from the false-color figures presented in Figure 6, the Case Study 3 performs better than other façades in case of degrees of opening of 50% and 75% following the biggest coverage of the task plane area of the UDI_a (100 lx < UDI < 2000 lx) and having a great part of the task plane area covered with DA_500 (DA > 500 lx) in all opening degrees. Additionally, it can be observed that the Case Study 3 performs better than the other case studies following the lowest DGP evaluated in the same DZ viewpoint position. Case Studies 1 and 2 showed very similar overall daylight availability performance. This information was further used to make a change in the initial dynamic façade geometry in order to reach the dynamic façade concept daylighting performance improvement.

3.2 Daylighting performance of the initial dynamic façade configurations: results and discussion

Figure 7 summarizes the results of daylighting performance of the initial dynamic façade configurations that are discussed in Section 2.4.

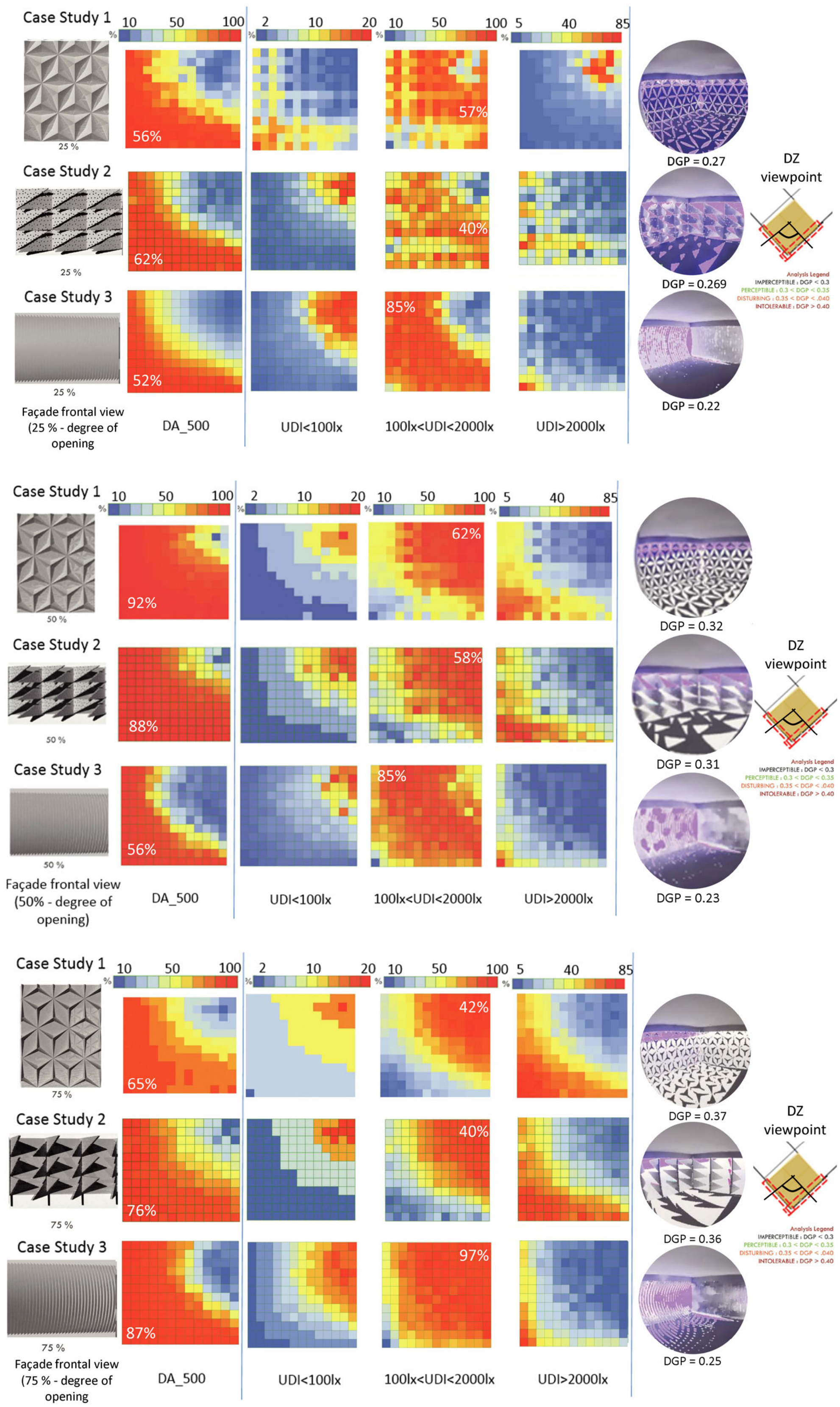


Fig. 6 The comparative daylighting performance analysis on the working plane in the DZ applying the case-study façades, degrees of opening of each façade are 25%, 50% and 75% (the percentage of area covered with 80%–100% of annual operating hours with sufficient daylight levels is indicated in the DA_500 and 100 lx < UDI < 2000 lx columns)

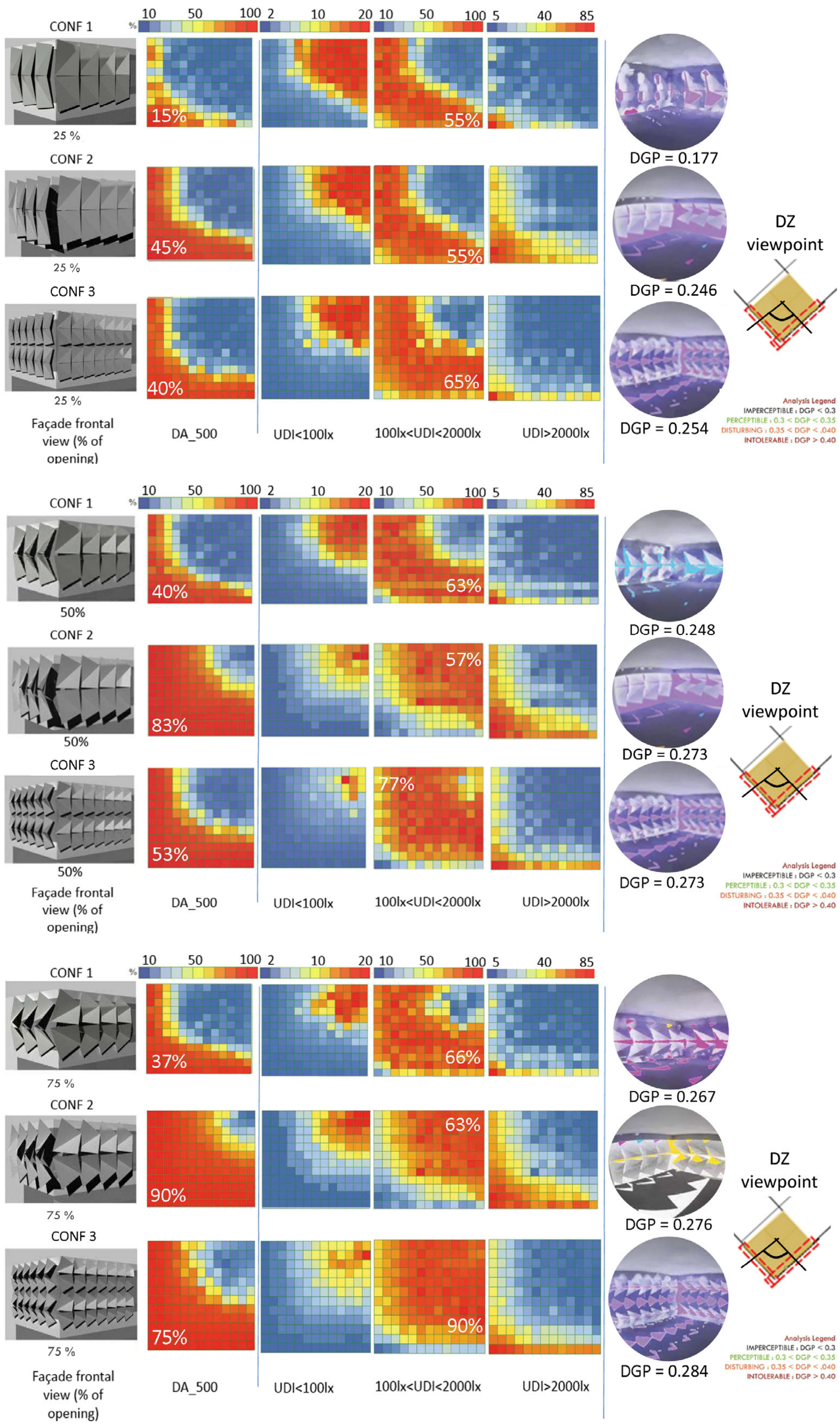


Fig. 7 The comparative daylighting performance analysis on the working plane in DZ applying the initial dynamic façade configurations, degrees of opening of each façade are 25%, 50% and 75% (the percentage of area covered with 80%–100% of annual operating hours with sufficient daylight levels is indicated in the DA_500 and 100 lx < UDI < 2000 lx columns)

As it can be observed from the false-color figures presented in Figure 7, the initial dynamic façade configuration 2 performs better than other configurations following the biggest coverage of the task plane area of both the UDI-a (100 lx< UDI < 2000 lx) and DA_500 (DA > 500 lx) in all degrees of façade opening. This result means that the biggest part of the task area is covered with the sufficient illuminance level with some parts of the area being either too illuminated or without sufficient level of illuminance.

3.3 The initial dynamic façade configurations and the case studies daylighting performance comparison using FDPI metric: results and discussion

The analysis based on the sole comparison of false-color figures (Figure 6 and Figure 7) makes it rather difficult to make any informative conclusion of dynamic façades performance difference. To indicate in the comparative terms the optimal dynamic façade solution in terms of daylighting performance, the authors used the FDPI metric, described in Section 2.7. The use of the FDPI metric made it possible to analyze the daylighting performance array of data received from the daylighting simulations inside the DZ.

As it is discussed in Section 2.7, it is required to select a "reference configuration" and with respect to its daylighting performance compare other façades', named as "modified configurations", daylighting performances.

As the first step, the authors made a daylighting performance comparison of the case study façades. The Case Study 1 (Table 2 and Figure 6) was selected as the reference configuration to conduct a comparative analysis of case study façades in terms of daylighting performance improvement. Table 4 summarizes the results of the comparative analysis.

As it can be observed from the FDPI analysis, taken from Table 4, the daylighting performance of the Case Study 3 showed significant improvement in comparison to the Case Study 1 (reference) daylighting performance – 257%. Additionally, it can be observed that overall daylighting performance of the Case Study 2 showed slightly worse results than the Case Study 1 daylighting performance – 9% decrease.

The authors made a similar performance comparison of the initial dynamic façade configurations. The Configuration 1 (Table 3 and Figure 7) was selected as the reference configuration to conduct a comparative analysis of the initial dynamic façade configurations. Table 5 summarizes the results of the comparative analysis.

As it can be observed from the FDPI analysis, taken from Table 5, the daylighting performance of the initial dynamic façade Configuration 2 showed significant improvement in comparison to the Configuration 1 (reference) daylighting performance – 384% improvement.

Table 4 Case study façades FDPI analysis

	$UDI_{25, 50, 75\%}$ [% of area with UDI-a]	$DA_{25, 50, 75\%}$ [% of area with DA_500]	$DGP_{25, 50, 75\%}$ [%]	$FDPI_{25, 50, 75\%}$
25% degree of the façades' opening				
Case Study 1	57	56	27	Reference
Case Study 2	40	62	26.9	−19%
Case Study 3	85	52	22	60%
50% degree of the façades' opening				
Case Study 1	62	92	32	Reference
Case Study 2	58	88	31	−8%
Case Study 3	85	56	23	64%
75% degree of the façades' opening				
Case Study 1	42	65	37	Reference
Case Study 2	40	76	35	−18%
Case Study 3	97	87	25	133%
FDPI				
Case Study 1		Reference		
Case Study 2		−9%		
Case Study 3		257%		

Table 5 Initial dynamic façade configurations FDPI analysis

	$UDI_{25, 50, 75\%}$ [% of area with UDI-a]	$DA_{25, 50, 75\%}$ [% of area with DA_500]	$DGP_{25, 50, 75\%}$ [%]	$FDPI_{25, 50, 75\%}$
25% degree of the façades' opening				
CONF. 1	55	15	17.7	Reference
CONF. 2	55	45	24.6	161%
CONF. 3	65	40	25.4	141%
50% degree of the façades' opening				
CONF. 1	63	40	24.8	Reference
CONF. 2	57	83	27.3	88%
CONF. 3	77	53	27.3	45%
75% degree of the façades' opening				
CONF. 1	66	37	26.7	Reference
CONF. 2	63	90	27.6	135%
CONF. 3	90	75	28.4	133%
FDPI				
CONF. 1		Reference		
CONF. 2		384%		
CONF. 3		319%		

The authors made a comparison between two dynamic façades that showed the best daylighting performance in the simulations.

The Case Study 3 (Table 2 and Figure 6) was selected as the reference configuration to conduct a comparative analysis of the initial dynamic façade Configuration 2 and the Case Study 3. Table 6 summarizes the results of the comparative analysis.

The negative result of the FDPI means that the Configuration 2 daylighting performance did not show the improvement over the Case Study 3 daylighting performance. This information was applied by the authors to the initial dynamic façade Configuration 2 that showed better daylighting performance among all the initial dynamic façade configurations in the shape finding procedure. The authors aimed to conduct the shape finding of the dynamic façade concept to improve its daylighting performance, which is discussed in Section 3.4.

Table 6 Initial dynamic façade Configuration 2 and Case Study 3 FDPI analysis

	$UDI_{25, 50, 75\%}$ [% of area with UDI-a]	$DA_{25, 50, 75\%}$ [% of area with DA_500]	$DGP_{25, 50, 75\%}$ [%]	$FDPI_{25, 50, 75\%}$
25% degree of the façades' opening				
Case Study 3	85	52	22	Reference
CONF. 2	55	45	24.6	−61%
50% degree of the façades' opening				
Case Study 3	85	56	23	Reference
CONF. 2	57	83	27.3	−3%
75% degree of the façades' opening				
Case Study 3	97	87	25	Reference
CONF. 2	63	90	27.6	−42%
FDPI				
Case Study 3	Reference			
CONF. 2	−106%			

3.4 The final dynamic façade concept shape finding

The final dynamic façade concept was customized by the authors in terms of shape – "shape-finding". It was assumed by the authors that the type of movement and the geometrical features of the Case Study 3 would ensure an improvement of the daylighting performance of the initial dynamic façade Configuration 2 (taking into consideration that the original orientation of the Case Study 3 is partially South exposed which is similar to the orientation of the DZ considered in this study).

The studies by Lee et al. (2017) and Akimov et al. (2021b) discuss that the introduction of vertical shading to the curtain wall system for the west and south-west exposure façades is beneficial, since vertical fins mitigate exceeding daylight illuminance (and harmful solar radiation) coming from the west exposure during fall and summer periods. The sun-chart analysis (Akimov et al. 2021b) of the south-west oriented glazed façade (façade bearing angle is 46° to west from south) of the same base-line building used in this research demonstrated that providing a vertical shading (0.55 m long vertical fins rotated 45° with respect to the façade plane) allows to mitigate 90% of harmful solar radiation hours. Therefore, it was assumed by the authors that the shape modification that would provide more vertical shading would decrease the light entrance through the transparent envelope parts, which was exceeding in the initial dynamic façade Configuration 2 (following the UDI > 2000 lx domain, Figure 7) and kept the UDI-a and DA_500 results lower compared to the Case Study 3.

To make a final dynamic façade design architecturally attractive, the authors made an analysis of the sun-path of the baseline building location. The sun-path was analyzed on December 21st when the sun position is the lowest on the sky in the given baseline building location. The authors made the sun-path projection on the façade plane mirroring it with respect to the horizontal axis and duplicating it along the façade plane (Figure 8).

The final size of each shading element was changed from 2m (*w*) × 4m (*l*) to 1m (*w*) × 8m (*l*). The perforation to the upper and lower triangular elements, that move in-plane (the perforated hole is 10 mm in diameter), was added following the study by Zapico et al (2022) to lighten the unit weight and allow the air flow regulation that would decrease the wind load (the perforation does not affect the façade transmittance in the simulation). The type of movement of the façade elements remained the same as the one described in Section 2.4. In Table 7 the final dynamic façade concept as well as the demonstration of the type of its movement are present.

3.5 The final dynamic façade concept daylighting performance: results and discussion

Figure 9 summarizes the results of daylighting performance of the final dynamic façade concept.

3.6 The daylighting performance comparison of the Case Study 3 dynamic façade solution and the final dynamic façade concept with the use of the FDPI metric

As the last step of the dynamic façade design, the authors made a comparison between the final dynamic façade

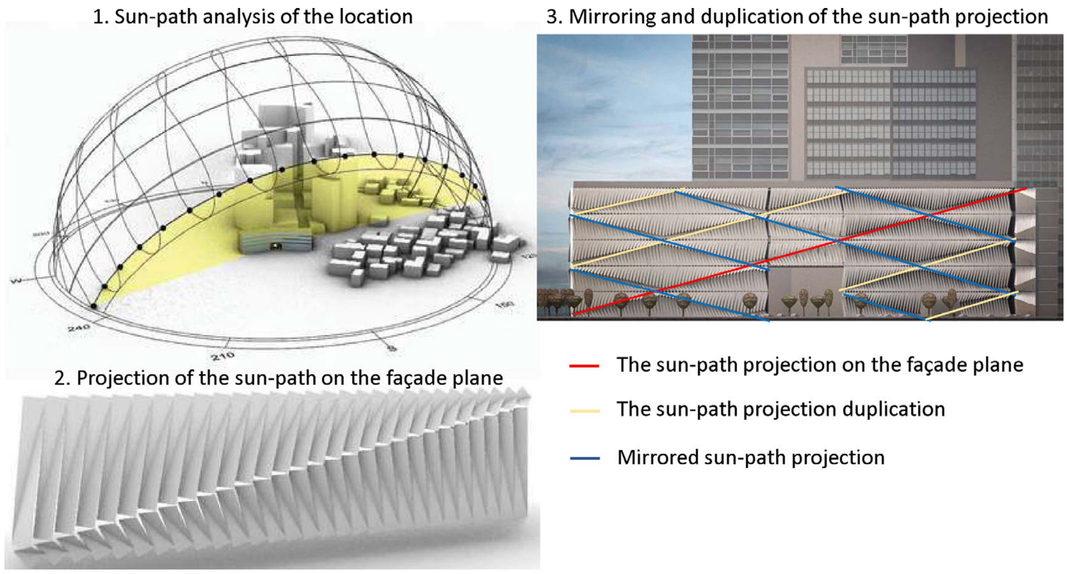
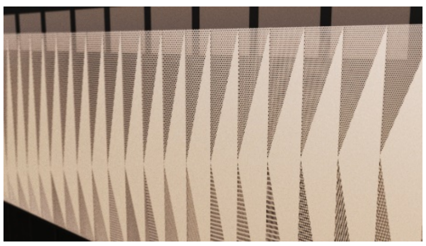
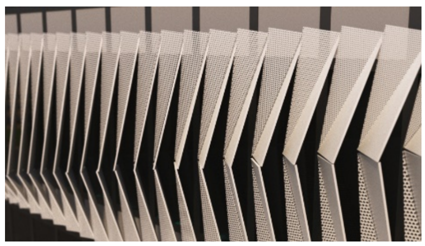
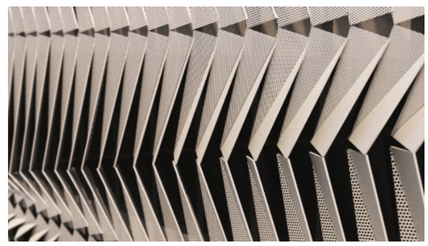


Fig. 8 The dynamic façade shape finding

Table 7 The final dynamic façade concept illustration

Degree of opening: 0%	Degree of opening: 50%	Degree of opening: 100%
		

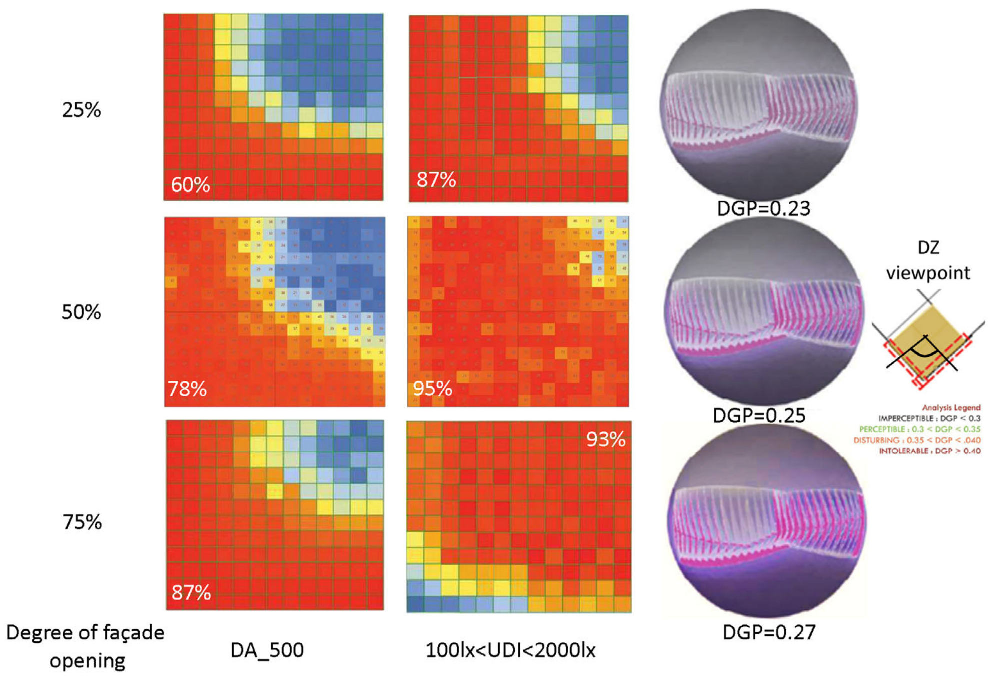


Fig. 9 The daylighting performance of the final dynamic façade concept, degrees of opening of the façade are 25, 50 and 75%

configuration and the Case Study 3. The initial dynamic façade Configuration 2 results were added to the comparative analysis, so that the amount of improvement after the optimization process could be seen directly.

The Case Study 3 (Table 2 and Figure 6) was selected as the reference configuration to conduct a comparative analysis of the final dynamic façade configuration and the Case Study 3. Table 8 summarizes the results of the comparative analysis.

Table 8 Final dynamic façade configuration, Configuration 2 and Case Study 3 FDPI analysis

	$UDI_{25,50,75\%}$ [% of area with UDI-a]	$DA_{25,50,75\%}$ [% of area with DA_500]	$DGP_{25,50,75\%}$ [%]	$FDPI_{25,50,75\%}$
25% degree of the façades' opening				
Case Study 3	85	52	22	Reference
CONF. 2	55	45	24.6	−61%
Final CONF.	87	60	23	13%
50% degree of the façades' opening				
Case Study 3	85	56	23	Reference
CONF. 2	57	83	27.3	−3%
Final CONF.	95	78	25	42%
75% degree of the façades' opening				
Case Study 3	97	87	25	Reference
CONF. 2	63	90	27.6	−42%
Final CONF.	93	87	27	−12%
FDPI				
Case Study 3	Reference			
CONF. 2	−106%			
Final CONF.	43%			

As it can be observed from the obtained results, the FDPI of the final dynamic façade configuration showed an improvement of 43% following the annual daylighting analysis of 25%, 50% and 75% degrees of opening.

3.7 Example-based description of the physical dynamic façade model design

In order to make the design of the dynamic façade feasible the authors followed the certain criteria:

(1) The dynamic façade merges the mechanical properties of the case studies façades (physically realized, discussed in Section 2.3) and/or is based on an existing mechanism;

(2) The dynamic façade is able to get integrated into unitized curtain wall system with additional support that would not drastically interfere into the structure of the curtain wall;

(3) The dynamic façade is designed using existing available on the market materials, durability and mechanical properties of which are investigated;

(4) The actuation mechanism is simple to use and accommodated on the structural part of the curtain wall system.

The realization of the criteria (1) in the dynamic façade design is discussed in Section 2.4.

Following the criteria (2):

The dynamic façade was designed as a simple mechanism attached to the unitized curtain wall system with an additional beam structure added. The dynamic façade load was transferred to the façade's structure that consists of transoms and mullions matrix, the distance between the mullions is 1 m. The exploded view of the façade's substructure is present in Figure 10.

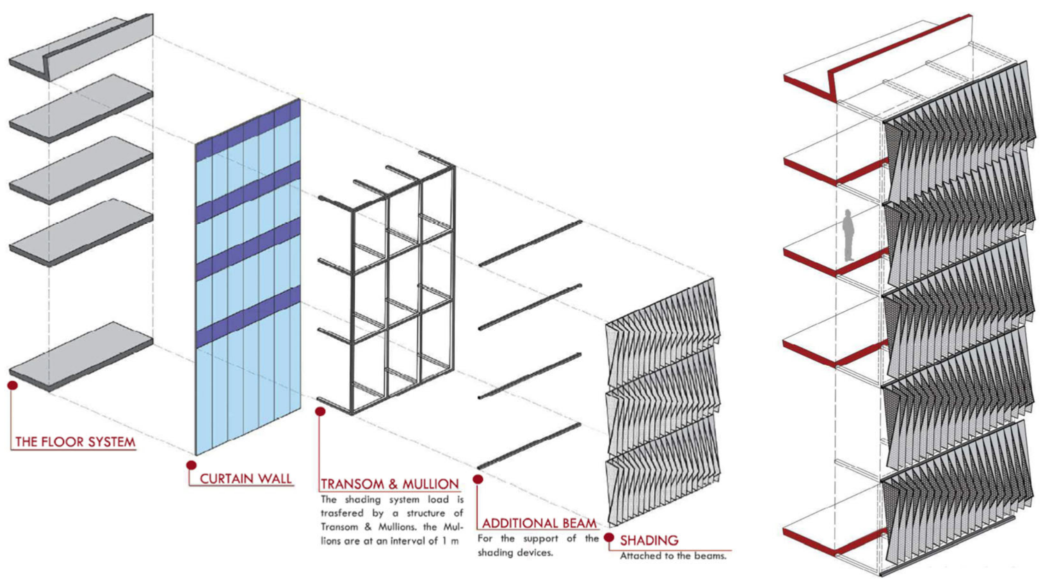


Fig. 10 The exploded and axonometric views of the façade system

The dynamic façade was connected to the substructural beam by rotary hinges/rods (structural elements) on the top and bottom of the shading structure, the substructural beam itself (200 mm × 100 mm) was connected to the structural element of the façade system (mullion) by 4 bolts every 0.5 m. The rotary hinge on the top is called active hinge, since it was connected to the actuation engine and provides the rotation movement to the screen elements (Figure 11).

The rotary rod itself is a part of actuation and, at the same time, is a structural element that was used to hang the shading unit from below and support the shading unit from above.

For the translation of rotary movement by 90 degrees' bevel gears were used. Bevel gears are gears where the axes of the two shafts intersect and the tooth-bearing faces of the gears themselves are conically shaped. Bevel gears are most often mounted on shafts that are 90 degrees' apart (Zaretsky and Branzai 2017).

The shading consists of 4 triangular elements: two on the top and bottom that move only in-plane (rotation) and two in the center, connected by spherical joint, that move out-of-plane. Connection of the triangles on the top and bottom with triangles in the middle was designed with the use of a hidden piano hinge (Figure 12).

From Figure 12, the element that connects two middle triangles that move out of plane is the spherical joint. This element is not structural and it controls only the movement of shading device elements.

Following the criteria (3):

Each triangle was made of perforated aluminum thin sheet. To provide rigidity to the element, edge of rigidity was made of the aluminum frame of 25 mm × 25 mm that was welded to all the edges of each triangle (Figure 13).

Following the criteria (4):

The actuation was done by means of the electrical rotary engine (Figure 14) that provides rotation motion to the rod that is connected to the active hinges with the spiral bevel gear that changes the rotation motion from one axis to another.

When the engine is actuated, the upper triangles start to rotate, that promotes middle triangles to move out of plane, providing discrepancy of triangular pieces.

Since the top triangles of different shading pieces have

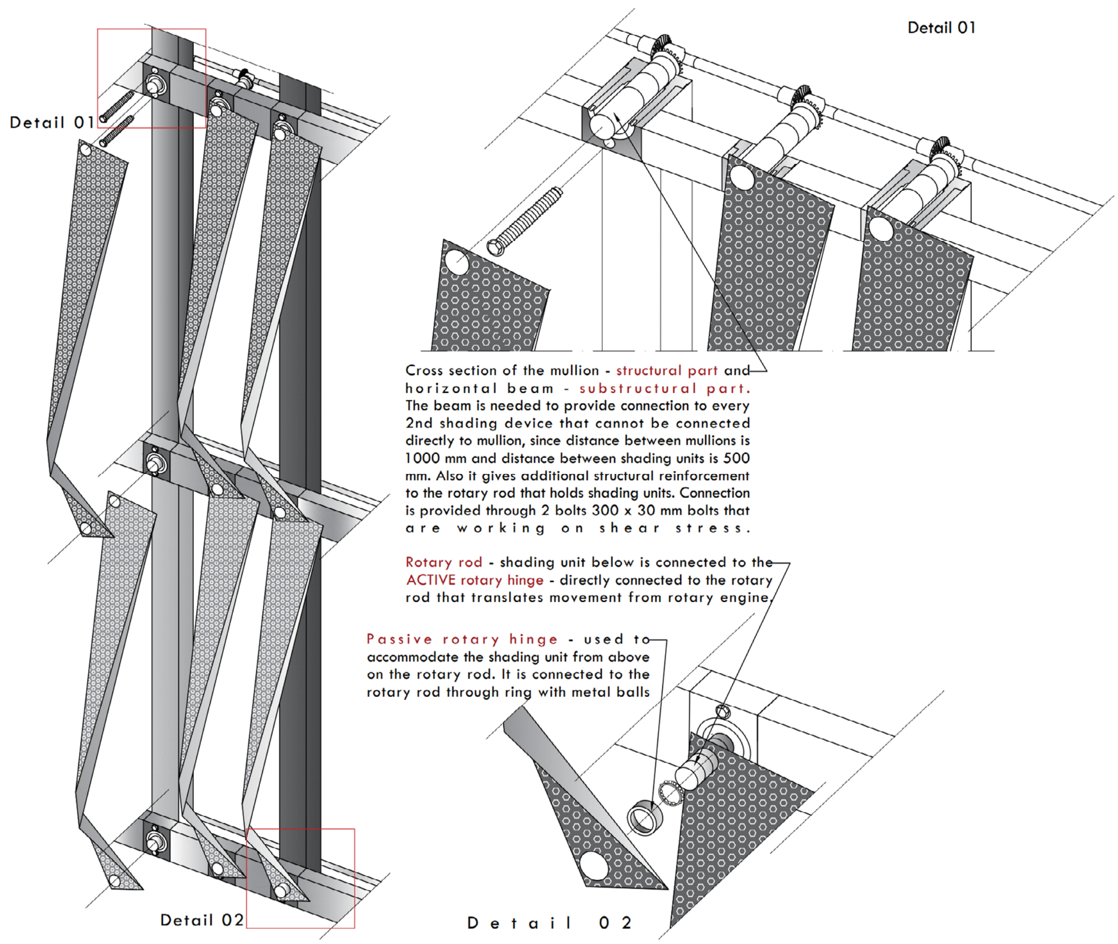


Fig. 11 An axonometric view of the structural constitution of the shading element

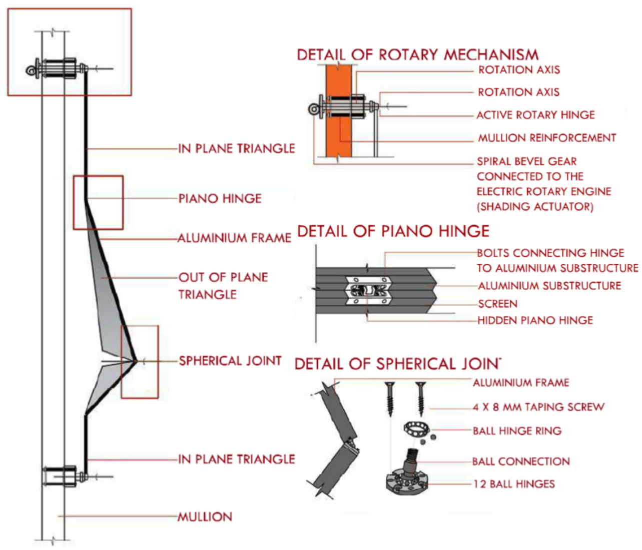


Fig. 12 The dynamic façade element connections

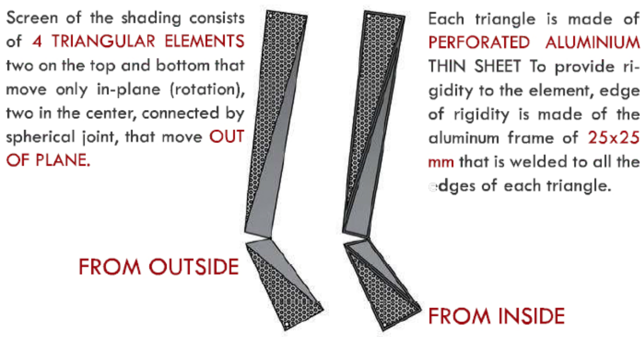


Fig. 13 The materials application

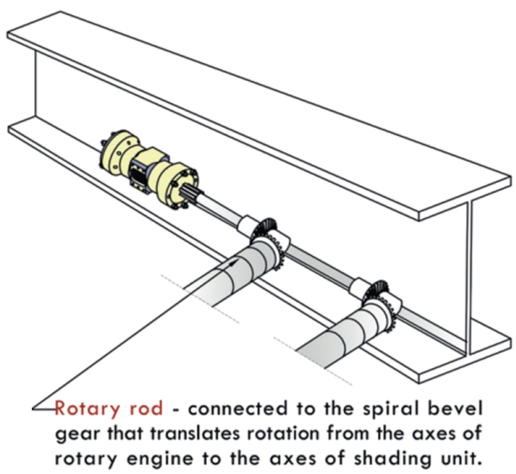


Fig. 14 The engine accommodation on the beam's web

different dimensions, corresponding bevel gears also have different dimensions that allow to make the same degree of opening to all the shading pieces connected to the same rod (Guenther et al. 2013). The engine controls the degree of opening and defines the maximum opening of the shading system.

4 Conclusions and further developments

In this paper, the authors discussed the FDPI-workflow which is a simple dynamic façade design methodology. It allows to consider multiple design criteria, such as the dynamic façade daylighting performance estimation, the shape finding approach and transition from analytical to physical model. As the key of the FDPI-workflow, the new metric – façade daylighting performance improvement (FDPI) was introduced. It can be used by the designers and researchers to conduct a comprehensive dynamic façade design from daylighting performance point of view at the early stage of the dynamic façade design since the methodology does not incur high computational costs. The FDPI is aimed to address the existing issue of the performance of dynamic façade systems assessment and allows to estimate the performance difference of the compared dynamic façades, quantifying it in relative terms. The authors were able to compare daylighting performance changes of the dynamic façade concept designed with shape finding analysis.

Analyzing the elements shape features of the case study that showed the best daylighting performance among case studies (Case Study 3): long and narrow elements with the combination of in plane movement (upper and lower part) and out (central part) of plane rotation with respect to the envelope plane, that provides mostly "vertical" shading, the authors emphasized these movement and geometrical features adding slenderness to the elements of the initial dynamic façade configuration that showed the best daylighting performance among the initial configurations (Configuration 2), modifying their size, keeping the type of movement unaltered. The performance improvement rating was indicated using the FDPI: 43% improvement of the final dynamic façade configuration over the best in daylighting performance case study dynamic façade.

The stage of the transition from the analytical model to the physical model was as well discussed on the basis of the example of the dynamic façade design. The introduction of other parameters for the performance improvement estimation of the designed dynamic façade to the FDPI-workflow that would be of interest of the designers, such as the LENI, is as well discussed in the paper.

However, this study has a certain degree of limitations. For example, only one typology of building was analysed in the paper – office building that was set as a baseline building. The analysis of dynamic façade performance that may ensure the effective functioning of engineering infrastructure of industrial buildings, such as factories of the future (defined in Burggräf et al. (2019) and Badenko et al. (2021)), might as well be a part of a detailed analysis in the future research.

Another limitation of the study is that it focuses on the daylight aspects by referring to the visual performance in terms of user comfort in the context of dynamic façades. Thus, solar radiation, heat gains in terms of thermal comfort, visibility of movement of the dynamic façade system and its control mechanisms in terms of user interaction should also be mentioned in the context of dynamic façade design process and, thus, is of interest for the future research.

Moreover, the research does not cover such aspects of the dynamic façade design as a single element shape-finding and automation of its opening focusing on the occupants' comfort influenced by the façade movement. As it is highlighted in Attia (2018c) the actuation schedule of the dynamic façade, its type of movement along with automation, might result in the users' discomfort, therefore, such investigation might be useful for architects and designers in the process of development of dynamic façade systems.

Since the introduced methodology is positioned as the approach that is useful for architects and designers in the early dynamic façade design stage, in order to speed up the preliminary dynamic façade evaluation some simplifications were introduced to the simulation. For example, the dynamic façades were analyzed in several distinctive fixed (discrete) positions which allowed to simplify the FDPI evaluation matrix (since continuous adjusting of the dynamic façade would considerably expand the simulation matrix). Additionally, overlooking the materiality of case study façades (focusing solely on their geometry and motion) helped to simplify the approach though adding another degree of limitation of the study. Therefore, the analysis of the applied materials properties along with the analysis of pros and cons of different possible materials that could be applied as the material of the dynamic façade's element (for example, thin metal façade skins with different perforation patterns, FRP with different degrees of translucency the bearing capacity of which was discussed in Akimov et al. (2021c)) should be introduced to the comprehensive dynamic façade design methodology.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

All authors contributed to the study conception and design. Conceptualization: Luka Akimov, Andrey Bezborodov and Vladimir Badenko; methodology: Luka Akimov; software: Luka Akimov; validation: Luka Akimov; formal analysis: Luka Akimov; investigation: Luka Akimov; resources: Luka Akimov; data curation: Luka Akimov; writing—original draft preparation: Luka Akimov; writing—review and editing: Luka Akimov; visualization: Luka Akimov; supervision: Andrey Bezborodov and Vladimir Badenko; project administration: Vladimir Badenko; funding acquisition: Andrey Bezborodov and Vladimir Badenko. All authors read and approved the final manuscript.

References

Akimov L, De Michele G, Filippi Oberegger U, et al. (2021a). Evaluation of EN15193-1 on energy requirements for artificial lighting against Radiance-based DAYSIM. *Journal of Building Engineering*, 40: 102698.

Akimov L, Lvov V, de Martino di Montegiordano D, et al. (2021b). Shading system design and solar gains control for buildings passive energy-efficiency improvement. In: Mottaeva A (ed), Technological Advancements in Construction. Lecture Notes in Civil Engineering, vol 180. Cham: Springer.

Akimov L, De Mei K, de Martino di Montegiordano D, et al. (2021c). The material-efficient design of bridges with the use of FRP. Cham: Springer.

Al Horr Y, Arif M, Kaushik A, et al. (2016). Occupant productivity and office indoor environment quality: A review of the literature. *Building and Environment*, 105: 369–389.

Alexander MG (2016). Marine Concrete Structures: Design, Durability and Performance. Amsterdam: Elsevier.

Alrubaih MS, Zain MFM, Alghoul MA, et al. (2013). Research and development on aspects of daylighting fundamentals. *Renewable and Sustainable Energy Reviews*, 21: 494–505.

ASHRAE (2006). Architectural design impacts. In: The ASHRAE GreenGuide (2nd edn). Oxford, UK: Butterworth-Heinemann.

Attia S (2018a). Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation. Hull, Canada: Butterworth-Heinemann.

Attia S (2018b). Regenerative and Positive Impact Architecture: Learning from Case Studies. New York: Springer.

Attia S (2018c). Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. *QScience Connect*, 2017(2): 6.

Attia S, Bashandy H (2016). Evaluation of adaptive façades: The case study of AGC headquarter in Belgium. In: Proceedings of Challenging Glass 5, https://doi.org/10.7480/cgc.5.2234

Attia S, Bilir S, Safy T, et al. (2018). Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy and Buildings*, 179: 165–182.

Attia S, Garat S, Cools M (2019). Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades. *Building and Environment*, 157: 268–276.

Badenko VL, Bolshakov NS, Tishchenko EB, et al. (2021). Integration of digital twin and BIM technologies within factories of the future. *Magazine of Civil Engineering*, 101: 10114.

Baranova D, Sovetnikov D, Borodinecs A (2018). The extensive analysis of building energy performance across the Baltic Sea region. *Science and Technology for the Built Environment*, 24: 982–993.

Battisti A, Persiani SGL, Crespi M (2019). Review and mapping of parameters for the early stage design of adaptive building technologies through life cycle assessment tools. *Energies*, 12: 1729.

Bellia L, Cesarano A, Iuliano GF, et al. (2008). Daylight glare: A review of discomfort indexes. Paper presented at International Workshop and the 7th Annex 45 Expert Meeting: Visual Quality and Energy Efficiency in Indoor Lighting: Today for Tomorrow, Roma, Italy.

Beute F, de Kort YAW (2014). Salutogenic effects of the environment: Review of health protective effects of nature and daylight. *Applied Psychology Health and Well-Being*, 6: 67–95.

Burggräf P, Dannapfel M, Schneidermann D, et al. (2019). Integrated factory modelling: Using BIM to disrupt the interface between manufacturing and construction in factory planning. *WIT Transactions on The Built Environment*, 192: 143–155.

Cantin F, Dubois MC (2011). Daylighting metrics based on illuminance, distribution, glare and directivity. *Lighting Research & Technology*, 43: 291–307.

CEN/TR (2017). CEN/TR 15193-2: Energy performance of buildings—Energy requirements for lighting—Part 2: Explanation and justification of EN 15193-1, Module M9.

Chaloeytoy K, Ichinose M, Chien SC (2020). Determination of the simplified daylight glare probability (DGPs) criteria for daylit office spaces in Thailand. *Buildings*, 10: 180.

COST (2014). COST Action TU 1403. Cost Action TU1403—Adaptive Facades Network. Available at http://tu1403.eu.

Cuce E, Riffat SB (2015). A state-of-the-art review on innovative glazing technologies. *Renewable and Sustainable Energy Reviews*, 41: 695–714.

DAYSIM (2013). DAYSIM 4.0 plus web-site. Available at https://www.radiance-online.org/pipermail/radiance-daysim/2013-February/000026.html. Accessed 24 Sept 2022.

Edwards L, Torcellini P (2002). Literature review of the effects of natural light on building occupants. National Renewable Energy Lab. (NREL), Golden, CO, USA.

El-Arnaouty H, Azab N, Omar O (2020). Health and wellbeing re-visited; an exploratory study towards a "healthy & wellbeing" university campus. *Architecture and Planning Journal* (*APJ*), 25(1): 1.

EN 12665-2011 (2011). Light and Lighting – Basic Terms and Criteria for Specifying Lighting Requirements.

EN 15193-1:2017 (2017). Energy Performance of Buildings; Energy Requirements for Lighting.

Fakourian F, Asefi M (2019). Environmentally responsive kinetic façade for educational buildings. *Journal of Green Building*, 14: 165–186.

Favoino F, Goia F, Perino M, et al. (2014). Experimental assessment of the energy performance of an advanced responsive multifunctional façade module. *Energy and Buildings*, 68: 647–659.

Freewan AAY (2014). Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy*, 102: 14–30.

Galatioto A, Beccali M (2016). Aspects and issues of daylighting assessment: A review study. *Renewable and Sustainable Energy Reviews*, 66: 852–860.

González J, Fiorito F (2015). Daylight design of office buildings: optimisation of external solar shadings by using combined simulation methods. *Buildings*, 5: 560–580.

Guenther A, Kniel K, Härtig F, et al. (2013). Introduction of a new bevel gear measurement standard. *CIRP Annals*, 62: 515–518.

Hosseini SM, Mohammadi M, Rosemann A, et al. (2018). Quantitative investigation through climate-based daylight metrics of visual comfort due to colorful glass and orosi windows in Iranian architecture. *Journal of Daylighting*, 5: 21–33.

Hosseini SM, Mohammadi M, Rosemann A, et al. (2019a). A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review. *Building and Environment*, 153: 186–204.

Hosseini SM, Mohammadi M, Guerra-Santin O (2019b). Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes. *Building and Environment*, 165: 106396.

Hviid CA, Nielsen TR, Svendsen S (2008). Simple tool to evaluate the impact of daylight on building energy consumption. *Solar Energy*, 82: 787–798.

IES (2012). IES Approved Method: Spatial Daylight Autonomy and Annual Sunlight Exposure. IES LM-83–12, USA.

IESNA (2000). IESNA Lighting Handbook, 9th edn. Illuminating Engineering Society of North America.

Jakubiec JA, Reinhart CF (2012). The 'adaptive zone'—A concept for assessing discomfort glare throughout daylit spaces. *Lighting Research & Technology*, 44: 149–170.

Jin Q, Overend M (2014). Sensitivity of façade performance on early-stage design variables. *Energy and Buildings*, 77: 457–466.

Kasinalis C, Loonen RCGM, Cóstola D, et al. (2014). Framework for assessing the performance potential of seasonally adaptable facades using multi-objective optimization. *Energy and Buildings*, 79: 106–113.

Kassem M, Mitchell D (2015). Bridging the gap between selection decisions of facade systems at the early design phase: Issues, challenges and solutions. *Journal of Facade Design and Engineering*, 3: 165–183.

Kim H, Clayton MJ (2020). A multi-objective optimization approach for climate-adaptive building envelope design using parametric behavior maps. *Building and Environment*, 185: 107292.

Kirimtat A, Koyunbaba BK, Chatzikonstantinou I, et al. (2016). Review of simulation modeling for shading devices in buildings. *Renewable and Sustainable Energy Reviews*, 53: 23–49.

Klemens Torggler (2014). Toggler's door movement. Available at https://www.dezeen.com/2014/02/11/door-reinvented-with-folding-mechanism-by-klemens-torggler. Accessed 24 Sept 2022.

Knaack U, Luible A, Overend M, et al. (2015). Adaptive facade network – Europe. Delft, the Netherlands: TU Delft Open

Knippers J, Jungjohann H, Scheible F, et al. (2013). Bio-inspirierte kinetische fassade für den themenpavillon "one ocean" EXPO 2012 in yeosu, Korea. *Bautechnik*, 90: 341–347.

Krarti M (2016). Energy Audit of Building Systems: An Engineering Approach, 2nd edn. Boca Raton, FL: CRC Press.

Kuru A, Oldfield P, Bonser S, et al. (2022). Biomimetic adaptive building skins: Design and performance. In: Gasparri E, Brambilla A, Lobaccaro G, et al. (eds), Rethinking Building Skins. Amsterdam: Elsevier.

Lee K, Han K, Lee J (2017). The impact of shading type and azimuth orientation on the daylighting in a classroom–focusing on effectiveness of façade shading, comparing the results of DA and UDI. *Energies*, 10: 635.

Le-Thanh L, Le-Duc T, Ngo-Minh H, et al. (2021). Optimal design of an Origami-inspired kinetic façade by balancing composite motion optimization for improving daylight performance and energy efficiency. *Energy*, 219: 119557.

Li DHW, Cheung GHW, Lau CCS (2006). A simplified procedure for determining indoor daylight illuminance using daylight coefficient concept. *Building and Environment*, 41: 578–589.

Li DHW (2010). A review of daylight illuminance determinations and energy implications. *Applied Energy*, 87: 2109–2118.

Loonen RCGM, Trčka M, Cóstola D, et al. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25: 483–493.

Loonen RCGM, Favoino F, Hensen JLM, et al. (2017). Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *Journal of Building Performance Simulation*, 10: 205–223.

Loonen RCGM (2018). Approaches for computational performance optimization of innovative adaptive façade concepts. PhD Thesis, Technische Universiteit Eindhoven, the Netherlands.

Mahmoud AHA, Elghazi Y (2016). Parametric-based designs for kinetic facades to optimize daylight performance: comparing rotation and translation kinetic motion for hexagonal facade patterns. *Solar Energy*, 126: 111–127.

Manzan M, Padovan R (2015). Multi-criteria energy and daylighting optimization for an office with fixed and moveable shading devices. *Advances in Building Energy Research*, 9: 238–252.

Michael A, Heracleous C (2017). Assessment of natural lighting performance and visual comfort of educational architecture in Southern Europe: the case of typical educational school premises in Cyprus. *Energy and Buildings*, 140: 443–457.

Nabil A, Mardaljevic J (2005). Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Lighting Research & Technology*, 37: 41–57.

Nabil A, Mardaljevic J (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38: 905–913.

Ne'Eman E (1974). Visual aspects of sunlight in buildings. *Lighting Research & Technology*, 6: 159–164.

Peel MC, Finlayson BL, McMahon TA (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11: 1633–1644.

Pilechiha P, Mahdavinejad M, Pour Rahimian F, et al. (2020). Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency. *Applied Energy*, 261: 114356.

Rafsanjani H, Ahn C, Alahmad M (2015). A review of approaches for sensing, understanding, and improving occupancy-related energy-use behaviors in commercial buildings. *Energies*, 8: 10996–11029.

Reinhart CF, Walkenhorst O (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*, 33: 683–697.

Reinhart CF (2002). Effects of interior design on the daylight availability in open plan offices. In: Proceedings of the ACE3 2002 Summer Study on Energy Efficiency in Buildings, Pacific Grove, USA.

Reinhart CF, Andersen M (2006). Development and validation of a Radiance model for a translucent panel. *Energy and Buildings*, 38: 890–904.

Reinhart CF, Mardaljevic J, Rogers Z (2006). Dynamic daylight performance metrics for sustainable building design. *LEUKOS*, 3: 7–31.

Ruck N, Aschehoug Ø, Aydinli S, et al. (2000). Daylight in Buildings—A Source Book on Daylighting Systems and Components. Lawrence Berkeley National Laboratory.

Sadegh SO, Haile SG, Jamshidzehi Z (2022). Development of two-step biomimetic design and evaluation framework for performance-oriented design of multi-functional adaptable building envelopes. *Journal of Daylighting*, 9: 13–27.

Sharaidin K (2014). Kinetic facades: Towards design for environmental performance. PhD Thesis, RMIT University, Australia.

Shi X, Abel T, Wang L (2020). Influence of two motion types on solar transmittance and daylight performance of dynamic façades. *Solar Energy*, 201: 561–580.

Sood R, Patil AS (2021). Analysis and review of the kinetic façades in Kolding campus, South Denmark University. In: Dubey HM, Pandit M, Srivastava L, Panigrahi BK (eds), Artificial Intelligence and Sustainable Computing. Algorithms for Intelligent Systems. Singapore: Springer.

Struck C, de Wilde PJCJ, Hopfe CJ, et al. (2009). An investigation of the option space in conceptual building design for advanced building simulation. *Advanced Engineering Informatics*, 23: 386–395.

Tabadkani A, Valinejad Shoubi M, Soflaei F, et al. (2019). Integrated parametric design of adaptive facades for user's visual comfort. *Automation in Construction*, 106: 102857.

Tabadkani A, Roetzel A, Li H, et al. (2021). Design approaches and typologies of adaptive facades: A review. *Automation in Construction*, 121: 103450.

Taveres-Cachat E, Favoino F, Loonen R, et al. (2021). Ten questions concerning co-simulation for performance prediction of advanced building envelopes. *Building and Environment*, 191: 107570.

Tian Z, Lin P, He Y, et al. (2021). A study of luminous environment with prism daylight redirecting fenestrations in classrooms. *Indoor and Built Environment*, 30: 461–475.

Tzempelikos A, Shen H (2013). Comparative control strategies for roller shades with respect to daylighting and energy performance. *Building and Environment*, 67: 179–192.

U.S. Green Building Council (2019). LEED v4 for Building Design and Construction.

Uribe D, Bustamante W, Vera S (2017). Seasonal optimization of a fixed exterior complex fenestration system considering visual comfort and energy performance criteria. *Energy Procedia*, 132: 490–495.

Wienold J, Christoffersen J (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38: 743–757.

Yang S, Wan MP, Ng BF, et al. (2021). Model predictive control for integrated control of air-conditioning and mechanical ventilation, lighting and shading systems. *Applied Energy*, 297: 117112.

Yitmen I, Al-Musaed A, Yücelgazi F (2022). ANP model for evaluating the performance of adaptive façade systems in complex commercial buildings. *Engineering, Construction and Architectural Management*, 29: 431–455.

Yu X, Su Y (2015). Daylight availability assessment and its potential energy saving estimation—A literature review. *Renewable and Sustainable Energy Reviews*, 52: 494–503.

Zapico A, Egiluz Z, García Frómeta Y, et al. (2022). Mechanical characterization of double-skin perforated-sheet façades. *Journal of Building Engineering*, 56: 104750.

Zaretsky EV, Branzai EV (2017). Rolling bearing service life based on probable cause for removal—A tutorial. *Tribology Transactions*, 60: 300–312.

Zemitis J, Terekh M (2018). Optimization of the level of thermal insulation of enclosing structures of civil buildings. *MATEC Web of Conferences*, 245: 06002.

Zhang X, Zhang H, Wang Y, et al. (2022). Adaptive façades: Review of designs, performance evaluation, and control systems. *Buildings*, 12: 2112.