

Feasibility Study of Implementing a Bio-Inspired Building Envelope for Energy Harvesting and Visual Comfort Improvement

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Abstract

A combination of sustainable architecture and renewable energy harvesting strategies are among promising path to sustainable development in construction sectors. This idea can be used on the building site and the building shell and on the scale of the building itself, which is exposed to renewable energy such as solar energy. This article aimed to analyze an adaptive façade inspired by insects' eyes geometrical arrangement and to consider several less-attended issues, in current literature, in the process of adaptive facade design. First, there was a lack of economic objectives in adaptive façade optimization. Second, few pieces of researches attempted to include the space utility, and occupants' activities in spaces while configuring adaptive façades towards comfort and building energy efficiency. Third, an integration of the previous items into solar water heaters was not taken into consideration through parametric approaches and Feresnel lenses materials while designing an adaptive façade for comfort and energy harvesting objectives. Given these, a parametric code was used for shaping the geometry, environmental analysis, and simulations for visual comfort consideration, heat gain, and economic analysis. Finally, after a multi-objective optimization for visual comfort, energy harvesting, and economic considerations, the best possible solution were proposed both in a kinetic and static mode. The results showed that there was 361.5 MWh annual energy harvesting potential using the proposed façade, while in comparison to the current condition of the façade, there was respectively 24.56, 15.04, and 18.23 times improvements in annual daylight performance in July, December, and March cases. Also, the economic analysis and the optimization showed that the payback time of the proposed system was 5.5 years.

1. Introduction

In the face of energy crises, there are no promising alternative rather than pursuing sustainable development solutions. A combination of sustainable architecture and renewable energy harvesting strategies are among the promising paths to sustainable development in construction sectors. In this regard, an optimal building envelope design is among the crucial success factors in buildings to address the comfort of occupants in indoor environments [1] and help to step towards improving building energy efficiency [2], energy saving [3], and energy harvesting [4, 5].

Building envelope design is an architectural and technical specialty that incorporate all aspects of building science and climate control [6]. The extent to which a building provides a comfortable environment for its occupants is one of the most essential concerns when constructing it. Building envelopes, separately or in an integrated multi-criterion design approach, fulfill several functions to provide acceptable indoor environment quality for different aspects of occupant's comfort.

Meanwhile, sun-facing façades—known as gold mine for quality daylighting and harvesting solar radiation [7]—would be better to prioritize while stepping towards high performance buildings. Moreover, the future of successful building envelopes embeds in adaptation [8], since, in contrast to static building

envelopes, adaptive building envelopes can respond to environmental factors [9], [10]. This is becoming more promising with advanced computational tools and parametric design trends [11].

On the other extreme, integrating green ideas and technologies into adaptive building envelope not only can improve comfort for occupants but also can help with minimizing energy consumption and energy harvesting [1–3]. Recent decades, many researchers adopted energy harvesting from building envelopes [15]. As such integration is solar water heater to façade design [13], [14], [16], [17]. Solar water heaters let for heating water by sunlight and there are a variety of configurations available to this end [18]. Using lenses to collect and direct daylight in a centralized manner is one of the integration and innovation processes [19]. The existence of lens, in solar water heaters, dates back to 1925 in the process of a project called: "Method and apparatus for using the heat of the sun for heating purposes" [20]. In this invention, the goal was to use solar power efficiently and economically. In the earlier attempts, mechanisms for extracting solar energy lacked continuous concentration and efficiency, and energy waste was a common problem. The main mechanism was outlined in such a way that a lens concentrated the sun rays on the vessel to warm up the fluid inside the system for later uses. Also, a mirror was used to direct sunlight vertically on the lens and the enclosure contained warmed liquid, associated with its tubes, could then be deposited in sand or concrete or freely in the air. See **Error! Reference source not found.**

A composite compact lens called a Fresnel lens is a type of composite compact lens that can be made much thinner than a comparable conventional lens, in some cases taking the form of a flat sheet. The Fresnel lens reduces the amount of material required compared to a conventional lens by dividing the lens into a set of concentric annular sections. See Fig. 2. At the same level of power compared to the common lenses, Fresnel lenses poses advantages of lower volume, weight, and cost, and shorter focal length. They are appropriate for concentrating and controlling the solar energy based on a predefined boundary conditions [21], [22].

In addition, building envelope design is associated with complexity due to the need for an interdisciplinary perspective to achieve an optimal design [23], [24]. A multi-objective optimization, in building envelope design process, has shown a promising way to fulfill several functions to provide occupants with acceptable indoor environment quality and protecting the internal condition from the adverse environmental condition [25]–[27]. As such is the integration of daylight improvement objectives to the energy harvesting aspect of building envelope design [28], [14].

Moreover, integrating occupants real needs and activities, and the function of spaces to other environmental stimulus, on-site renewable resources, and engineering aspects can evolve the perception of adaptive and responsive adaptive facade to a more functional state and bring more interactive results for more comfortable and energy-efficient [23], [29], [2].

As many authors put forwards, one of the important pillars of sustainable development is the economic aspect. This is why it would be logical to consider the economic aspect of adaptive facade structures in

the design process. Many of the adaptive facade proposed in the literature are deprived of this factor [30], [31], which makes the implementation of the final product ambiguous or expensive to implement.

Given the introduction above, the literature review, in Sect. 2, put forwards to study relevant articles and narratively, revealed some gaps and less-attended issues.

First, a combination of solar water heater was not considered, through parametric approaches, using Fresnel lenses materials.

Second, there was a lack of economic optimization objectives regarding the prices of structural components while configuring adaptive façade. Third, the above-mentioned items had not been included simultaneously with daylight improvement objectives in a multi objective optimization analysis. Finally, a few pieces of researches attempted to include occupants' real needs and activities and the function of spaces in adaptive façade design towards comfort and building energy efficiency.

As a result, following the potentials and gaps found in the literature, in this study, Zarrinshahr, Iran, was chosen, as a rich in daylight region [32], to simulate, optimize, and analyze a sun responsive kinetic façade inspired by insect' eyes inspiration for geometrical arrangement for a café space. To this end, a parametric approach was used to calculate heat gained daylighting, the annual performance of visual comfort, to consider economic assessments, and to do a multi objective optimization analysis. Furthermore, an action research was conducted using a small mock up panel, as a conceptual experiment, to shed light on likely hidden structural challenges of the proposed façade [33].

2. Literature Review

Luo et al., 2019 [4] reviewed the role of active building envelope systems in harvesting renewable and sustainable energies, in four branches, including air-based, water-based, solid-based, and dynamic configurations. Also, a review of opaque solar building envelopes had been conducted in [34], while, the transparent and translucent ones were reviewed in [35].

According to a review on case-based scenario analysis of solar thermal collector, by Buker & Riffat, 2015, a combination of passive solar design strategies, for active solar thermal collector, can reduce energy demands, from 50–70%, for hot water and, from 40–60%, for heating. In addition, it has been estimated that approximately 30–40% of total global heating demands can be met through these systems [5]. Besides, if building envelopes—that harvest energy—become able to improve sunlight availability for visual comfort as well, the energy efficiency would be higher, because the artificial lighting loads would be addressed too [13, 18].

The following is a discussion on the literature and patents pertinent to the subject of this study while providing information on concentration and objectives, dates, whether they improve daylight for interior, whether there is any consideration of occupants' real needs, activities, and the function of space, energy

harvesting feasibility, construction price optimization, kind of Building envelope, methodologies, and a relevant figure.

A solar water heater is known as one of the oldest systems for harvesting energy from sunlight and transferring it into hot water. The idea regarding the use of solar water heaters in combination with building envelopes is a recent subject matter. There are several articles that have combined solar water heater into building envelope. In another study, the bottom part of a window was equipped with heat exchange tubes which were located between two tempered glasses. These pipes had an inlet and outlet for hot liquid storage which were located somewhere around the window. Whenever cooled down, the hot water, resulting from solar radiation moved to the storage tank and returned to the window pipe. Moreover, from the space between the pipes, sunlight could penetrate into the building to partially provide the residence with sunlight [37].

Shen & Li, 2016, [13], and Yan et al., 2019, [16], studied the thermal performance of a double skin façade facing the sun. There were Venetian shadings filled with water located inside the double skin window, capable of rotating in some limited angles. The purpose of the system was to capture the radiant heat and reduce cooling loads through evaporative cooling. For this purpose, the developers used the idea of cooling towers with water as a natural cooling source. The quality of daylight for indoor lighting was not thoroughly addressed, in their attempt, using contemporary visual comfort indices. The façade darkened the interior while the Venetian shadings closed, resulting in energy-consumption for artificial lighting. Also, the elements of the facade did not follow the sun position, and there was not any continuous, or intelligent, control for this system except for the users' manual interferences [13], [16]. Similarly, a transparent water-filled louver was set up to modify daylight and glare while exposing to sunlight to analyse the system energy efficiency. Due to the water thermal mass, the façade harvested thermal energy from the sun. Subsequently, thermal harvesting and energy consumption for cooling, heating, artificial lighting, and fan were measured. According to the authors, the outflow of heated water, from the façade, and its replacement with urban water helped improve the thermal performance of the skin. For evaluating daylight performance, they used Radiance simulations. For visual comfort quality, they used Daylight Glare Probability (DGP), and for visual comfort quantity Useful Daylight Illuminance (UDI) metric was used. This is while for the quantification of energy consumption (heating, cooling, and fan energy use) and solar radiation absorbed by the façade, they used EnergyPlus simulation. The kinetic sun tracing version of this façade was reported non-optimal compared to the static one [14].

Algae façades are, also, among the clean and transparent thermal harvesting building envelopes. Talaei et al., 2020, [38], reviewed thermal an energy performance of microalgae bio-reactive facades while discussing these systems from thermal, shading, and ventilation features point of view.

In combination with a Fresnel lens, a solar water heater was mounted on a high-rise building, on a small window, on the southern side of the building. The system made it possible to use the solar water heater in the high-rise building, individually, in each floor—something that was previously installed only on the roof of buildings. The higher level of efficiency of this system, compared to traditional ones, was due to the

use of the Fresnel lens [19]. In another study, following a bioinspiration idea, a building envelope equipped with Fresnel lenses was proposed to improve the thermal performance of a building. The Fresnel lenses concentrated the solar energy on metal plates equipped with storing material and thermal distributed fins. The authors used numerical modelling and experimental measurement to explain the performance of this skin. The prototype was designed to improve the thermal performance of building envelope, while there were neither any consideration regarding daylight improvement, occupants' real needs and activities, and the function of spaces, nor any economic objectives for construction prices [17]. In another system designed exclusively for sunlight energy harvesting, a group of lenses focused sunlight on some points through a solar tracker that traced the sun's position by black and white images, stepper motors, and gears. This machine was suitable for the exterior installation for energy harvesting [39].

The uses of lenses, in building envelope, was not limited to energy harvesting. Using a flexible, transparent panel with insulation property, and heat preservation feature was installed on the most outer layer of a building. A layer of water was connected to the bottom of the panel, and there was a dome-shaped transparent plastic filled with transparent liquid. A controller also controlled the behavior of the panel so that the panel let the light penetrate inside following the seasons while managing thermal insulation accordingly. In the summer, the controller moved the transparent liquid inside the lens, resulting in a panel with concave form that spread the sunlight and only a small amount of it could go into the space. On the contrary, in winter, the controller filled the panel with a transparent liquid that lets for a converge form. This type of madeup lens allowed more daylight entering the space, causing more heat available. Finally, the panel matched the room environment quality and occupants' comfort according to different season conditions, which ended up with more visual and thermal comfort, and decreasing building energy consumption [40].

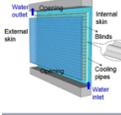
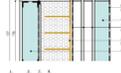
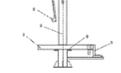
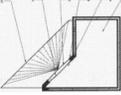
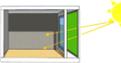
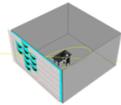
In 2010, Center for Architecture Science and Ecology (CASE) designed a sun tracing solar façade, by which electricity was generated by concentrating solar energy on photovoltaic panels. In addition to electricity generation, this façade enhanced daylighting [28]. There was no description of the methodology used for the daylight assessment metrics and sun tracking movement.

In recent years, several studies have designed and evaluated kinetic façade morphologies for improving occupants' comfort, in comparison to the static conventional ones. For example, a kinetic hexagonal façade was proposed in [41] for which point in time daylight index and annual Daylight Factor was used using Diva plugin in Grasshoper. The simulation results showed that the façade can improve daylight conditions, by 50%, in summer and spring, and 20%, in wintertime [41]. In the article, there was neither energy harvesting modules devised for the façade system, nor there was any construction prices optimization objectives. Similarly, there are other articles that had used the same approach in the recent years [30], [42], [43]. This is while occupants' involvement has been added to this approach approach in recent practices [44]–[46]. Occupants' involvement in the process of adaptive façade design and operation is necessary to guarantee the usefulness of façade systems. Accordingly, a user detective adaptive facade for improving visual and thermal comfort was proposed by Rizi & Eltaweel, 2020 [45]. For the visual comfort evaluation process, UDI index and for point-in-time evaluation, illuminance

measurement were used in parametric multi-objective optimization process. Finally, the dynamic interactive proposed system showed its usefulness through improving visual comfort quantity and quality, in tandem with heat gain modification based on time and environmental stimuli. Still, the façade lacked optimal and logical structure and energy harvesting compensation for the movements. As a result of a parametrical combination of structural and environmental analysis towards an energy harvester adaptive façade, a building envelope was designed and experimentally employed by Jayathissa et al., 2018, [15]. This façade was among the examples of kinetic energy harvesting shadings. The material used for this shading surface was photovoltaic panels that kinetically followed the sun's position in the sky while the morphology of the façade elements improved the interior daylight performance for occupants' visual comfort.

With respect to the narrative examination of the relevant literature, as well as the classified information in Table 1, it is apparent that daylight improvement has not been studied by all studies that concentrated on adaptive building envelope design towards comfort and energy harvesting. Also, there is almost no consideration of occupants' real needs, activities and the function of space while designing adaptive building envelopes aiming to improve energy harvesting. Besides, almost no one of the articles took into consideration the optimization of construction component prices integrated with other aspects of façade configuration scenarios towards comfort and energy harvesting or energy efficiency. Despite the advantages and convenience to manage design variables and data analysis[11], a parametric approach is not frequently considered in building envelope aimed for energy harvesting objectives. Also, building envelopes that harvest energy from the sun are mostly switchable and kinetic. Moreover, using parametric techniques and Fresnel lens materials, a combination of solar water heaters was not explored in adaptive façade design.

Table 1. A summary of recent relevant articles and patent discussed in Section 2

Ref.	Concentration and Objectives	Year	Daylight Improvement	Consideration of occupants' real needs, activities and the function of space	Energy harvesting	Construction Price Optimization	Type of Building envelope [47]	Methodology	Figure
[28]	harvesting solar energy to convert it to electricity using lenses without hurting interior receiving daylight	2010	Yes	No	Yes	No	Kinetic	Not specified or limited	
[13], [16]	A double skin façade with built-in pipes utilizing evaporative cooling water in cooling season	2016	No	No	Yes	No	Switchable	CFD analysis for ventilation and heat distribution using ANSYS Fluent	
[41]	A parametric design for a hexagonal kinetic facade to optimize daylight performance. A similar approach was used in several articles in recent years such as in [30], [42], [44].	2016	Yes	No	No	No	kinetic	A parametric and optimization approach using Grasshopper for modeling and Diva plugin for daylight analysis (Illuminance point in time analysis and Daylight Factor)	
[17]	Heat transfer analysis of a building wall with lens integration	2017	No	No	Yes	No	Switchable	Numerical modelling and experimental measurement	
[37]	Improving building heating condition while letting daylight penetrate inside	2017	Yes	No	Yes	No	Switchable	Not specified or limited	
[14]	Improving visual comfort and thermal harvesting	2017	Yes	No	Yes	No	Switchable	Visual comfort quality: Daylight Glare Probability (DGP), visual comfort quantity: Useful Daylight Illuminance (UDI) Quantification of energy consumption (heating, cooling, fan energy use, and solar radiation absorbed by the façade): EnergyPlus simulation	
[39]	Grey image sun tracking for energy harvesting	2017	No	No	Yes	No	Kinetic	Not specified or limited	
[15]	a performative design environment that enable designer to combine structural strength analysis, energy engineering, control, industrial design, and architecture	2018	Yes	No	Yes	No	Kinetic	A Parametric approach to develop a method to combine structural analysis including collision detection and structural simulation by Karamba Preparing manufacturing plans, visual renders, as well as daylight analysis, using a linear daylighting model based on the total flux methodology to determine the luminosity The geometric modelling software: Rhinoceros 3D plus parametric plug-in Grasshopper, and python as a scripting language.	
[19]	A Wall-seating solar water heater	2018	No	No	Yes	No	Smart	Not specified or limited	
[40]	Improving daylighting from a roof with heat-insulating and heat preserving effect	2018	Yes	No	Yes	No	Passive	Not specified or limited	
[38]	A review of the state-of-the-art knowledge on microalgae bio reactive facades for energy harvesting	2020	Yes	No	Yes	No	Smart	A literature review	
[45]	A user detective adaptive facade towards improving visual and thermal comfort	2020	Yes	Yes	No	No	Interactive/ Responsive	A parametric simulation and multiobjective optimization analysis Visual comfort quality: Daylight Glare Probability (DGP), visual comfort quantity: Useful Daylight Illuminance (UDI) using Radiance Quantification of heat gain analysis: Ladybug heat gain analysis component	

3. Methodology

In this study, first a briefing process was taken place in tandem with a field survey study to make sure about the occupants needs and the contextual factor of the test cell. After that a semi-incomplete bioinspiration let for adopting a geometry configuration for an energy harvester adaptive façade. Following this, a simulation methodology was used to analyze and proposed a building envelope configuration with a case study. Zarrinshahr, Iran's weather file was used for the simulation. For modeling,

Grasshopper, Rhino [48] was used and the Ladybug plugin was employed for environmental analysis and heat gain calculation. Also, the Honeybee plugin was employed for daylight analysis [49]. In addition, a parametric approach was used for financial considerations and a linear optimization, for which the Grasshopper plugin scripting was chosen as a tool. The Colibri plugin [50] was used to perform the linear optimization management and Design Explorer website [51] was used to visualize the optimization candidates and how the independent variables affected the results. The parametric tools was used following their advantages including ease of managing design variable, data analysis, ease of updating and iteration of inputs, and the appropriate link between geometric environment to the environmental analysis scenarios [11], [52]. The following elaborates on briefing process, visual comfort metrics used in this study, energy harvesting analysis tools, and the optimization process and tools.

3.1 Briefing process

OB consideration, in BED, happens in three periods including pre-design, such as in a briefing process, during design, such as in [1] and [2], and after design, in operation periods, such as in [53].

OB involvement in Pre-Design of building envelopes refers to any plan or consideration beforehand the actual design one to make sure about the people's behaviors and factors that affect their behaviors. This can happen in different modes. For example, a direct user involvement and its associated briefing process in building projects take place to understand customers' and occupants' needs for preparing to implement them in design [54]. This helps for making sure about the accordance of needs to the facilities and acceptance, as well as learning from experiences [54]. Also, user-based methodologies for connecting designers to deep understanding the users' real needs can happen through innovative storytelling, scenario writing, behavioral mapping for understanding the needs [55], and automated brief generation framework via artificial intelligence, and so forth [56].

In this study, a pr-design occupants' involvement was taking into consideration. To this end, a field study and an interview with the manager of this cafeteria was take place to learn about the function of space and the occupants' need to be used while designing the façade.

3.2 Visual comfort quantity

For visual comfort analysis, Useful Daylight Illuminance (UDI) index was used to show the annual performance of the proposed system. It shows the percentage of occupied time, in a year, when the daylight quantity, in the indoor environment, falls in a predefined useful range. Moreover, this index presents two lower bonds and higher bonds of the useful daylight range defined as Under lit UDI and Over lit UDI [29]. The three ranges mentioned above were used for this study and are presented in Table 2. See

Equation 1, where w_f is a Weighting factor, t is time (hour), and E is illuminance (Lux).

According to the national building regulations of Iran, code 13, which focuses on the design and implementation of electrical installations [10], there is no specific boundary for illuminance quantity distribution in coffee shop spaces. However, it mentioned that 300 lux is enough for general activities.

Table 2
UDI ranges assumption

UDI ranges	
Under lit UDI	Less than 100 Lux
Appropriate UDI	100–2000 Lux
Over lit UDI	More than 2000 Lux

$UDI = \frac{\sum_i wf_i \cdot t_i}{\sum_i t_i} \in [0, 1] \left\{ \begin{array}{l} UDI_{Overlit} \text{ with } wf_i = \begin{cases} 1 & \text{if } E_{Daylight} > E_{Upper \text{ limit}} \\ 0 & \text{if } E_{Daylight} \leq E_{Upper \text{ limit}} \end{cases} \\ UDI_{Useful} \text{ with } wf_i = \begin{cases} 1 & \text{if } E_{Lower \text{ limit}} \leq E_{Daylight} \leq E_{Upper \text{ limit}} \\ 0 & \text{if } E_{Daylight} < E_{Lower \text{ limit}} \vee E_{Daylight} > E_{Upper \text{ limit}} \end{cases} \\ UDI_{Underlit} \text{ with } wf_i = \begin{cases} 1 & \text{if } E_{Daylight} < E_{Lower \text{ limit}} \\ 0 & \text{if } E_{Daylight} \geq E_{Lower \text{ limit}} \end{cases} \end{array} \right.$	<p>Equation 1</p>
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Moreover, for point-in-time illuminance analysis, the Illuminance (Lux) index was employed, which is the ratio of the luminous received by a surface to the area of that surface [29]. See

Equation 2, where illuminance at point P (E_p) of a surface is defined as a physical quantity of light measured in Lux. It is the ratio between luminous flux on a point in a surface near P and the surface area.

$E_p = \frac{d\phi}{dA_{rec}} \quad [lx].$	<p>Equation 2</p>
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3.3 Solar heat gain

For finding the amount of heat gained by the lenses, employed on the facade, a parametric component was used. The context, the model, and the geometry on which the solar radiation will be evaluated were required as the inputs for this component. Moreover, among the surrounding inputs were the weather file data—including the geographical direction and the sky matrix. The heat gain was measured in $\frac{kWh}{m^2}$, for individual test points and in kWh, for the total area of the evaluating surfaces.

3.4 Optimization process

According to the objectives of this study, the optimization process was to come up with the structural configuration that maximizes the heat gain received by Fresnel lenses, increases appropriate UDI, and decrease the payback time of the proposed facade system. For the multi-objective optimization process,

Colibri optimization tool [50] and Design explorer online tool were used [51]. Diagram 1 shows the linear multi objective optimization flowchart.

4. Case Study And Assumptions

4.1 Case study area

Iran is a rich country in terms of solar radiation. More than two-third of the country climate condition is hot and arid [58]. Figure 3 presents the world map and the location of Zarrinshahr, Iran.

Figure 4 shows the average solar radiation in Isfahan province. As is evident, this province is located in rich solar radiation grounds while Zarrinshahr is in the richest part in terms of solar heat gain.

Figure 5 shows the global horizontal radiation (Wh/m^2) in Zarrinshahr from January 1st, 1:00 am to December 31st, 24:00 pm.

Façades located in the west orientation, in this region, cause difficulties in terms of visual and thermal comfort. For example, the owner of the space—under the consideration of this study—indicated that he usually dimmed this façade due to the harsh sunlight exposure and relied on artificial lighting during daytime. The test cell chosen for this study is a small-scale cafeteria that is west-oriented and is more often used in the noon and afternoon by the visitors, while the preparation areas almost always occupied all day long. The reason to choose this space as a test cell is that according to a field study and an interview with the manager of this cafeteria, the space becomes hot in the noon and afternoon. Also, in summer, cooling machine should work to provide a comfortable environment for visitors. In addition, due to the potential of solar glare in the period of visitors' occupation, all the interior shadings should be dimmed, which prevents view to the outside and causes artificial lighting loads. Besides, as far as the manager owns the space and cooking and drinking preparation is the only profession she knows, she cannot leave the space for renting somewhere else or change the job. According to the owner of the place, the most significant need for this space is hot water—for cooking, preparing drinks, and washing—as well as electricity for cooling the space. Also, to improve the attraction and restorative quality of the space, the owner needed special decorative with can be pleasing to visitors. This often leads to illogical and costly decorations which can sometimes even create the opposite result, far from the goals of sustainable architecture [59]. As a result, the designer needed to take into account the space function, users' needs in addition to improve occupants' comfort and the space energy-efficiency.

Figure 6-a shows the location of this test cell. Plus, Fig. 6-b and Fig. 6-c, respectively, represents the window frame of the façade and current status of this building.

4.2 Geometry explanation

The second floor of the above-mentioned building was chosen as the test cell for this study. The two building envelopes of this test cell, shown in Fig. 7-a, b, receive solar radiation for 4364 hours of year. In this paper, a new design was proposed for these two transparent surfaces that almost face west and

northwest. Figure 7-a, b shows the geometry in the urban context and the annual status of sun exposure in the hours that these two-building envelope receive daylight. Plus, Fig. 7-f shows the test cell dimensions.

The proposed façade, in this paper, was incompletely inspired by the morphology of the geometric array of the lenses of insects' compound eyes. See Fig. 8. In this morphology, an array of lenses was arranged following the layout of insects' eyes to process the light for an appropriate vision. This was an starting point to arrange the façade structure shown in Fig. 7-c,d.

In this proposed facade, the Fresnel lens was in such a way that a set of lenses can follow the movement of the sun in the sky. After receiving solar energy and concentrating it on liquid chambers located in the focal point of the lenses, it was possible to extract energy from the facade. See **Error! Reference source not found.** and **Error! Reference source not found.**. For the structural deployment, an array of support grids were defined to hold the lenses and the water containers. Water containers were connected to each other with flexible, semi-transparent pipes. The pipes direct and circulate water to the containers and exit if necessary. The flexibility feature of the pipes is to avoid probable damages to the structure of the system, when moving and adjusting the lenses to the sun's position. The pipes would be filled with urban water through the inlet part. **Error! Reference source not found.** illustrates an example of nine hypothetical lenses array associated with the connected water pipes and water chambers. The upper blue arrow shows the water inlet, and the bottom orange arrow shows the outlet warmed water.

The determined shape and structure of the system would be the result of the optimization analysis (Diagram 1) on the dependent variables (Table 4).

4.3 Material properties

Table 3 shows the generic materials of the test cell and Fresnel lens properties.

Table 3
Generic materials

Materials	Reflectance
Interior walls	40%
Interior floor	20%
Interior Ceiling	50%
Window glass	Variable (65%, 75%, 85%)
Street surface	10%

Also, for enabling façade elements to move, in this study, a pneumatic motion engine, developed in [12], was proposed.

Figure 10 shows this actuator and its application in an adaptive building envelope structure. The selection of this piece of equipment was due to ease of implementing and a rather appropriateness of size in proportion to the candidate lenses sizes in this study.

4.4 Energy consumption and economic considerations

The energy bills of the cafe space, in 2018, were used to calculate the energy needed for hot water supplies. The financial statement of the bills, along with the amount of energy consumption, were achieved following the owner's request from the National Iranian Gas Company [62]. Figure 11 shows the daily energy consumption of this space for hot water needed for beverage and food preparations.

Given Iran's gas prices, which account for \$0.018 per m³, \$170.720 was used for heating water required for beverage and food supplies in this space. However, considering the global price of natural gas, the price of energy consumed in this space was \$0.155 per m³, in 2018. According to the global price of natural gas, the amount of energy consumption for hot water, in this space, was \$1470.08.

In addition, weather file information was obtained from Zarrinshahr's meteorological office [63] for the simulation inputs.

To analyze the cost-effectivity of an optimal system, the payback time was calculated based on energy prices, energy consumption, and system configuration and structural cost, in the optimization process Diagram 1.

4.5 Heat gain analysis

For the solar heat gain analysis, the Ladybug radiation analysis tool [64] was employed by which it was possible to calculate solar radiation falling on a given surface surrounding by the urban context and sky condition. For defining the sky matrix, a fine 580 pieces were utilized, in a clear sunny sky condition, and the sky matrix was set to Reinhart sky. The evaluating surface for calculating solar heat gain was the surface of lenses. Heat gain calculations were performed following hourly sun-tracking procedures.

After concentrating the sunlight on the façade chambers filled with urban water, the heated water can be discharged from the façade at a suitable time interval and refilled with new water. This process not only helps for thermal harvesting from the façade—to be used for the hot water—but also ultimately helps for cooling the space in summer. According to outdoor and indoor climate conditions, in winter, the procedure would keep the heat in the skin for a more extended time to increase thermal comfort.

4.6 Design variables

Table 4 shows the optimization variables, units, amount, and variable codes. Assigning code to the attributes of variables was for the sake of simplicity in defining the optimization code and analyzing the results.

The variables were distances between the center of deployed lenses on the façade, the model of lenses—for which the radius of the candidate lenses were chosen as variable [65]—the reflectance of window and

glass.

The simulation and optimization analysis covered the whole hours in a year when the two building envelopes of this test cell shown in Fig. 6-a, b, receive solar radiation which accounts for 4364 hours in a year. Nevertheless, time of using the proposed façade, in terms of optimal performance, was defined as a variable for understanding the time when the proposed system works better in terms of this study objectives in addition to studying the annual kinetic performance of the proposed facade. The time included 4 P.M on March 21st, June 21st, December 21st. The selection of hour was due to the report of the space owner on pick of visually and thermally uncomfortable time and presence of people in the space. The selection of months was followed by the critical annual minimum, equinox, and maximum daylight availability in a year [66]. The same approach to involve time as a variable and to consider the critical daylight availabilities time, in a year, was used by similar articles such as [45], [66].

Table 4
Optimization variables

parameters		Unit	Range of variability	Codes
Distances between the centre of lenses	Layout 1	Centimetre	55	2
	Layout 2		80	3
	Layout 3		105	4
Model of lenses	Model 1	Radius	20	1
	Model 2	Centimetre	25	2
	Model 3		12.5	3
Window glass material	Model 1	Reflectance%	75	1
	Model 2		85	2
	Model 3		65	3
Time		4 pm, March 21st		3
		4 pm, June 21st		2
		4 pm, December 21st		1

Table 5 shows the variable prices of installation materials that make differences in the final cost of the proposed façade. For the lenses, three models were chosen, as candidates, and for each, the associated prices are mentioned [65]. The other construction materials were flexible transparent pipes, water chambers, holder networks, and motion engines.

Table 5
Variable prices of installation materials

Name		unit	Price (\$)
Candidate lenses model	Model 1	Each one	7.5
	Model 2	Each one	14.85
	Model 3	Each one	4.25
Flexible transparent pipes		Meter	0.3
Water chambers		Each one	2
Holder networks		Meter	1
Motion engines		Each one	10

5. Results And Discussion

In this study, a parametric approach was used for a techno-economic feasibility analysis of a sun-tracking façade in a rich daylight space. One of the conspicuous gaps the author came across in the similar literature on adaptive façade was the absence of occupant's involvement in the adaptive building envelope design and operation, except for very few examples such as [44], [45], [59]. In this study, the consideration of occupants' real activity and needs, as well as space function shaped the objectives of this façade configuration. As mentioned earlier hot water, entertaining decoration, and acceptable visual comfort was the important needs of the space owner, workers and the visitors.

Accordingly, the simulation and optimization analysis covered the whole hours in a year when the two building envelopes of this test cell—shown in Fig. 7-a, b—received solar radiation while the façade modules (lenses) hourly followed the sun position in the sky and concentrated the received radiation on the liquid chambers on their focal points. Despite the annual performance assessment, the inclusion of critical daylight availability time as variables were added to determine the time when the proposed system works better in terms of multi-objective optimization objectives—increasing energy harvesting via facades, increasing $UDI_{(appropriate)}$, decreasing $UDI_{(Underlit)}$ and $UDI_{(Overlit)}$, and decreasing the payback time. This option allows the technical designer to set the stationary mode, optimally, if he chooses a fixed mode instead of a moving mode for any reason. In this case, the orientation of the lenses towards the sun can only happen in a more optimal state. The same approach was used in [30] and [44].

The other independent variables were three options as model of lenses, three modes for distances between the center of lenses, three options of window glass materials, and three critical months, each of these variables affected the finishing façade price, energy harvesting, and visual comfort differently. Accordingly, eighty-one alternative façade configurations were evaluated in the optimization process.

Following the optimization process, the best configuration fit for the proposed façade system was the one that constitutes the properties shown in Table 6, where the radius of the selected lens type is twenty centimeters; distance between the deployed lenses is fifty-five centimeters. Also, the number of lenses used is 180 and the window glass material reflectance is sixty-five percent. In addition, 4 pm, June 21st showed the most potential to use this system in terms of solar energy harvesting, and daylight improvement, when solar radiation in the critical time of year was 298.30 kWh. Moreover, the system construction and installation price was \$3595.37 and the total solar radiation while hourly tracing the sun in one year was 361471.72 kWh.

The division of the amount of the money spent on its construction, \$3595.37, and the annual financial profit out of system energy harvesting, \$650.90, indicated that the payback time of the proposed façade system was 5.5 years. Most of the proposed adaptive skins do not provide a payback time, such as [30], [41], [42], [44], [45], and only a few of them have energy harvesting features, such as [14], [36]. These two negatively affect the popularity of these useful building envelopes and make the entry of these technologies to the markets too slow.

Results of daylight simulation in the best possible fixed mode—which happens while the lenses orientation were fixed to face the sun position at 4 pm, June 21st —showed that UDI (Underlit) was 0.00% when a window was plain, while the UDI (Overlit) was 97.57%, and the UDI(appropriate) was only 2.42%. This shows how the space occupants suffer a visual discomfort in this space. The current condition of the space which was show in Fig. 6-c provided the space with 0.00% UDI (Underlit), 96.89% UDI (Overlit), and 3.10% UDI(appropriate), all of which shows that the current condition of the façade fails to provide the people inside space with an totally insufficient level of annual visual comfort too. This is while, the proposed façade, respectively, made 96% and 95% improvement in the UDI(appropriate) compared to plain window and the current condition of the space. In addition, it can three times decrease the UDI (Overlit) and make highly negligible changes in UDI (Underlit) compared to the current condition and plain window mode of façade. Table 7 shows annual daylight performance of the space with plain window and current condition of the façade. Also, Table 8 shows the proposed facade annual daylight performance for the three modes of static façade while the lenses face the sun at the three variable sun positions in terms of time, among which case of 4 pm, June 21st showed the best improvement. Table 6 shows the quantity of the values related to the best design solutions and a representative render of the facade.

Table 6. The best configuration obtained from optimization results and the specifications selected values

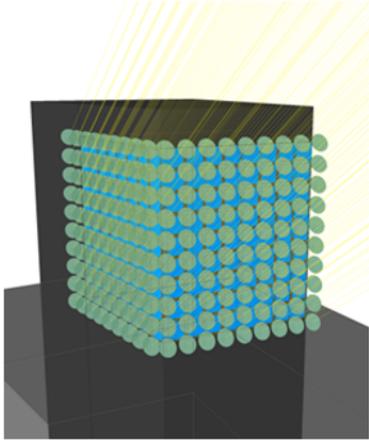
Figure	Specifications	Specifications of the selected values
	Kind of lens	Radius= 20 Cm
	Distance between lenses	55 Cm
	Number of lenses	180
	Glass material	Reflectance= 65%
	The critical time	4 pm, June 21st
	System construction/installation price	\$3595.37
	Solar radiation in the critical time of year	298.30 kWh
	Total solar radiation while hourly tracing the sun in one year	361471.72 kW
	UDI (underlit)	0.09%
	UDI (appropriate)	76.16%
	UDI (overlit)	23.49%
	The system payback time	5.5 years

Table 7
Annual daylight performance with plain window and current condition

Plain window	UDI _(Underlit)	0.00%
	UDI _(appropriate)	2.42%
	UDI _(Overlit)	97.57%
Current condition	UDI _(Underlit)	0.00%
	UDI _(appropriate)	3.10%
	UDI _(Overlit)	96.89%

Table 8
annual daylight performance in different sun positions

Case of 4 pm July 21st	UDI _(Underlit)	0.09%
	UDI _(appropriate)	76.16%
	UDI _(Overlit)	23.49%
Case of 4 pm Dec 21	UDI _(Underlit)	0.00%
	UDI _(appropriate)	46.63%
	UDI _(Overlit)	53.25%
Case of 4 pm March 21	UDI _(Underlit)	0.00%
	UDI _(appropriate)	56.51%
	UDI _(Overlit)	43.28%

In addition, the point-in-time illuminance analysis of the test cell with current and proposed facade in critical times of daylight availability are shown in

Figure 12, in Lux. As is shown, the quantity of daylight concentration was almost ten times of visual comfort quantity level—300 lux [57]—especially in March and July, 4 pm.

Figure 13 shows the real annual energy consumption, in 2018, from natural gas, in a black curve, which was requested from National Iranian Gas Company [62], based upon the space owner application. Plus, in this figure, the heat gained, through the optimal configuration of sun-tracking elements of the façade, are illustrated in blue.

Figure 14 shows eighty-one alternative façade configuration variables and the result out of those while showing how the results vary for sets of dependent variables. The independent design variables were elaborated in Table 4 and the attributes of them were coded in the last column of Table 4. These codes help to read the variables and their impact on performance of the alternative facades.

Figure 15 shows the best possible results for the multi objectives optimization and how the combination of configuration attributes allowed for this solution.

The independent variables are shown in a red box in Fig. 14 and Fig. 15.

Between the eighty-one analyzed scenarios, the best configuration was reported in Fig. 15. The specification of the values of this option was shown in Table 7. The best option addressed the

optimization objective, since it followed the least UDI (overlit and underlit), the most appropriate UDI, and the least payback time resulting from higher solar radiation harvesting and least construction prices.

6. A Conceptual Prototype For Initial Check

A prototype semi-similar to that in the simulation scenario was created for an initial check using commonly available accessories and equipment in markets. The base for constructing the prototype to hold the facade elements was inspired by a modular-grid based structure in [15], [28]. The authors confirm that the setting of the conceptual prototype, for the initial check, is different from the simulated conditions, such as the size of lenses and structure. The aim of this prototype was not to validate the results of simulation in this study. Rather, it was to understand the workability of the proposed system and to extract the probable challenges during the construction process [33].

To do this, lenses with a diameter of 9 mm, each equipped with four beams in such a dimension that they could hold a water chamber at their focal point (Figure 16-a), were the first components of this small-scale example panel. The connection points of lenses and the supporting beams were named to 1, 2, and 3. The lenses were then mounted on horizontal beams on the panel from point 3 Figure 16-b, while from points 1 and 2, in Figure 16-a, two cables (transparent fishing yarn) connected the lenses to two controlling beams. See Figure 16-c, d, e. These two beams were used to adjust the angle of the lens in response to the sun's position in the sky, while the lenses were mounted on the support beam from point 3 in Figure 16-a. This lowest point of the lens was attached to the retaining bars so that it only allowed the lenses to rotate from point threes. In other words, the lenses, along with the retaining bars, water chambers, and the adjustment cables, were connected from the third connecting point to the support rod attached to the mainframe of the panel (Figure 16-a-f).

Transparent pipes connected the water chambers—to carry the heated water from the solar radiation on the focal points and the cold urban water into the façade system. The water pipes were arranged with a gentle slope to facilitate the flow of water in the system. After filling the water chambers and water pipes from the inlet point Figure 16-f, the outlet valve was closed to prevent unwanted outflows of water from the system. The prototype was then exposed to solar radiation of a south-faced building while the surface of the lenses was manually set to be perpendicular to the solar array using two control beams. See Figure 16-g. The proof of this claim was the focus of sunlight at the focal points of the lenses (where the water chambers were located). See Figure 16g-h.

The experiment took place on August 01st, 2019, at 2:30 pm, while the sky was clear. During the test, which lasted less than 10 minutes, the light transmitted from the lens and then from the water chamber and then reached the ground. As is evident, the harsh daylight that transmitted from the facade and met the ground was a moderated of light that was unprocessed. After the experiment, the water was removed from the container, and at that moment, its temperature was measured. Water temperature increased from 26 ° C to 29° C. Also, a Mobile app lux meter let for measuring the Illuminance of the space lighted through simple window, without utilizing the panel, and the Illuminance of the treated daylight affecting

by the panel—where the former showed 2039 Lux and the later was 230 Lux. As far as the panel was not optimized, like the proposed façade in this study, the results are not discussable to a logical contribution, so the authors limited the discussion to the structural lessons learned from the experiment.

Also, there was no logic behind the color of the water chambers and these plastic chambers were the most accessible material for this experiment. Nevertheless, it turned out to recall the colorful building envelopes modifying the daylight [44] and provoked a sense of spirituality for mental comfort out of daylight conditions recalling traditional color glass façade design, Orsi [67].

During the experiment, several plastic chambers melted, as the result of the heat gained from the sun, and the water extracted. Also, sealing the wipes were challenging and time consuming which might call for partial additive manufacturing products for future construction of the panels to reduce construction challenges including attachments and weight management [68].

7. Conclusion

Following the unfavorable occupants' comfort conditions of an over lit space and a high amount of energy required for conditioning the space and preparing hot water for the space services, a façade was proposed in this study. Through the optimization process, the best possible configuration of the proposed façade system aimed to improve visual comfort, to increase solar energy harvesting through the façade, and to minimize the structural cost of the façade system whereby decreasing the façade payback time. The daylight analyses were conducted for both kinetic façade and an optimal static mode of the proposed façade. This option allows the technical designer to set the stationary mode, optimally, if they choose a fixed mode instead of a moving mode for any reason. In this case, the orientation of the lenses towards the sun can only happen in a more optimal state.

The results showed that there was 361471.72 kWh annual energy harvesting potential using the proposed façade. In addition, the results indicated that the space was highly over lit, as much as respectively 97.57% $UDI_{overlit}$, while the windows were plain, and 96.89% for $UDI_{overlit}$ using the current facade. This is while the $UDI_{appropriates}$ were only 2.42% and 3.10%, respectively, for the two above conditions. In comparison to the current condition of the façade, there were, respectively, 24.56, 15.04, and 18.23 times improvements in annual daylight performance in July, December, and March cases. Also, the economic analysis and the optimization showed that the payback time of the proposed facade was 5.5 years. The parametric adaptive façade configuration associated with economic and financial consideration, in optimization processes, that was used in this article can be added to the contemporary methodologies of designing adaptive building envelope to increase the market potential of these proposed systems. Also, this methodology can be added to BIM processes.

The conceptual prototype showed the construction challenges and potential of a small sample of this proposed system. The challenges included the need for careful sealing consideration and weight management, for which additive manufacturing might be helpful. Also, temperate glass materials

associated with self-cleaning properties that can increase the maintenance quality of the proposed system would be recommended. In addition, using colorful water chambers or carrying pipes in tandem with daylight modification aspect recalled in a sense of entertainment, attraction, beauty (mental comfort quality [44], [59]) that inadvertently was understood while choosing available materials.

As future work, an experimental analysis would be conducted to compare the results of the proposed façade, in real-time, to that of simulations. Also, the feasibility analysis of implementing the proposed façade, in this study, on high-rise buildings and urban scale scenarios (Figure 17-a). would Furthermore, evidence from the literature indicated that a double skin façade, with a flexible control strategy, can improve the thermal condition of spaces and ventilation [69]. As a result, in future work, ventilation analysis would be conducted between a double glass skin façade while the type of two glasses would be selected from self-cleaning glass [69], for ease of maintenance, and tempered glass, such as in [69] and [37], to increase security. See Figure 17-b.

8. Declarations

Availability of data and materials

All data, models, or code that support the findings of this study are available from the corresponding author upon request.

Competing interests

The authors confirm that there is no conflict of interest between the authors of the manuscript.

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Authors' contributions

Rana Abdollahi Rizi: The primary idea, first draft of article, methodology, simulation and data analysis;

Mehdi Jahangiri: methodology, Supervision

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Figures

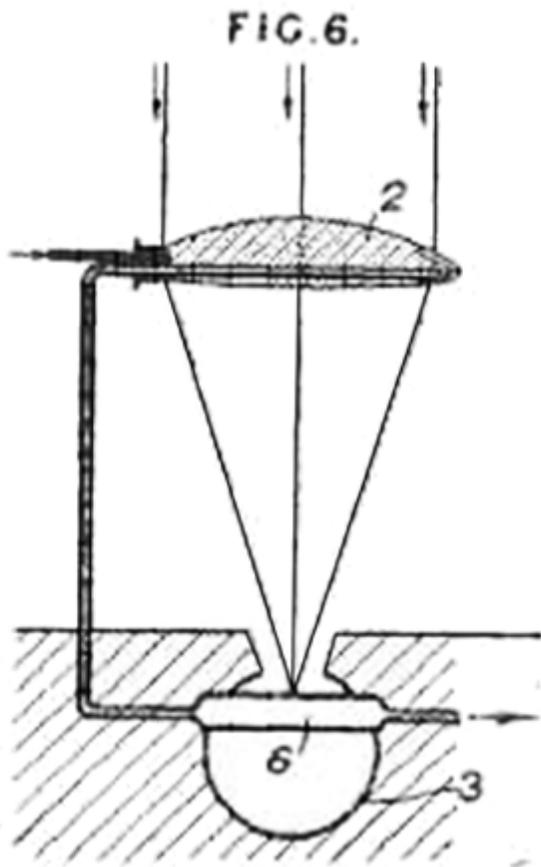


Figure 1

The first use of a lens in a solar water heater

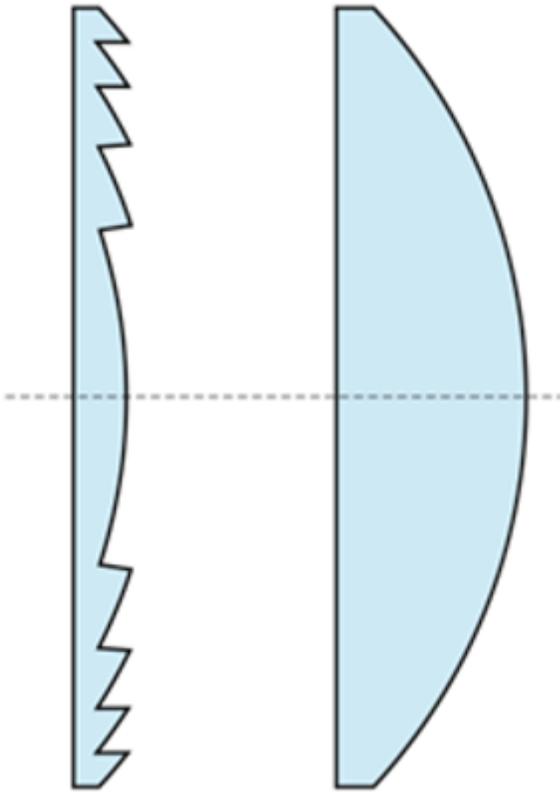


Figure 2

Volumetric difference of a conventional lens (right) versus a Fresnel lens (left)



Figure 3

Case study area

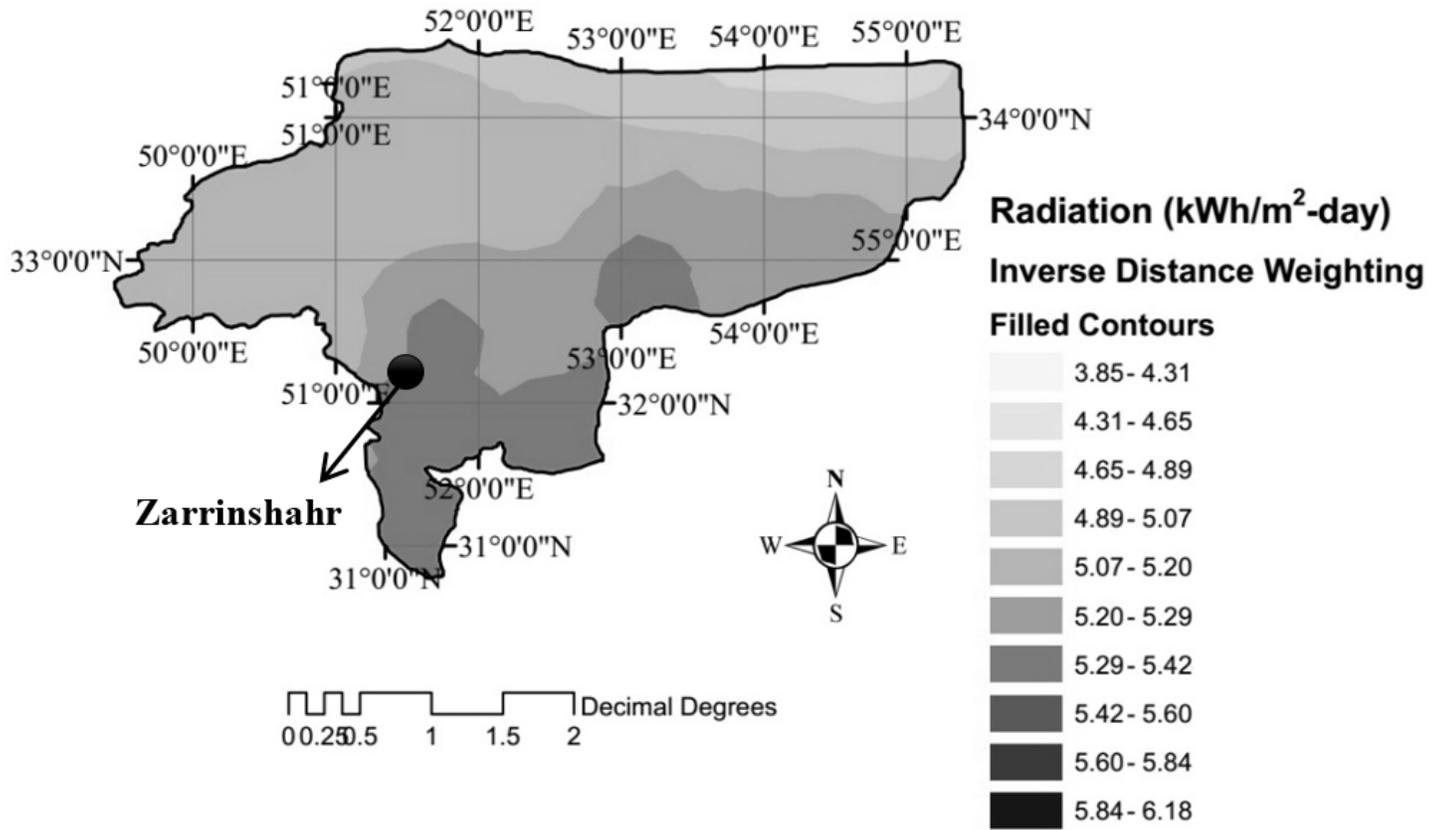


Figure 4

Colored map of average solar radiation in Isfahan Province [32]

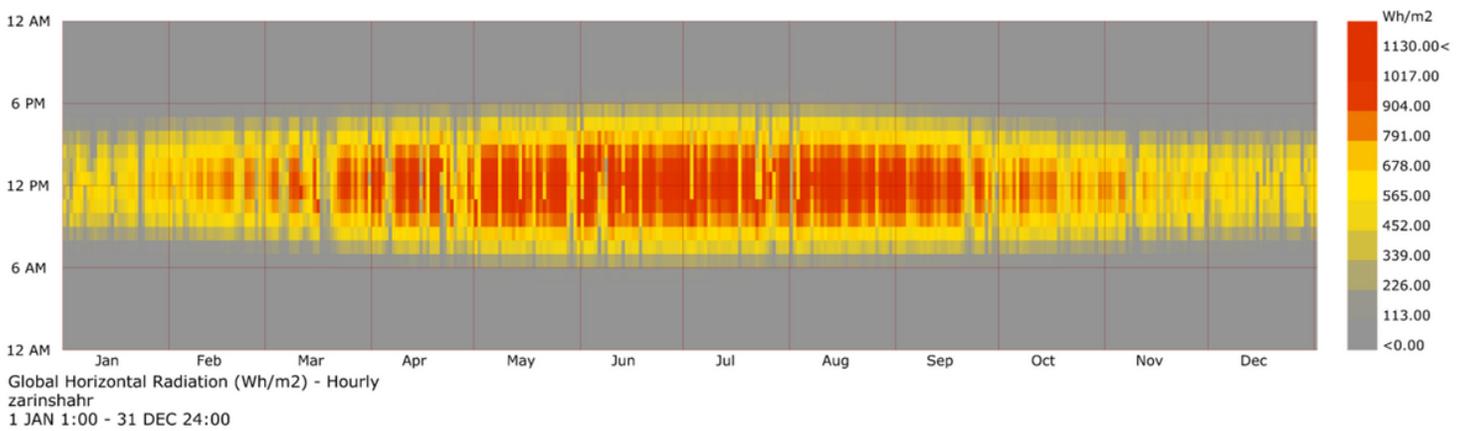


Figure 5

Global horizontal radiation (Wh/m²) in Zarrinshahr from January 01st, 1:00 am to December 31st, 24:00 pm



Figure 6

The case study building: a. The location of the building, b. The northwest façade frame without shadings and glazing, d. The northwest façade current condition

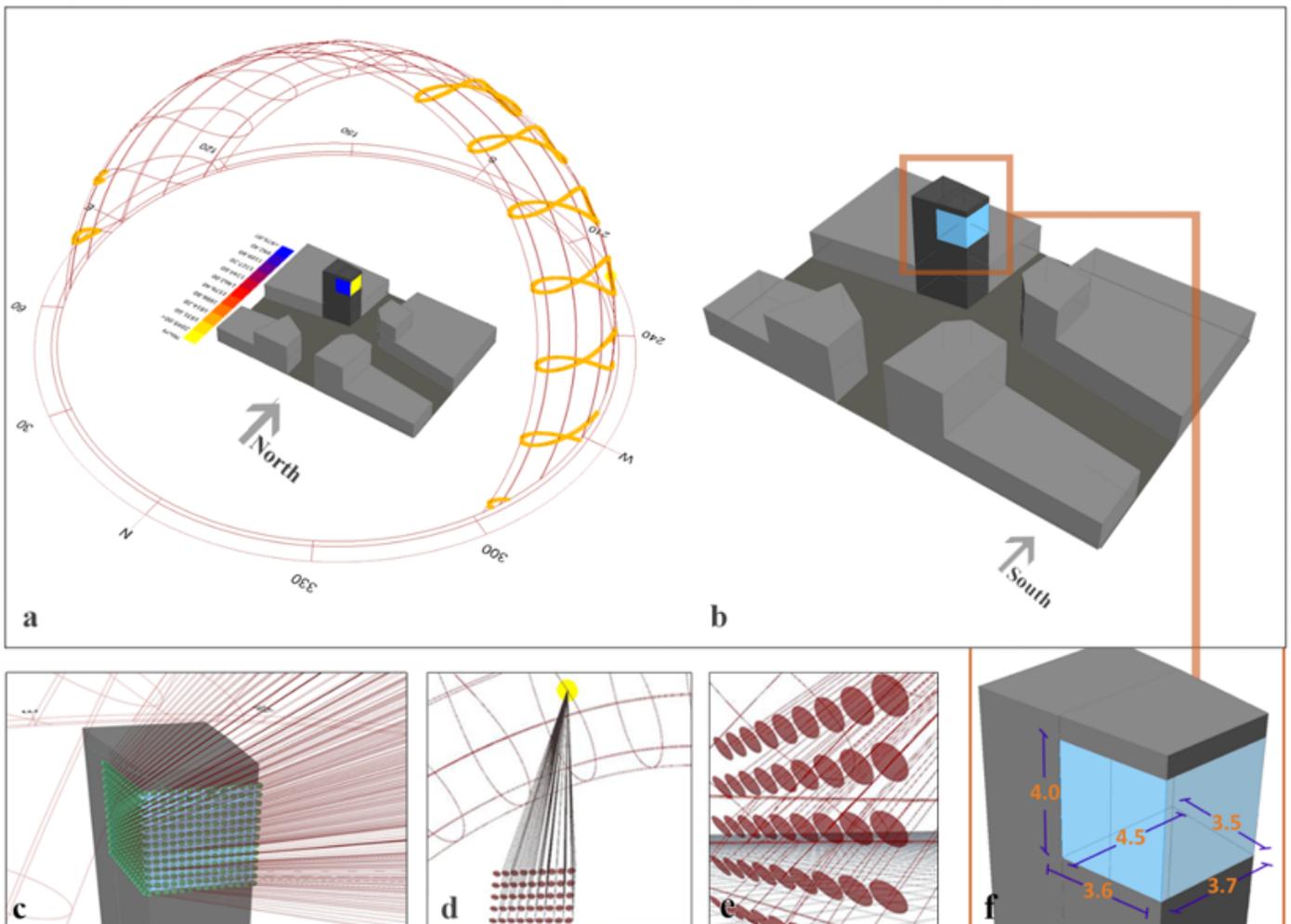


Figure 7

T geometry formation; a. The annual status of sun exposure, b. The geometry in the urban context, c. An example of the arrangement of lenses on the façades, d. Lenses orientation according to sun, e. Perpendicular sun rays on the lenses surfaces f. The test cell dimension

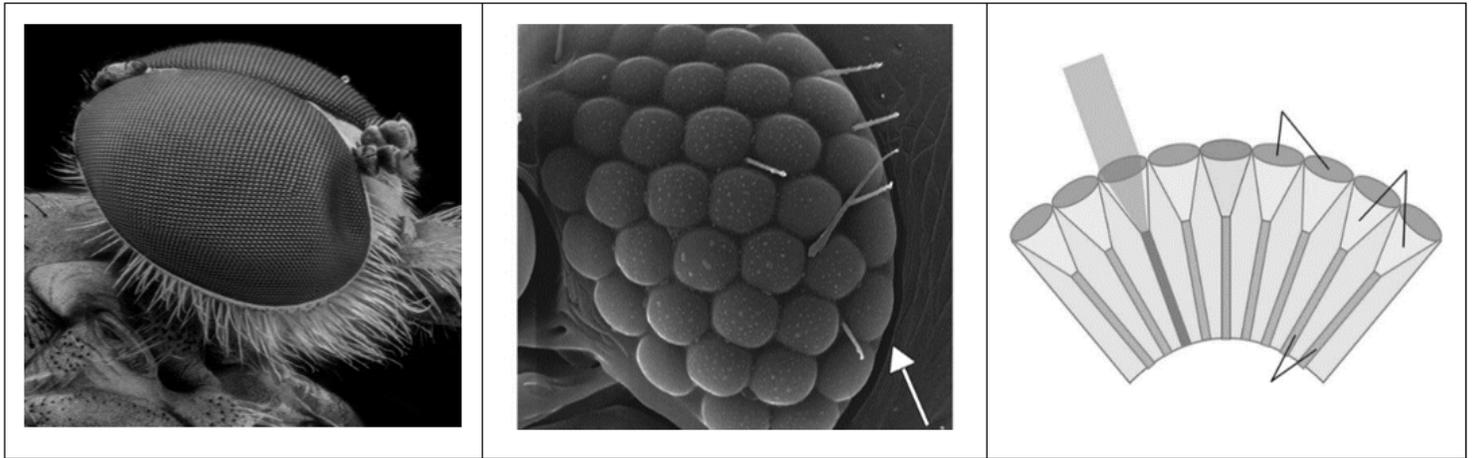


Figure 8

An example of the compound anatomy of insects' eyes [60], [61]

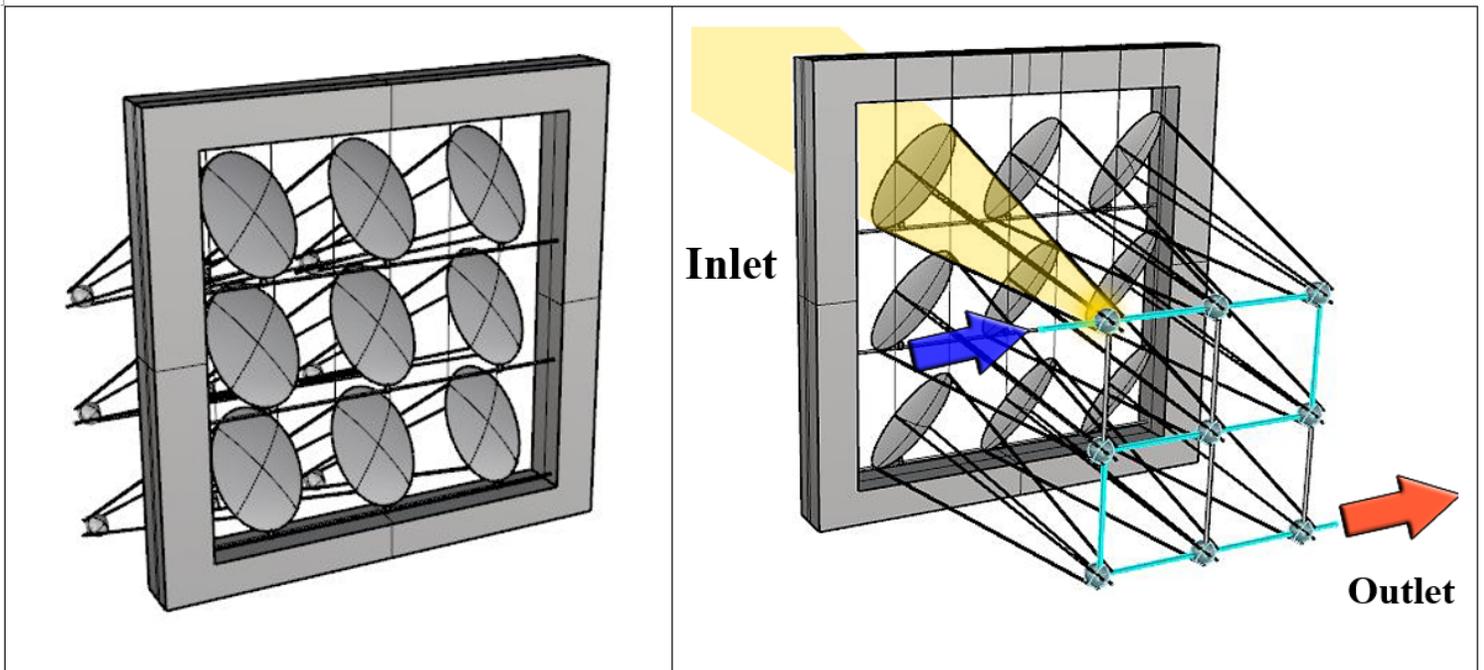


Figure 9

An example of a hypothetical arrangement of lenses in a network piece of the facade and water circulation in the pipes

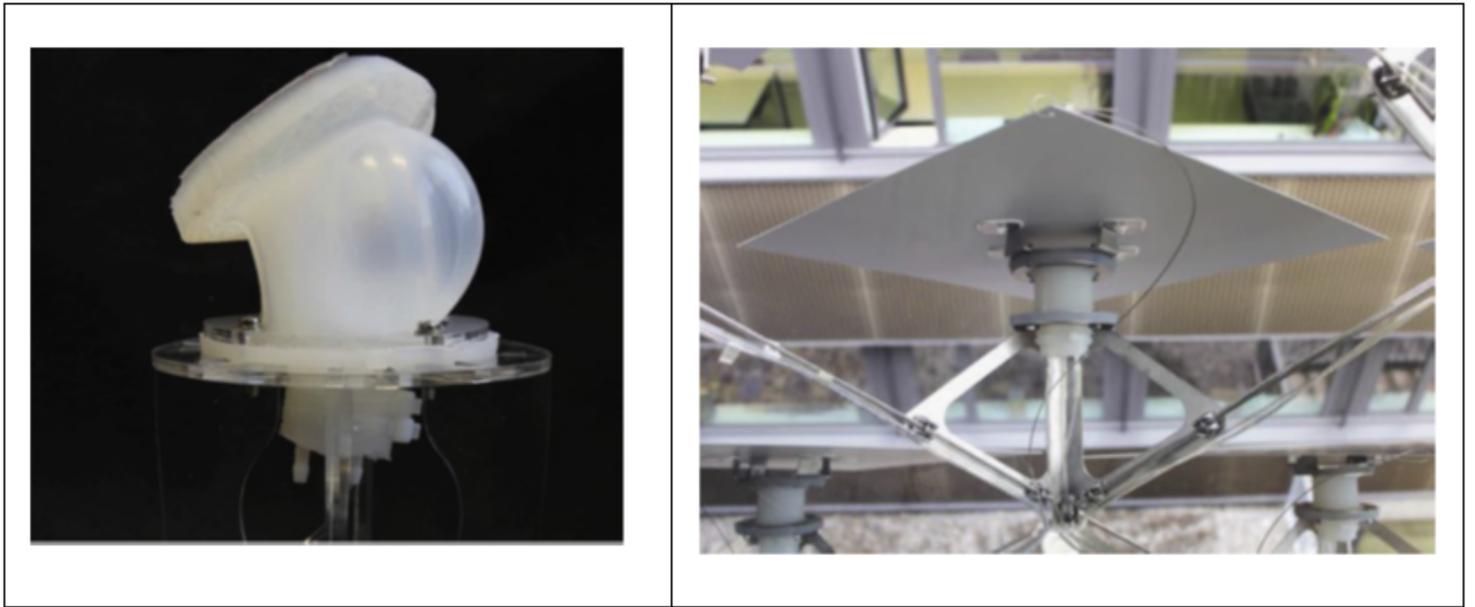


Figure 10

The proposed motion actuator engine (left), and the application of it an adaptive façade [12]

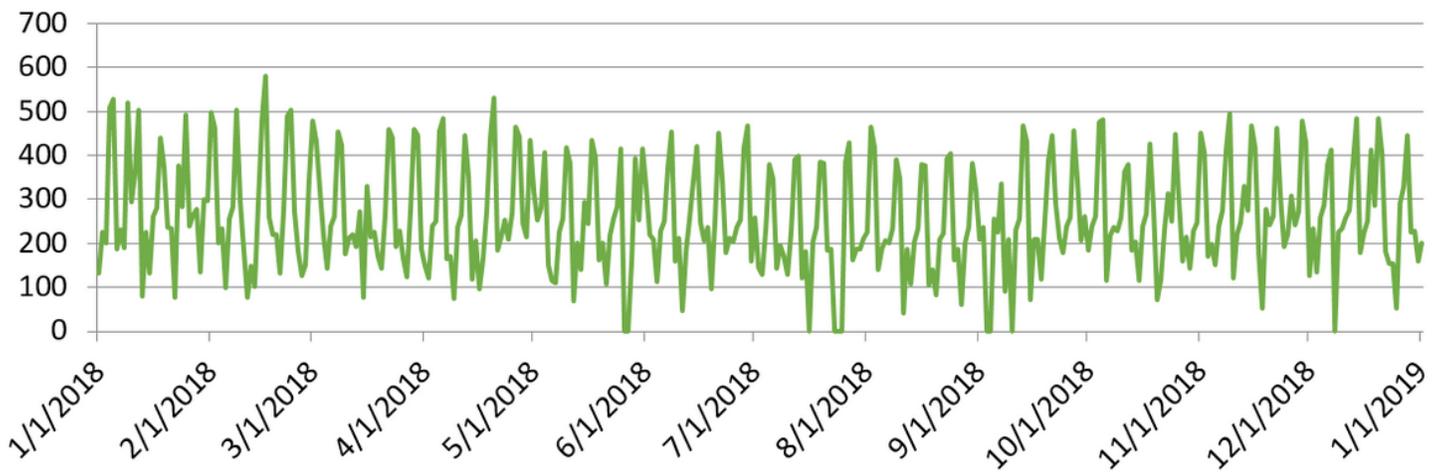


Figure 11

Daily energy consumption (kWh), in 2018

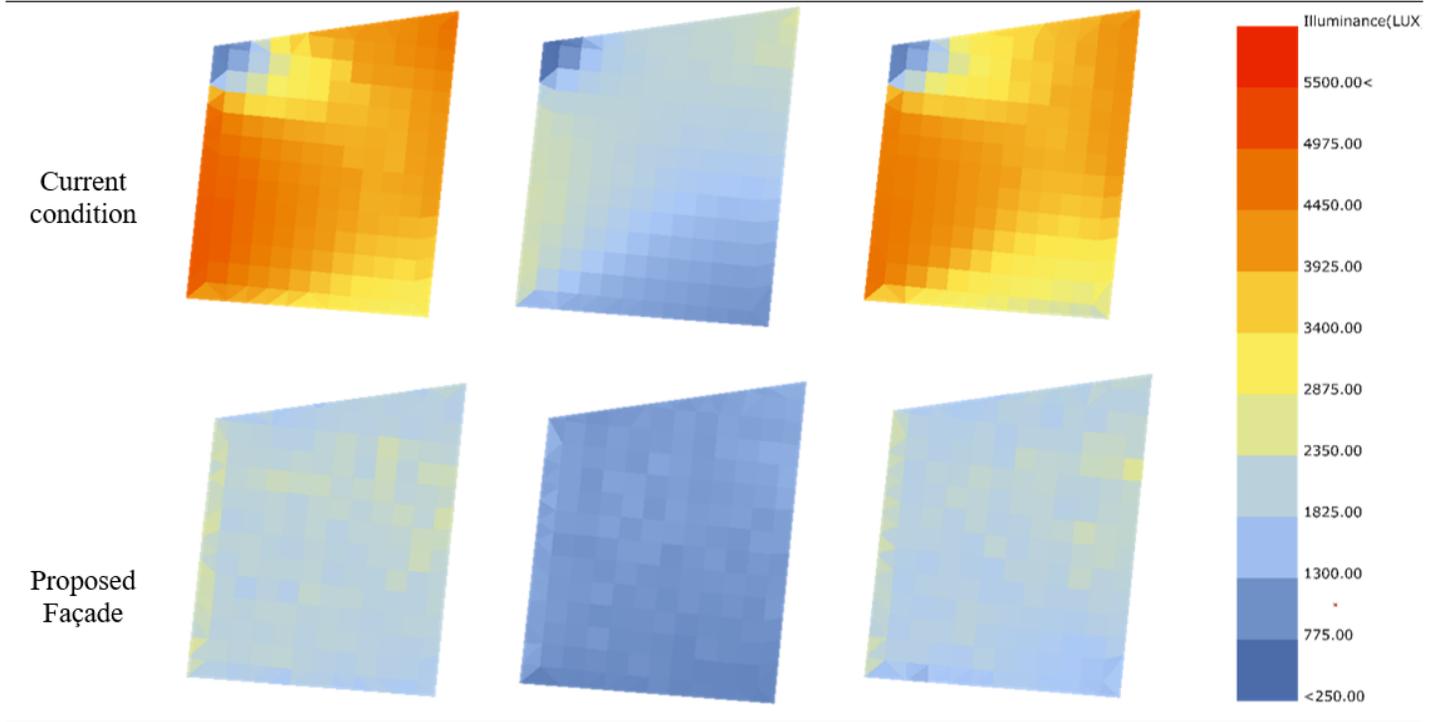


Figure 12

Point-in-time illuminance analysis of the current condition and the proposed condition of the facade in critical times of daylight availability

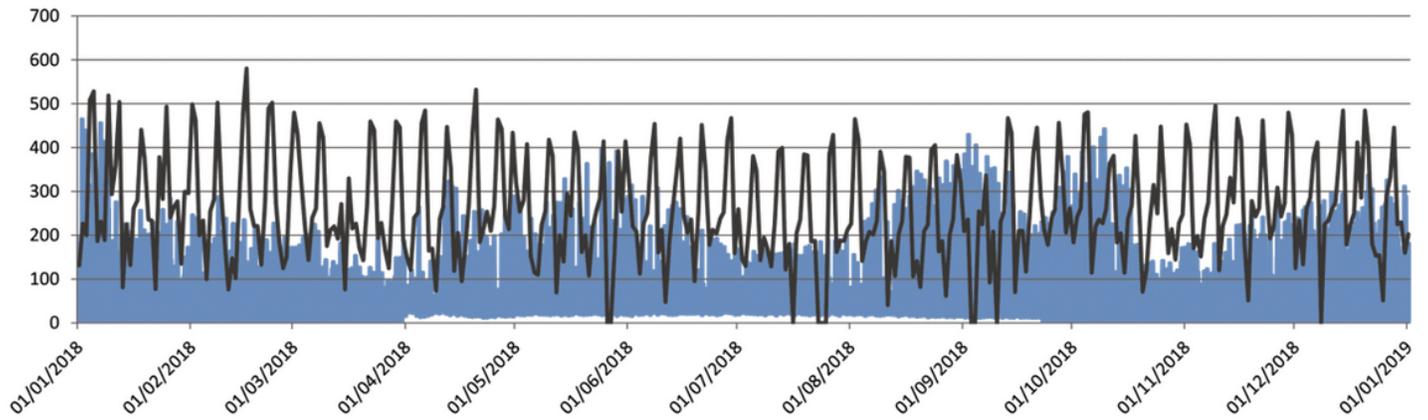


Figure 13

Energy consumption for heating the water for the café use (black curves), Energy harvesting from solar radiation through the proposed facade (blue curve) (kWh)



Figure 14

All the design variables and their impact on the total performance

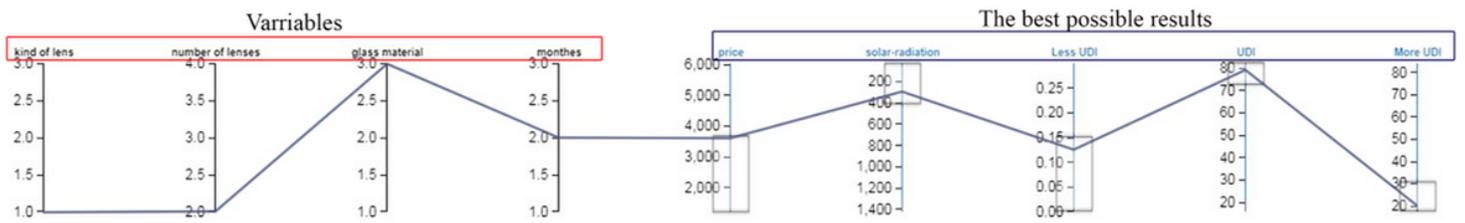


Figure 15

The best possible result for the multi objectives

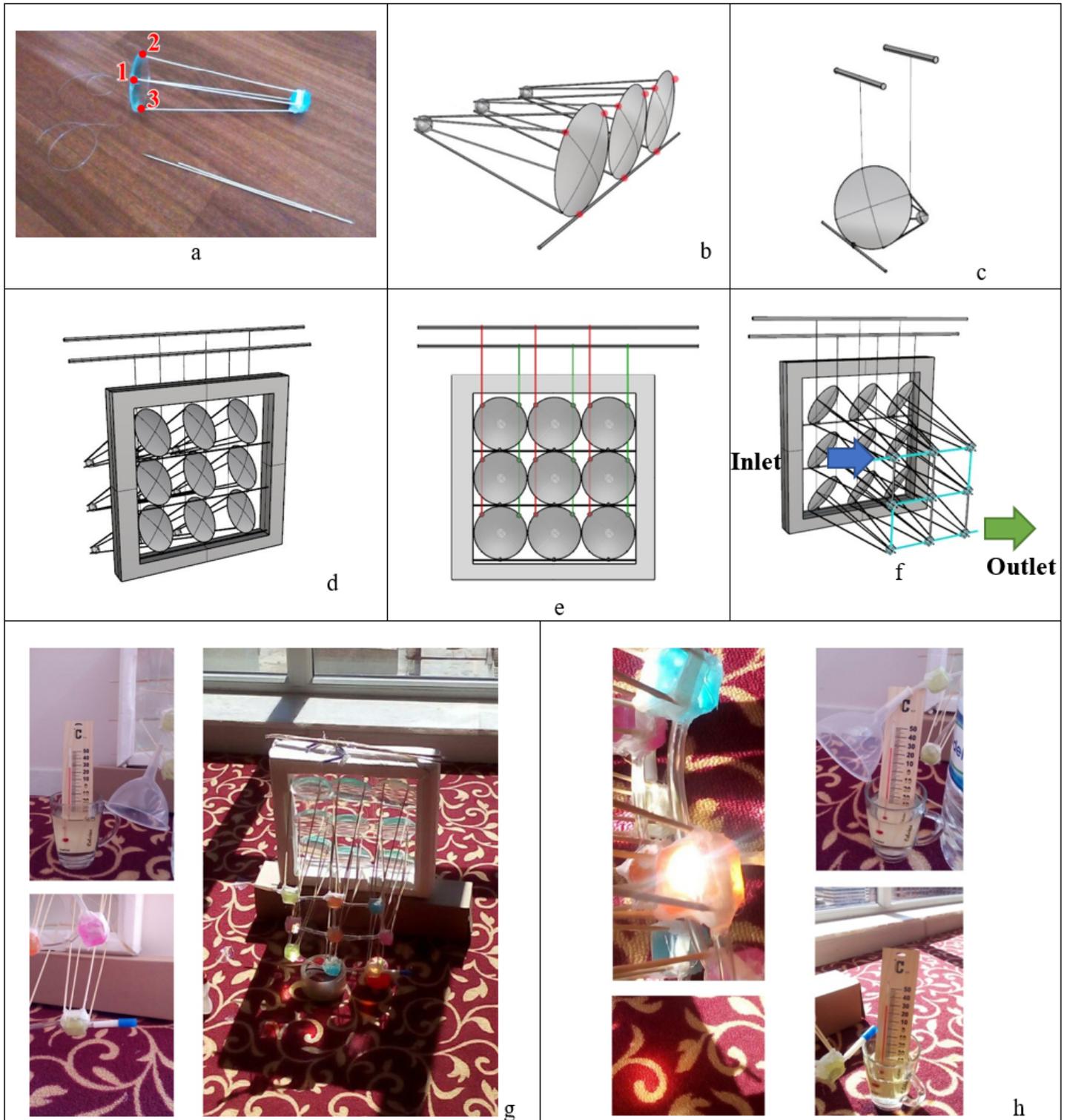


Figure 16

A conceptual prototype check—a. A lens equipped with three beams to hold a water chamber at their focal point of the lens, b. The lenses mounted on horizontal beams on the panel, c. Using transparent fishing yarn to manage the lenses movements from two point., d. The combination of nine lenses with their manual controlling apparatus (perspective view), e. The combination of nine lenses with their manual controlling apparatus (front view), f. The circulation of water inside the panel, g. The focus of sunlight at

the focal points of the lenses and the water duct inlet (top-left) and outlet (bottom left), h. The focus of sunlight at the focal points of the lenses from a close view and the temperature of the inlet water (top-right) and the outlet one (bottom-right)

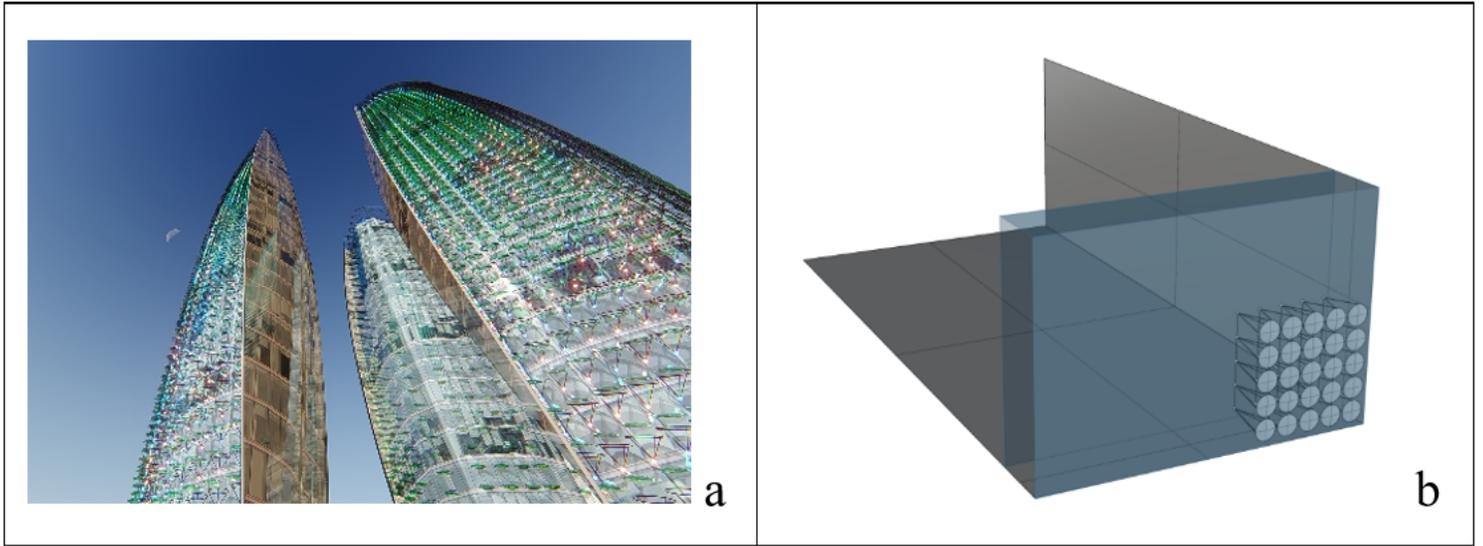


Figure 17

a. implementation of the proposed façade in this study on highrise buildings b. A double skin facade equipped with the proposed facade for the future potentiometric of CFD ventilation analysis

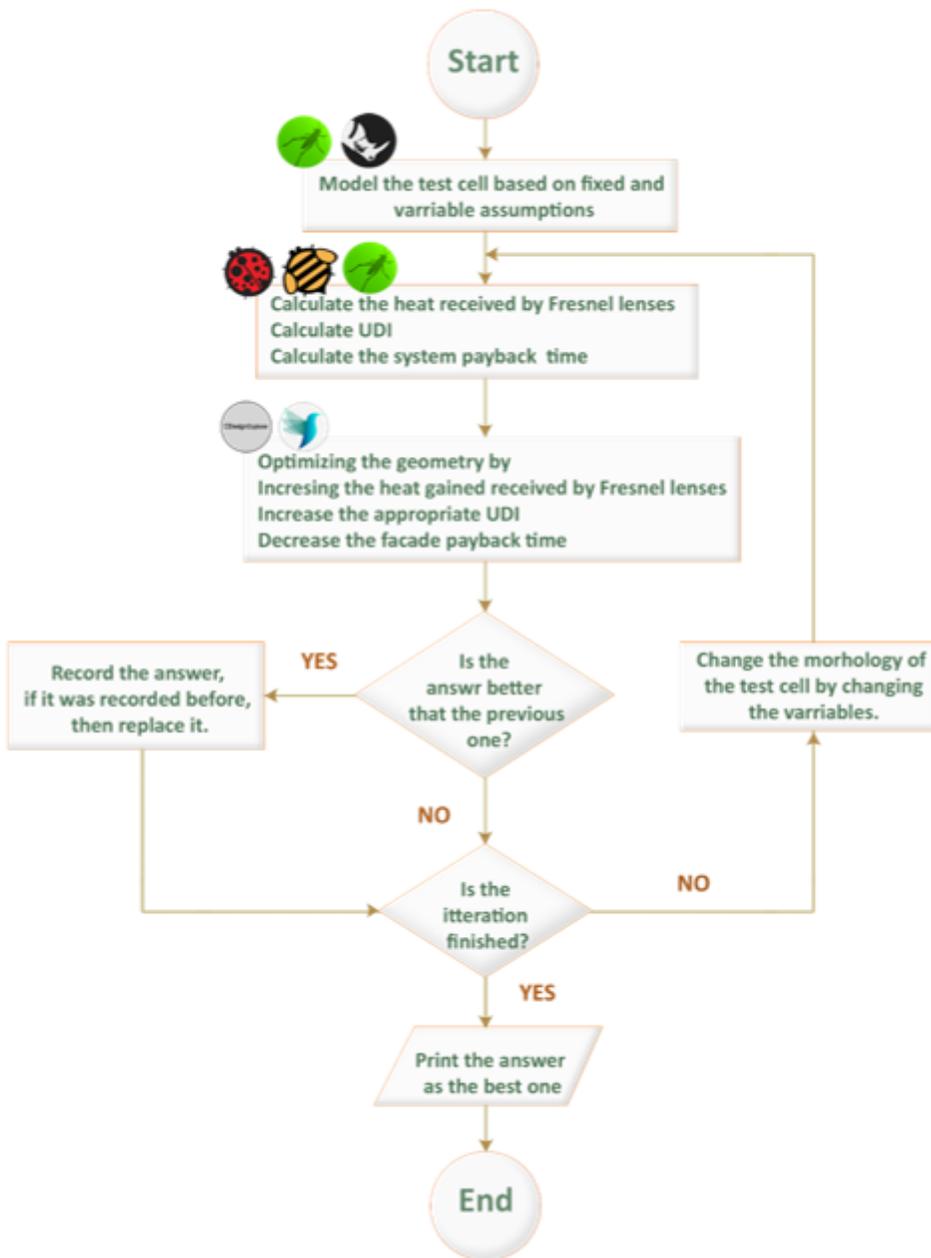


Figure 18

The linear multi-objective optimization process