SELF-ADAPTING FAÇADE SYSTEMS: EXPERIMENTATION REGARDING THE EXPLOITATION OF THERMAL DILATION

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ABSTRACT

An original and innovative solar device orientation system is illustrated, together with the results of research and experimentation. The system proposed uses only the force generated by natural thermal dilation, without the help of motors, computerized devices or external energy sources, thus overcoming some critical aspects of the self-adaptive type of building envelopes used up until now. In the course of the research a mathematical model was developed to correlate the variation of the environmental temperature with the consequent expansion of the dilating elements of the system. The results of the tests carried out confirmed an excellent correspondence between the theoretical results and the experimentation. The state of the art of the research has all its theoretical aspects defined and some partial prototypes created. It is planned to build some complete prototypes with the realistic prospect of productive development.

KEYWORDS

façade systems, building envelope, solar panels, sunblind, thermal dilation.

1. INTRODUCTION

The most advanced technological concepts aim to achieve an "organic" behavior of the building envelope. It consequently becomes "dynamic," that is variable, because it is sensitive and self-adapting as regards external environmental conditions. Within the Polytechnic Department of Engineering and Architecture (DPIA) of the University of Udine, a series of research projects and experiments have been carried out on a new, original and innovative system for orienting solar devices. These systems exploit only natural thermal expansion, without the aid of motors, computerized devices or external energy sources. They have been developed with inspiration gained from the observation of plants that react to light stimuli and optimize their exposure to the sun through the differential expansion of plant fibers.

The system is made up of two main parts: the dilating elements and the mechanisms of multiplication and transformation of movement. The elements to be moved are connected to these, depending on the different possible applications: photovoltaic panels, solar shading or shielding elements integrated in passive solar systems.

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At the basis of the development of the technological systems, a mathematical model has been developed capable of describing the temperature and therefore the expansion of the "dilating elements," according to hourly climate data. This model takes into account all the components that determine heat exchange with the environment: conduction, convection and radiation. It has been studied how to relate the thermal expansion of the dilating elements (in our case easily available aluminum bars, and of limited cost) to the position of the panels or slats, so as to satisfy pre-ordered system requirements.

The system can be calibrated so as to optimize solar tracking (as in the case of photovoltaic panels), or to enable the passage of solar radiation in the coldest periods of the year and to reflect it in the summer period (in the case of sunblinds or screening systems integrated with solar air panels). The system has been tested through a series of experiments, whose means of creation and results are illustrated here. These confirm an excellent correspondence between theoretical and experimental results.

This research has already received significant regional[4] and national[5] Start Cup awards. The validation experiments of the theoretical hypotheses on the behavior of the dilating elements and on the mechanical aspects, initially conducted for horizontal dilating elements, were completed for vertical elements by the research group of the DPIA, within the international research project "Biomimic Solar Tracker. Eureka Eurostars, project 65103," also developed a passive biaxial solar tracker based on the same principles.

2. FAÇADE SYSTEMS—STATE OF THE ART

The recent rapid technological evolution of the building envelope makes it increasingly the undisputed protagonist of contemporary architecture, at times drawing an all-encompassing attention to itself and exercising on designers and insiders a sort of monothematic fascination.

A consolidated trend considers the envelope to be a filter system between two energy systems, that of environmental forces (climate) and that of human metabolism (biology). In this sense it is interpreted as a "medium" of the interactions that man establishes with the environment. In fact, technological components are being developed that are capable of achieving "interactive variability," changing their characteristics of shape, color, position, and adapting to the circumstances, in order to control lighting, heating, ventilation and air conditioning.

Initially, the principles of "artificial intelligence" were applied in this sector by simulating human behavior in relation to environmental variations, in terms of capacity of understanding, making decisions and implementing them, by means of a network of peripheral "neurons." In recent years, however, there has been a change of direction, with research being based on the observation of living species. For example, there have been studies on the adaptability of plant species to different climatic changes, reactions to light or other adaptations. In particular, there have been attempts to imitate the behavior of human skin, which responds to external stimuli according to what is ordered by a centralized activation system (the hypothalamus).

The complex innovation of technologies is accompanied by a parallel innovation in definitions, highlighting some of its innovative features from both functional and communicative point of view; the building envelope has been variously defined: as intelligent, interactive,

4. Start Cup FVG 2009 Project finalist and winner of the prize for innovation and research with "Warm Motion," an innovative self-adapting façade system based on thermal dilation.

5. Working Capital 2011 Torino. Project selected among finalists in the category "Bio and nano tech" with "Biomimetic Solar Tracker," an innovative passive mechanical system that exploits the properties of some materials that enable sun tracking without the need for motors.

sensitive, digital, a membrane, etc. Beyond the greater or lesser congruence between these definitions and the constructed reality, it is undeniable that new functions have been added to the traditional ones, no longer only linked to the "form," but to a more complex "trio" which includes technology and energy.

In this scenario, solar shielding devices take on considerable relevance, and in some cases they can be integrated with particular types of glass (thermal, chromogenic, thermochromic, etc.) or with "active" components such as solar panels.

Recently, envelopes of the self-adaptive type have been produced which use electro-mechanical actuators and sensors. These, however, present critical issues both as regards the high investment and maintenance costs involved, and their poor reliability, resulting in their being used exclusively in the field of representative buildings.

Shape memory materials have also been experimented upon. However, these are also costly and the systems that use them present problems associated with the discontinuity of movement and the difficulty in making intermediate adjustments.

The orientation system of the solar devices described below, on the contrary, uses exclusively thermal expansion for self-regulation, one of the simplest and well-known laws of physics, combining a reduction in energy consumption with the minimum environmental impact.

2.1 The Solar Hybrid Systems-Heat Pump

With regard to the research in the field of hybrid solar-heat pump systems, the work of Karagiorgas M.[6] focuses on the development of a simulation tool combining the use of an air-water heat pump and solar air collectors in two operating modes: direct and indirect. With the direct mode, the air heated by the solar air collectors is supplied directly to the internal rooms, while with the indirect mode the evaporator of the heat pump uses the pre-heated air from the solar collectors, thereby increasing the COP of the heat pump.

Ruschenburg J., Herkel S. and Henning H.[7] carried out a review of the hybrid solar thermal-heat pump systems in order to verify their availability on the market and analyze their possible uses. The various systems analyzed were also tested and evaluated for each of their main components.

Among the numerous works related to the field of hybrid systems, in the article by Klein K., Hutchtemann K. and Muller D.[8], a numerical analysis of a hybrid system consisting of an air-air heat pump and a wall-mounted gas boiler was conducted, showing excellent performances.

Regarding the air solar collectors, the work of Yang M., Wang P., Yang X., Shan M.[9], aimed to evaluate the effect of five parameters on the overall efficiency of the panel in order to determine which are the parameters that can most influence the performance of an air solar panel. The analysis was carried out by means of field tests, varying one single parameter each time, while maintaining the same working conditions. The results show that the parameter having the greater influence on the thermal efficiency of the collector is the thermal resistance of the channels where the air passage is located.

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6. Karagiorgas, M. (2010). Solar assisted heat pump on air collectors. Solar Energy(84).
7. Ruschenburg, J., Herkel, S., & Henning, H. (2013). A statistical analysis on market-available solar thermal heat pump systems. Solar Energy(95).
8. Klein, K., Hutchtemann, K., & Muller, D. (2014). Numerical study on hybrid heat pump system in existing buildings. Energy and Buildings, 69.
9. Yang, M., Wang, P., Yang, X., & Shan, M. (2012). Experimental analysis on thermal performance of solar air collector with a single pass. Building and Environment(56).

With regard to the self-adaptive façade systems, the work of Bakker L.G., Hoes-va Oeffelen E.C, Lonen R.C. and Hensen J.L.[10] analyzed the influence, the type of interaction and comfort for the occupants of environments with automated façade systems. Various control strategies for façade shielding have been tested. The results don't show particular problems in the interaction between occupants and automated systems. Furthermore, many studies have been carried out in order to define optimal algorithms for the control of solar shading on the façade. The study of Moon JW, Yoon S., Kim S.[11] developed a control method for double-skin façades in winter through the use of an algorithm based on artificial neural networks (Artificial Neural Network, ANN).

2.2 Passive Regulation Systems of Façade Systems

Passive systems group together all the applications in which the behavior of an element or a set of elements are obtained without the use of any fossil fuel or electricity, but only using the behavior of materials or physical phenomena.

Among the implementation and regulation systems applicable in the building envelope sector, innovative technological solutions have recently been developed which mainly concern the following materials:

1. *Thermo-responsive materials.* Their functioning is triggered by heat and temperature variations. Metallic materials, some gases, some shape memory materials, and thermochromic materials are part of these materials.
2. *Mechano-responsive materials*. These materials respond in relation to the application of stress and pressure. Some shape memory materials belong to this category.
3. *Chemo-responsive materials.* The behavior of these materials is influenced by changes in pH, humidity and solvents.
4. *Photo-responsive materials.* The stimulating reagent of these materials is light; photochromic materials are an example.

As regards self-regulation mechanisms of solar devices, the research has identified some systems that have similarities with the one proposed, even if they differ in various aspects both in the operating principle and in the application possibilities. They work mainly through the application of bi-metallic elements.

A "Thermal rotary vent" patent[12] refers for example to a system of expulsion vents and air intakes. The opening is self-regulating according to the air temperature through some bimetallic springs that twist thanks to the difference between the coefficients of thermal expansion of the metals of which the springs are composed. A second "Shutter device"[13] applies to solar shading systems. The sensor is made up of a cylinder having an external surface exposed to sunlight and containing a gas sensitive to temperature variations (freon). When the sun heats the cylinder, the gas contained within it expands, causing the translation of a piston which moves a lever that changes the inclination of the slats, shielding sunlight.

10. Bakker, L. G., Hoes-van Oeffelen, E. C., Loonen, R. C., & Hensen, J. L. (2014). User satisfaction and interaction with automated dynamic facades: A pilot study. Building and Environment, 78.
11. Moon, J. W., Yoon, S., & Kim, S. (2013). Development of an artificial neural network model based thermal control logic for double skin envelopes in winter. Building and Environment, 61.
12. Godsey, E. L., & Franks, J. (1999, 11 16). USA Brevetto n. US5984196 A.
13. Wild, E. (1975, 01 14). USA Brevetto n. 3860055.

Another system *"Dispositif à pouvoir réflecteur variable en fonction de la température et son application autorégulation d'un dispositif héliothermique"*[14] finds application in the field of thermal regulation of solar collectors, shielding from excess sunlight in the summer, but allowing the passage of the sun in winter. It consists of fins made up of two sheets having different thermal expansion coefficients, capable of changing their shape with the change of temperature.

3. WORKING PRINCIPLES OF THE SYSTEM, THERMO-DYNAMIC MODEL AND EXPERIMENTATION

The system is made up of the following components: a frame, the dilating elements, a movement multiplication system, the elements to be moved, that is, depending on the different possible applications: photovoltaic panels, solar shades or shielding elements integrated in passive solar systems.

The dilating elements act as the engine of the façade system. They are made up of elongated flat aluminum bars, painted black and a few meters in length. They are arranged externally along the façade and are hinged on one side making them solidly attached to the supporting structure, while they are free to expand on the other side. The relative motion of the sun during the year, the air temperature and meteorological agents induce temperature variations in the bars. The thermal variations are translated into thermal deformations (of a few mm.) that are amplified by a movement multiplication mechanism that transforms them into a rotation of the elements to be moved (Figure 1).

The dilating elements are externally exposed. The convective component is always present and tends to shift the temperature of the elements to the same temperature of the surrounding air while the radiative component, due to solar radiation, varies with the solar height, with the changing of the seasons and with the passage of time. The development of technological systems has been elaborated on the basis of a thermodynamic model able to describe the temperature and therefore the expansion of the "dilating elements," according to the hourly weather data.

This model takes into account all the components that determine heat exchange with the environment: conduction, convection and radiation. In order to perform numerical simulations, the hourly weather data for the Udine area were adopted for a ten-year period and a typical year was constructed to represent the most probable time sequences of data.

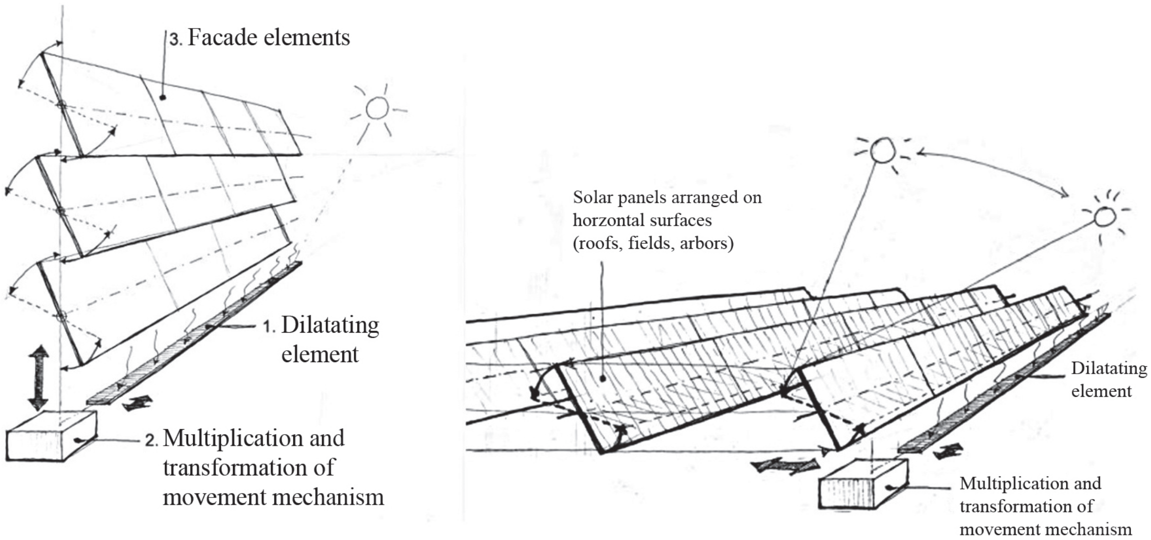
Therefore, the mean value and variance of the air temperature were calculated for each month of the year, out of the entire data population. Then the typical months were selected, that is the real months with the meteorological values that are closer to those of the mean months. Finally, the typical year was constructed as a composition of the typical months.

The meteorological quantities available are: air temperature [°C], the total global radiation on the horizontal plane [W/m2], the humidity of the air [%], the average wind speed at 10 m from the ground [m/s]. The heat exchange between the dilating elements (HRE) and the environment is given by the sum of the radiative, convective and conductive components. The latter component, in this analysis, will be neglected as the HRE considered are of very small thickness and in any case connected to the frame (or to other elements) only at two ends.

$$q_{\text{tot}} = q_r + q_c$$

14. Huet, P. F. (1981, 05 27). Francia Brevetto n. 2 506 913.

FIGURE 1. General scheme of the WM system applied to solar panel orientation systems on horizontal surfaces (left). Scheme of the function of the WM system for the orientation of façade elements on portions of buildings (right).



3.1 MODEL DEVELOPMENT

3.1.1 Radiative component

The radiative exchange with the environment is expressed below considering all its components:

$$q_r = H_s + H_l + E_l$$

Where H_s is the solar energy absorbed at short wavelength ($\lambda \leq 4\ \mu$m), H_l is the solar energy absorbed at long wavelength (4 μm $\leq \lambda \leq$ 100 μm) and E_l is the radiation emitted at long wave.

Short wave solar component

For the calculation of this component of solar radiation, the course of the solar trajectories will be defined as the first step according to the method described by Cucumo (Cucumo, Marinelli, & Oliveti, 1994).

The solar height is expressed according to the following formula:

$$\alpha = \sin^{-1}(\sin L \sin\delta + \cos L \cos\delta \cos h)$$

Where L is the latitude of the place, h the hour angle and δ is the solar declination calculated according to Cooper (Cooper, 1969).

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$$

Where n represents the progressive number of the day of the year. The azimuth angle is calculated according to:

$$A = \sin^{-1}\left(\frac{\sin h \cos\delta}{\cos\alpha}\right)$$

The energy radiated by the sun in the unit of time, for a unitary surface oriented orthogonally with respect to the sun's rays, is described according to the following relationship:

$$I_0(t) = I_{cs}e(t)$$

Where the two components are described by the following relationships:

$$I_{cs} = 1367\left[\frac{W}{m^2}\right]$$

$$e(t) = 1 + 0.033\cos\left(\frac{2\pi n}{365}\right)$$

The capturing surface (that of the ED), however oriented, is defined by means of two angles: the angle of inclination with respect to the horizontal plane (β) and the angle of azimuth (Aw) which expresses the angle between the projection in the horizontal plane of the normal to the surface and the south direction. In this work it is considered negative if facing east and positive towards west. The angle of incidence between the sun's rays and the surface normal will be indicated with the letter i.

The global instantaneous power incident on an oriented surface is the sum of the direct, diffuse and reflected component.

$$H_s = H_b + H_d + H_r$$

Where the direct component is expressed according to the following:

$$H_b = H_{bh}R_b$$

Where H_{bh} is the instantaneous direct radiation incident on the horizontal plane and the term R_b is the inclination factor and is expressed according to the following relationship:

$$R_b = \frac{\cos i}{\sin\alpha}$$

Where $\cos i = T + U \cos h + V \sin h$

With the terms T, U, V expressed according to the following relations:

$$T = \sin\delta\left(\sin L \cos\beta - \cos L \sin\beta \cos A_w\right)$$

$$T = \sin\delta\left(\sin L \cos\beta - \cos L \sin\beta \cos A_w\right)$$

$$V = \cos\delta \sin\beta \sin h$$

The diffuse component incident on the surface, making the hypothesis of isotropic sky, turns out to be:

$$H_d = H_{dh} R_d$$

Where:

H_{dh} the radiation diffused on the horizontal plane,

$R_d = \frac{1+\cos\beta}{2}$ = inclination factor of diffuse radiation

The following report describes the radiation reflected from the ground on the capturing surface.

$$H_r = \left(H_{bh} + H_{dh}\right) R_r$$

Where:

$R_r = \rho\left(\frac{1-\cos\beta}{2}\right)$ = inclination factor of the reflected radiation,

With ρ the ground reflection coefficient.

Hourly global radiation data are usually available and, in order to extrapolate the direct and diffuse component, the Reindl and Beckman correlation will be used (Reindl, Beckman, & Duffie, 1990):

$$\begin{cases} \frac{H_{dh}}{H_h} = 1 - 0.323k + 0.0239\sin\alpha - 0.000682T_a + 0.0195\varphi \leq 1 & \text{Per } 0 \leq k \\ \frac{H_{dh}}{H_h} = 1.329 - 1.716k + 0.267\sin\alpha - 0.00357T_a + 0.106\varphi \geq 0.1 & \text{Per } 0.3 \leq k \\ \frac{H_{dh}}{H_h} = 0.426k + 0.256\sin\alpha - 0.00349T_a + 0.0734\varphi \geq 0.1 & \text{Per } k \end{cases}$$

Where: $k = \frac{H_h}{H_{h,\text{hex}}}$ = hourly serenity index

Where: $H_{h,\text{hex}} = I_{cs}\left[1 + 0.033\cos\left(\frac{2\pi n}{365}\right)\right]\left(\cos L \cos\delta \cos h + \sin L \sin\delta\right)$ = hourly energy incident on the horizontal plane outside the atmosphere.

The hourly direct radiation on the horizontal plane is expressed by the following relationship:

$$H_{bh} = H_h - H_{dh}$$

Long wave radiation component

The flux of incident long wave radiation on a surface is expressed by the following formula:

$$H_l = H_{l,a} - H_{l,t}$$

Where $H_{l,a} = F_{s,a}\sigma T^4_{vc}$ is radiation from the atmosphere.

With σ representing the Boltzmann constant:

$T_{vc} = 0.055 T^{1,5}_e + 2.625N$ = equivalent temperature of the sky,

Where $N = 8(1 - k)$ = cloud cover expressed in eighths,

$F_{s,a} = \frac{1 = \cos\beta}{2}$ = view factor of the surface with respect to the atmosphere,

$H_{l,t} = F_{s,t}\sigma T^4_t$ = albedo radiation,

with: $F_{s,t} = 1 - F_{s,a}$ the inclination factor of the reflected radiation and T_t is the soil temperature.[15]

Radiation emitted

The radiation emitted, in the field of large wavelengths, is expressed by the following expression:

$$E_l = \varepsilon_l \sigma T_s^4$$

Where ε_l is the surface emissivity and T_s is the body surface temperature (Guglielmini & Pisoni, 1990).

3.1.2 Convective component

The specific flow between a solid body and the fluid that laps it is expressed by:

$$q_c = h_c\left(T_s - T_\infty\right)$$

Where h_c is the convection coefficient, T_s is the temperature of the solid wall and T_∞ is the undisturbed flow temperature.

Referring to the following figure, for the definition of the dimensionless numbers, length will be referred to $l = A/l_c$

Hourly wind speed data are collected in weather stations in the open field and at a height of 10 m, the use of these values cannot be realistic due to the proximity to other buildings, the roughness of the ground and the orientation. In order to make the wind speed data more consistent with reality, the wind speed reduction coefficient proposed by Eurocode1 (ENV, 1991).

$$v_m = \begin{cases} v_{\text{ref}} K_r \ln\left(\dfrac{z_p}{z_0}\right), & se\ \mathrm{z}_p > z_{\min} \\ v_{\text{ref}} K_r \ln\left(\dfrac{z_{\min}}{z_0}\right), & se\ \mathrm{z}_p \le z_{\min} \end{cases}$$

Where v_{ref} is the detected wind speed, K_r is the roughness factor, z_0 is the roughness length, $z_{\min}$ is the height below which it is assumed that the wind speed remains constant. In this study the values corresponding to the category IV of soil will be considered with $K_r = 0.24$, $z_0 = 1$m, $z_{\min} = 16$m. The correct wind speed turns out to be: $u = v_m$.

15. To reduce the amount of calculations, the T_t will be considered equal to that of the air.

In the case of forced convection, Gnielinski correlations will be used (Hewitt, 1998) for generic profile pipes immersed in an air flow orthogonal to them.

For $1 < Re_l < 10^7$ e $0,6 < Pr < 10^3$ the Nusselt number is calculated according to the following relationship:

$$Nu_l = Nu_{l,\min} + \sqrt{Nu_{l,\mathrm{lam}}^2 + Nu_{l,\mathrm{turb}}^2}$$

With $Nu_{l,\min} = 0.3$ in the case of finished cylinders and where:

$$Nu_{l,\mathrm{lam}} = 0.664\sqrt{\mathrm{Re}_l}\sqrt{\mathrm{Pr}_l}$$

$$Nu_{l,\mathrm{turb}} = \frac{0.037\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l}{1+2.443\mathrm{Re}_l^{-0.1}\left(\mathrm{Pr}_l^{2/3}-1\right)}$$

In case of $Re_l < 1$ the following relation holds:

$$Nu_l = 0.75\sqrt[3]{\mathrm{Re}_l\,\mathrm{Pr}_l}$$

In the case of natural convection it's used, as indicated by Lienhard (Lienhard & Lienhard, 2008) a correlation for vertical surfaces

$$Nu_l = 0.0678\mathrm{Ra}_l^{1/4}\left(\frac{\mathrm{Pr}_l}{0.952\,\mathrm{Pr}_l}\right)^{1/4}$$

In the case of mixed convection, the correlations proposed by Churchill will be used (Churchill 1977).

3.1.3 Calculation of the equilibrium temperature

The equilibrium temperature of the dilating elements is calculated by means of an overall balance of the radiative and convective heat exchanges:

$$\ddot{q} = H_s + H_l + E_1 + q_c = 0$$

All the quantities of the previous equation refer to the surface unit and their contribution on the global budget was placed in relation to the surface of the element in which these components intervene. The equation is solved iteratively by explaining the term of the surface temperature (T_s), using the method of subsequent replacements.

In a metallic material (in this case the materials are aluminum and steel), the link between the thermal expansion and its temperature is linear.

$$\Delta L = \alpha \cdot \Delta T \cdot L$$

where α is the thermal expansion coefficient of the material, ΔT is the tempereature difference and L is the la "body" length.

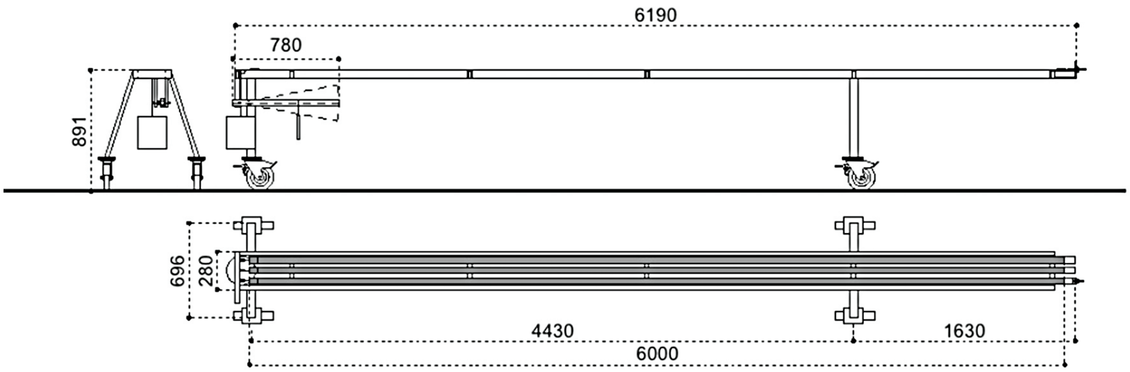
3.2 DEFINITION OF CASE STUDIES

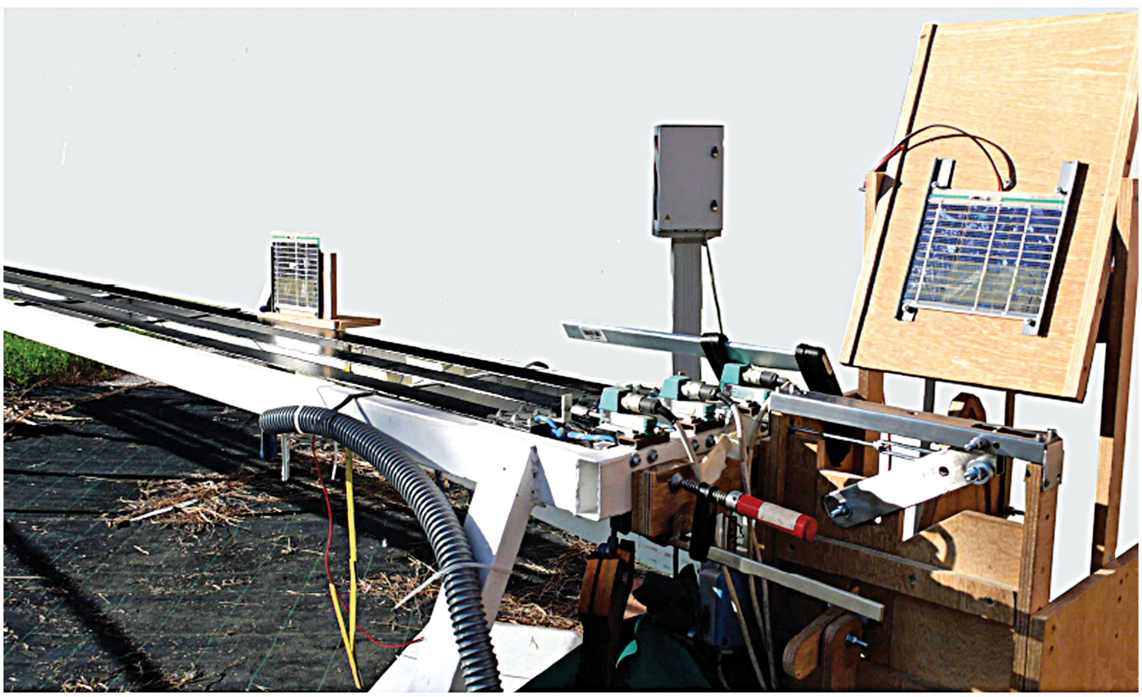
3.2.1 Case study 1

A first series of experiments focused on the horizontal arrangement of dilating elements. To analyze their behavior in relation to atmospheric agents, a test bench was built on which three equal-sized bars were installed, all with the same surface treatment (Figure 2).

Al_Mg_Si 6060 T6 "Anticorodal" aluminum bars were used with a 50x2 mm section. Each of them was thermally insulated from the frame by PVC rods and bound to it at one end. In this way the bar remains free to expand and retreat, due to thermal action, on the other side. A load of was applied to each bar, from 5 kg up to a maximum of 255.6 kg. This is much lower than the yield point, since each plate can withstand, still remaining in the elastic range, a load of up to 2 tons.

FIGURE 2. Experiments carried out at the University of Udine with horizontal arrangement of the dilating elements. Above: testbed scheme. Below: experimental apparatus of the case study 1.





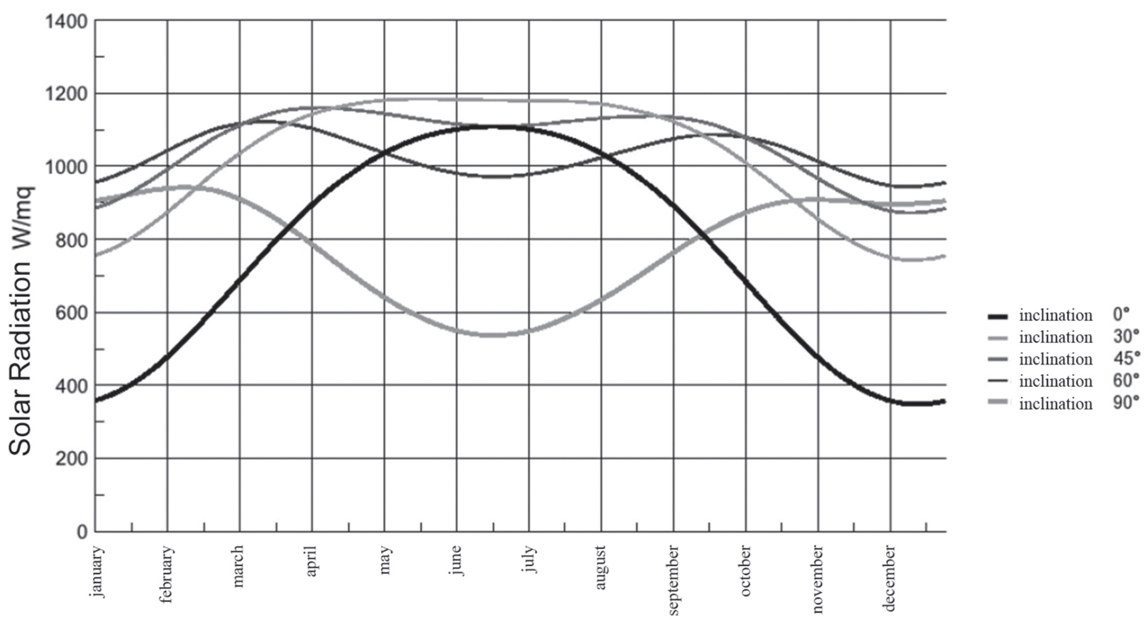
One factor that has an important influence on the thermal behavior of the bars is their surface treatment. In the tests carried out they were treated with a black two-component paint, specific for aluminum, which creates an absorption coefficient of the surface that is included in a range between 0.85 and 0.90.

Throughout the course of a calendar year, recordings were made of the temperature variations of the bars and the deformation differences between the bench and the bars. This was done using thin-film platinum thermos-resistance sensors of Pt100 class A type, and potentiometric transducers, respectively.

Two possible arrangements of the dilating elements were studied, horizontal and vertical, and two possible technological applications, with the application of the solar panel mechanism arranged on the façade or with solar shading elements (independent sunblinds or integrated with the solar panels). The two possible arrangements of the dilating elements are not equivalent. The horizontal position is the one that guarantees the maximum difference between summer and winter temperatures, while the vertical surface produces fewer diurnal temperature variations between the two seasons. This is due to the fact that the vertical surface, in winter, is almost orthogonal with respect to the solar rays and therefore the radiative component is high (Figure 3). This is even greater than the summer position and the direct radiative component partially compensates the convective component, which is proportional to the temperature and obviously higher in summer. The diffuse radiative component remains similar in both cases (horizontal and vertical).

The horizontal arrangement therefore guarantees a greater range of expansion of the dilating elements. Since the rotation of the slats occurs around a horizontal axis, the coupling with a horizontal dilating slat can be mechanically more complex. From this point of view, the coupling of the movable elements with dilating bars arranged vertically may be simpler, even if this implies a greater amplification of the thermal expansion movement, which is lower.

FIGURE 3. Solar radiation absorbed during one year per surface unit depending on surface inclination with respect to horizontal.



If the system is designed according to the "solar panel" model, the objective is to guarantee the orthogonality of the panel with respect to the direction of the solar rays. For example, in winter, starting from an almost vertical initial position (night position), a progressive increase in heat exchange with the environment involves the expansion of the dilating element and so the solar panel rotates, following the height of the sun.

It is possible to calibrate the mechanism so that an almost horizontal position (the sun at the summer zenith) corresponds to the maximum temperature of the dilating elements. If the sky remains overcast, the radiative component will be smaller, with prevalence of diffuse radiation and the temperature of the bar will be closer to that of the air, ensuring an effective rotation of the element.

In the experiments carried out with horizontal dilating elements (fig. 2) and therefore with lower dilations in winter and greater dilations in summer, the measured quantities were: air temperature, bar temperature and differential deformation between the bars and the frame on which they were mounted.

3.2.2 Case study 1 results

The recording of temperatures carried out over the course of a year is summarized in Figures 4 and 5. The experimental results confirmed the theoretical model. There were slight deviations in the maximum temperature values (with higher values in reality than in the mathematical model), due to the fact that the measured values are instantaneous, while the model is based on mean hourly values.

The maximum difference between the air temperature and that of the bars was recorded in June, equal to 32°C. Similar values of difference between the two temperatures were recorded

FIGURE 4. Yearly and monthly trend of air temperature and dilating elements.

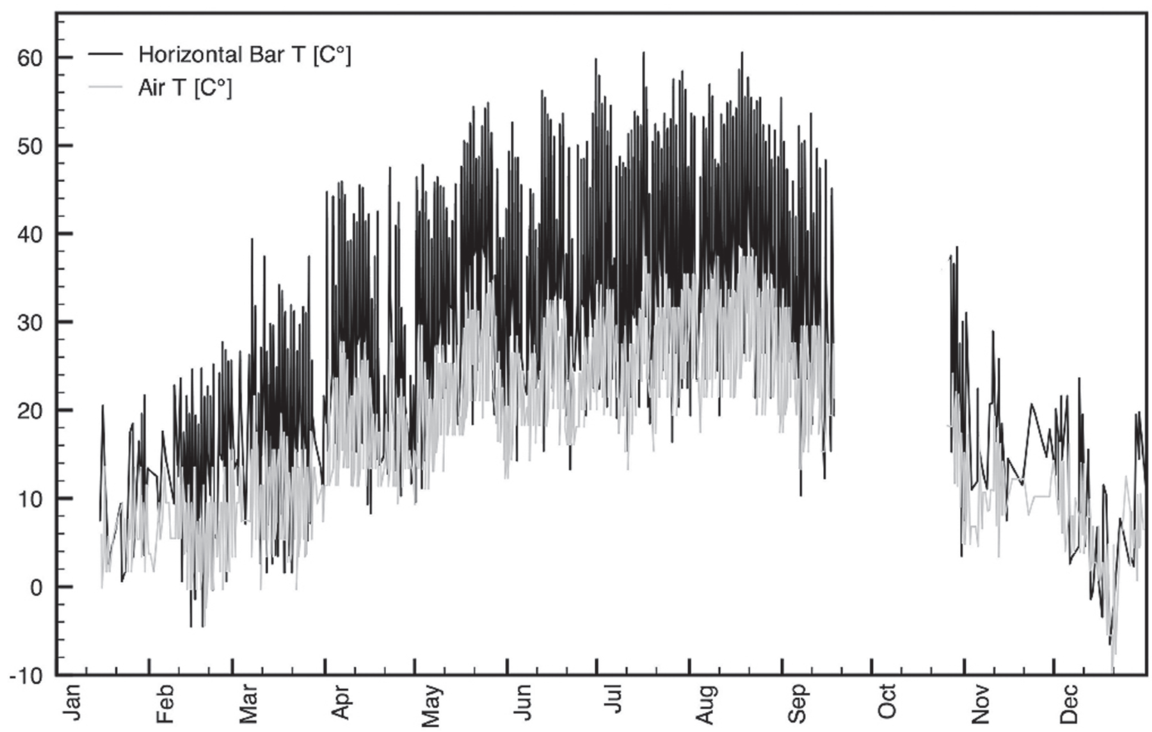
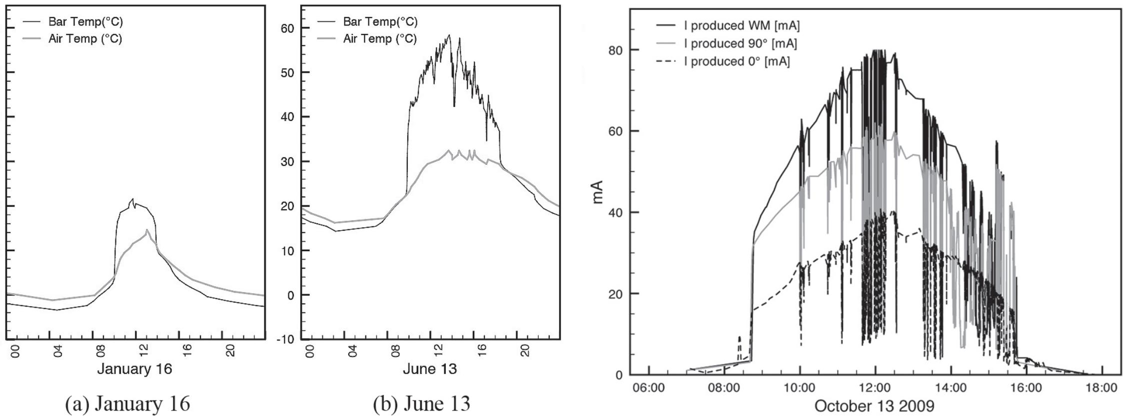


FIGURE 5. Daily diagram with data collected during the experimentation of air temperature and dilating elements (left). Comparison diagram between the electricity production of a photovoltaic panel applied to the WM system, a photovoltaic panel in a horizontal position and one in a vertical position (right).



throughout June and July. The maximum summer temperature reached by the bars was 62.7°C. At that moment the air temperature was 38.4°C. The maximum winter temperature was 29.2°C whilst the air temperature was 13.8°C. The minimum temperature recorded by the bars was –12.6°C with an air temperature of –11.5°C. The overcast days were characterized by minimum temperature differences between the bars and the air.

Comparing the trend of the temperature of the dilating elements during the year and, more in detail on a typical day with the trajectory of the sun during the year (fig. 5), it can be seen how the paths are qualitatively comparable.

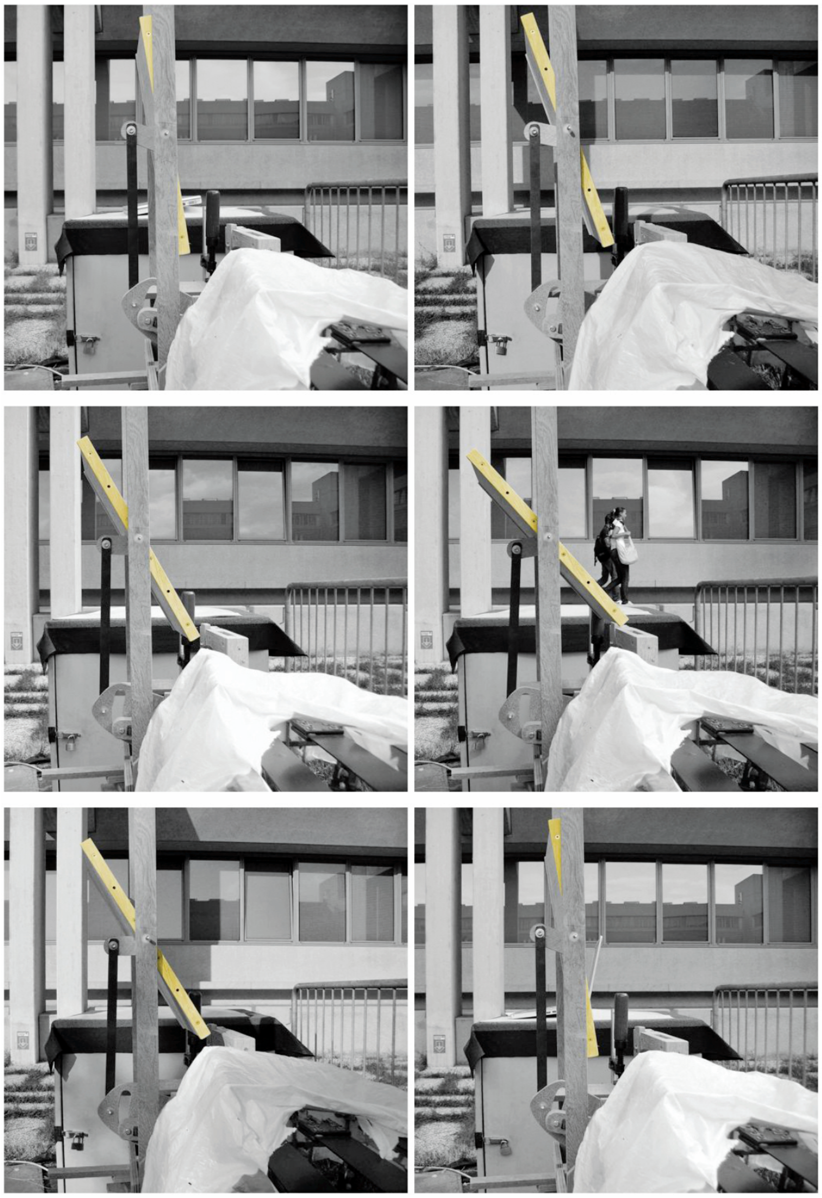
A second series of experiments, more recent and carried out with a more finely adjusted apparatus, involved the vertically arranged elements. Also, in this case it was verified that there is an almost perfect correspondence between the theoretical and real values.

The system is therefore able to function autonomously by orienting a surface towards the sun. This can be seen from the photographic sequence (Figure 6), which shows the various positions taken by a small solar panel moved by the WM system during a typical day in autumn. In addition to verification of movement, a comparison was also made regarding the production of electric current between three small photovoltaic panels. One of these was mounted on the WM system, while the others were arranged in a fixed position, with an inclination of 0° and 90° with respect to the horizontal respectively. The electric current production of a PV panel mounted on this system was greater than a fixed panel arranged vertically by 25% while, compared to the horizontal position, the increase was 40%. According to the "solar shading" model, using vertical dilating elements, the requirements to be met are more complex, regarding both the lighting aspects and the thermal values.

3.2.3 Case study 2

For the application of the system to solar air panels, coupled with a heat pump, it is possible to design the mechanism in order to maximize the contributions of winter energy and to annul, or almost annul, the summer contributions. This makes sure that the solar energy can reach the panel in winter and be shielded during the warmest periods. Therefore, a certain "daily"

FIGURE 6. Photographic sequence of various positions adopted by the trial solar photovoltaic panel during a day in October.



variability is not considered important, but rather a behavior linked to the external temperature of the air. By shielding the vertical dilating elements from direct radiation, it can be presumed, as a first approximation, that their temperature is equal to that of the surrounding air. This hypothesis enables, among other things, the dilating elements to be considered as completely "integrated" in the façade, located for example within the support frames of façade systems.

The essential geometric elements of the system, highlighted in Figure 7, are the inclination angle of the slats (β) and the profile angle of the solar rays (ω). The reflected radiation is obtained as the one's complement of the undisturbed transiting radiation, through the fictitious cavities identified by the slats.

FIGURE 7. Geometric scheme of the position of the orientable slats and their inclination (β) in relation to the radiation entering and reflected and to the profile angle of incidence of the solar radiation (ω).

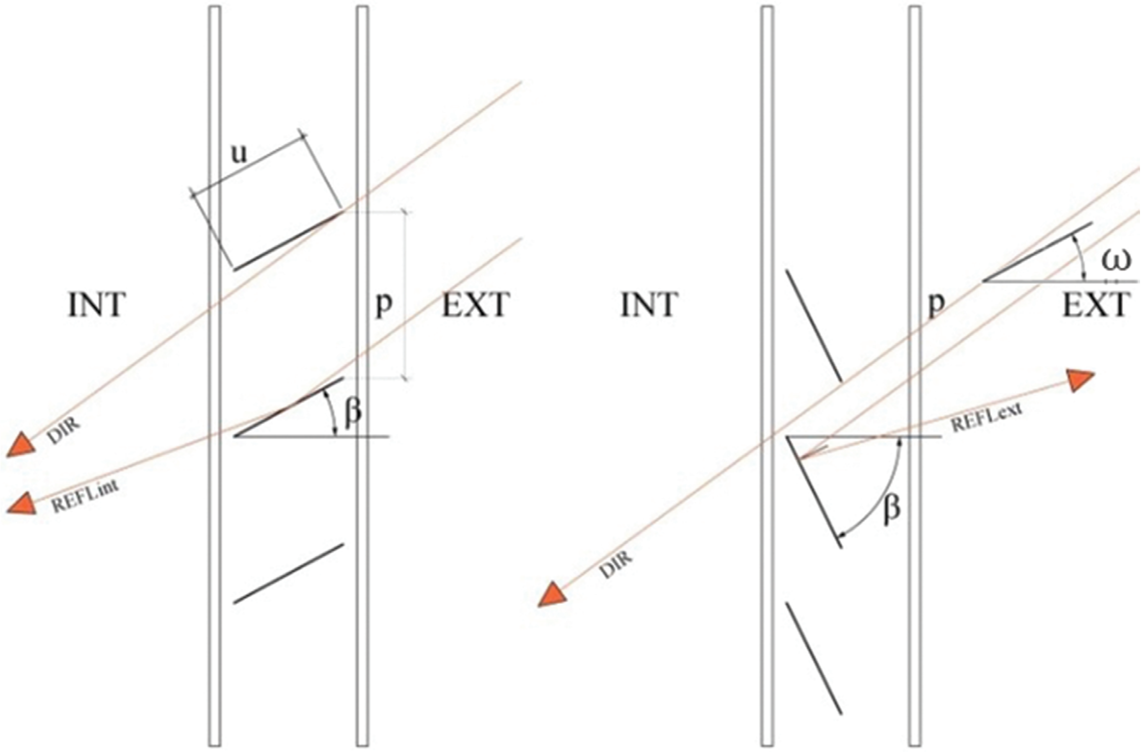
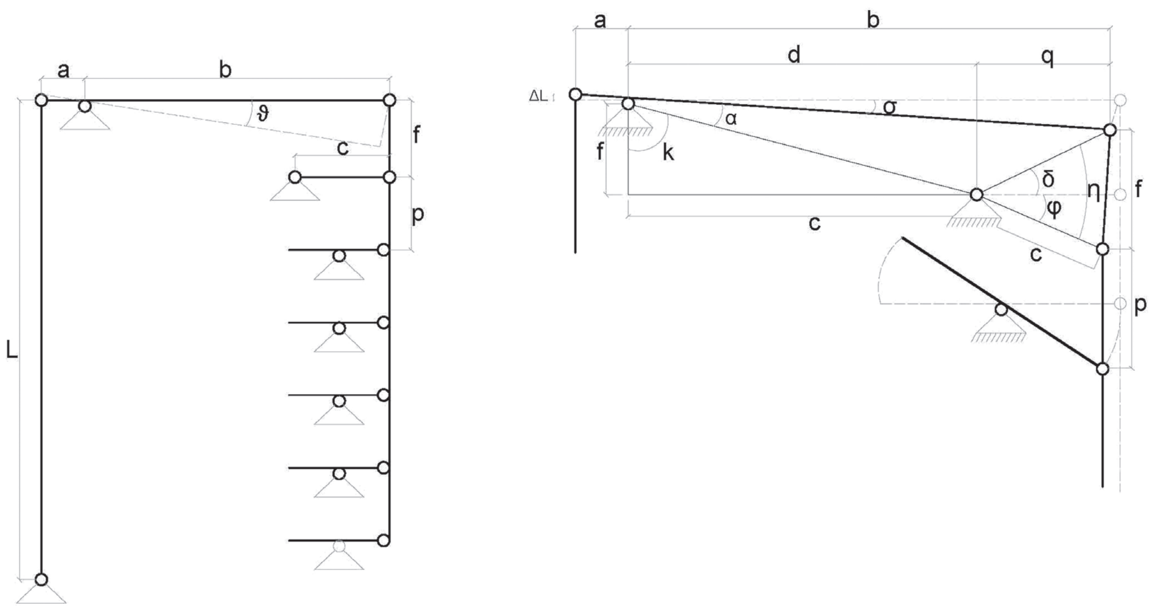


FIGURE 8. Geometric scheme of the working of the passive control mechanism of inclination of the slats.



The mechanism, shown in Figure 8, generates a rotation of the slats of the sunblind by means of the exploitation of the difference in thermal expansion (ΔL) between the steel frame and the dilating elements, consisting of aluminum bars, of a length equal to the frame, with a thickness of about 1 mm, attached to the frame by a hinge (in the lower part).

Their upper part is connected to a first-degree lever, with the fulcrum hinged to the frame and the opposite end connected to a connecting rod that controls the rotation of the slats. The slats are linked by connecting rods which impose the same movement on all of them. The lever amplifies the small deformations (ΔL) due to thermal expansion and by means of the resistance arm (b) and the connection lever (f) rotates the first slat, which in turn, through the connecting rods, transmits the same rotation to all the others.

The kinematic mechanism has been designed in such a way as to transmit to the dilating elements only tensile stresses since these (slender elements) can be subject to instability due to peak load starting from limited compression efforts. Traction is produced by the weight of the slats and by the set of levers that causes their movement.

Il sistema può venire dimensionato in modo tale da minimizzare gli apporti solari nel periodo estivo e massimizzare gli apporti solari nel periodo invernale.

With increasing temperature, the aluminum bar expands by an amount that is almost twice that of the frame (presenting a double thermal expansion coefficient), causing the mechanism to reach a new equilibrium position. In this way a gradual rotation of the slats takes place.

The thermal expansion ΔL is in fact univocally linked to the rotation of the first degree lever (θ) and this is due to the length of the arms of the lever and of the connecting rods, as well to as the pitch and size of the individual slats, to their rotation angle.

The system can be sized to minimize solar contributions in summer and maximize solar contributions in winter.

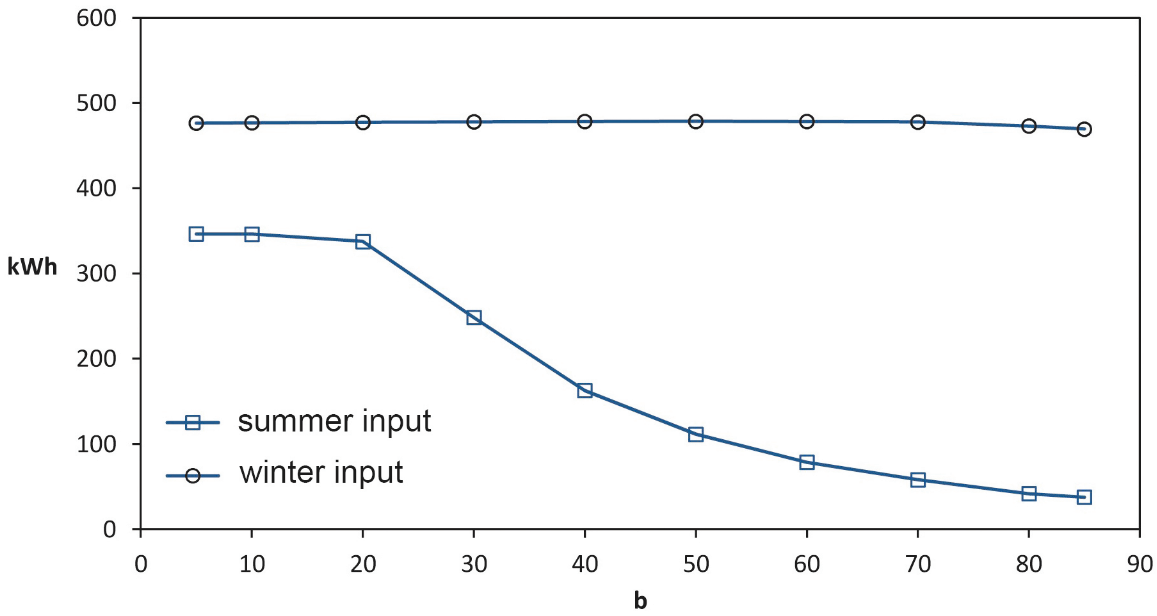
3.2.4 Case study 2 results

In order to define the dimensions of the various parts that make up the mechanism, numerical simulations were carried out. A Visual Basic program was created which, through an iterative procedure, is able to calculate, in the course of the typical year, direct inward solar inputs, components reflected inwards and outwards with variation of the dimensional parameters.

The dimensions of the various parts of the kinematic mechanism can thus be sized on the basis of climate data and constructive considerations for integration into a given façade system. The parameters are all interdependent. In a theoretical simulation for the application to a solar air panel, for example, the following dimensions of the system were determined on the basis of architectural and technological considerations (with reference to Figures 7 and 8): arm-power (a) 6 mm; system connecting lever (c) 8 mm; connecting rod (f) 30 mm; slat pitch (p) 38 mm: slat depth (u) 40 mm. Aluminum slats of type Al_Mg_Si 6060 T6 "Anticorodal" were chosen with a section of 20 × 2 mm and length of 3m. Once these dimensions had been set, it was possible to analyze the behavior of the system by varying only the parameter (b) (resistance arm).

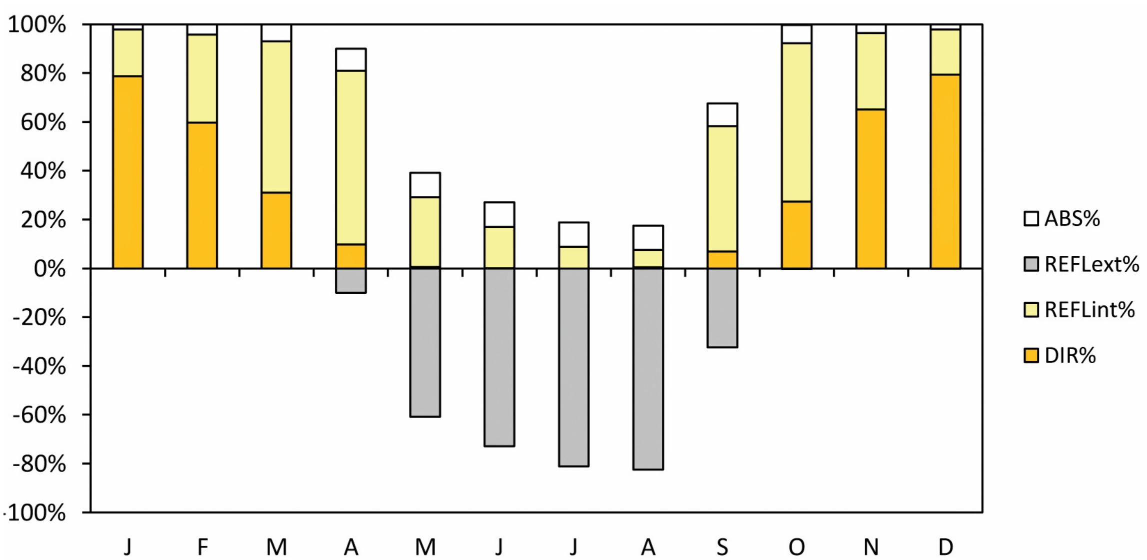
The diagram in Figure 9 shows, in terms of kWh, the amount of passing energy, including the direct and reflected component, during the winter months (from October to March) with variation of this parameter. It can be observed that the trend of the incoming winter solar radiation has an almost regular course, with a maximum recorded for values of b equal to 70 mm. The curve of the incoming summer solar radiation, on the other hand, shows a decreasing trend as the value of b increases. Therefore, a value of b was chosen so as to maximize the winter solar contribution and minimize the entry of summer solar radiation: this value is equal to 70 mm.

FIGURE 9. Incoming solar radiation in summer and winter months with variation of parameter b.



The diagram shown in Figure 10 describes in percentage terms the entity of the incoming and reflected components of solar radiation during the typical year, considering the optimal size of the dimensional parameter b = 70 mm. It can be noted that in the winter months the totality of the solar radiation penetrates through the action of the self-adapting slats while in the summer only a small portion manages to penetrate inside. This percentage of incoming energy is due exclusively to the fraction reflected and absorbed by the slats. The total exclusion of direct radiation through the external "skin" is therefore ensured.

FIGURE 10. Percentages of radiation components in the months of the year (b = 70 mm).



As far as the application to the sunblinds is concerned, selecting the cut-off angle as an operational parameter and using a mechanism similar to that described above for the solar air panels, we can satisfy lighting requirements (brightness level, external visibility and glare). However, this is at the price of excessive overheating in the summer. In order to allow external vision, while intercepting the direct radiation, a considerable amount of reflected radiation is introduced towards the interior. Changing approach, paying more attention to thermal aspects and leaving the user the possibility of installing other internal systems (e.g. a light-colored roller blind) to avoid any winter glare, maximum and minimum temperatures were considered for carrying out normal daily activities in winter and summer. It was observed that for outdoor temperatures below 18°C it is better to orient the sunblind slats similar to the angle of solar incidence, so as to maximize, for the purposes of heating, the direct transmittance. On the other hand, for temperatures above 18C°, in the summer period, it is advisable to tilt the screening elements so as to be orthogonal to the angle of incidence of the solar rays in order to block them, possibly avoiding also reflection towards the interior.

For intermediate situations with respect to those mentioned above, an intermediate adjustment can be hypothesized, counting on the reflection towards the interior in the coldest periods and on a partial shielding in the warmer periods.

Starting from the annual temperature trend, the directly transmitted and reflected radiation fraction was calculated according to the combination of the possible profile angle values (ω) and to the inclination of the slats (β) (see Figure 7). Figure 11 shows the hourly trend of the optimal inclination according to the temperature and profile angle. It is evident that at the value of 18C° the values of the optimal inclination make a "jump" imposed by the conditions mentioned above.

Obviously, this behavior is purely theoretical. Therefore, the least squares of the data were performed to obtain a linear law to approach with the movement system. The result was a straight line (Figure 12) of the equation $O = -2.3221T + 44.1256$ (with O = inclination and T = temperature).

Also, for this application to the sunblinds, we determined in a theoretical simulation the dimensions of the leverage that enabled an approximation to this ideal straight line and which jointly guaranteed an adequate resistance of the elements as well as the correct space of maneuver of the elements. That is, in summary: arm-power (a) 6 mm; connecting rod (f) 40 mm; slat pitch (p) 38 mm: slat depth (u) 40 mm. The aluminum slats were always with a section of 20 × 2 mm and a length of 3m.

However, different resistance arm values were adopted, finally choosing a length of (b) equal to 200 mm, obtaining a good compromise between the need to limit the structural dimensions and guarantee the optimal functioning of the shielding.

Based on a series of experiments carried out at the University of Udine, for the year 2014 the values of temperature, air humidity and wind speed were obtained and could be applied to the actual data. The temperature-inclination association was therefore determined and it was verified that the resulting straight line, with equation $O = -3.4818T + 53.632$ does not differ much from that determined theoretically. The considerations made can therefore be considered correct, at least on a first approximation.

Among other things, it has been verified that the mechanism responds to air temperature, irrespective of the season. Therefore, a considerable percentage of radiation was observed to be externally reflected also in October, which was, in the 2014 test year, a fairly warm month (with average temperatures of 18°C and maximum values of 28°C).

FIGURE 11. Optimal inclination of the sunblind slats according to temperature.

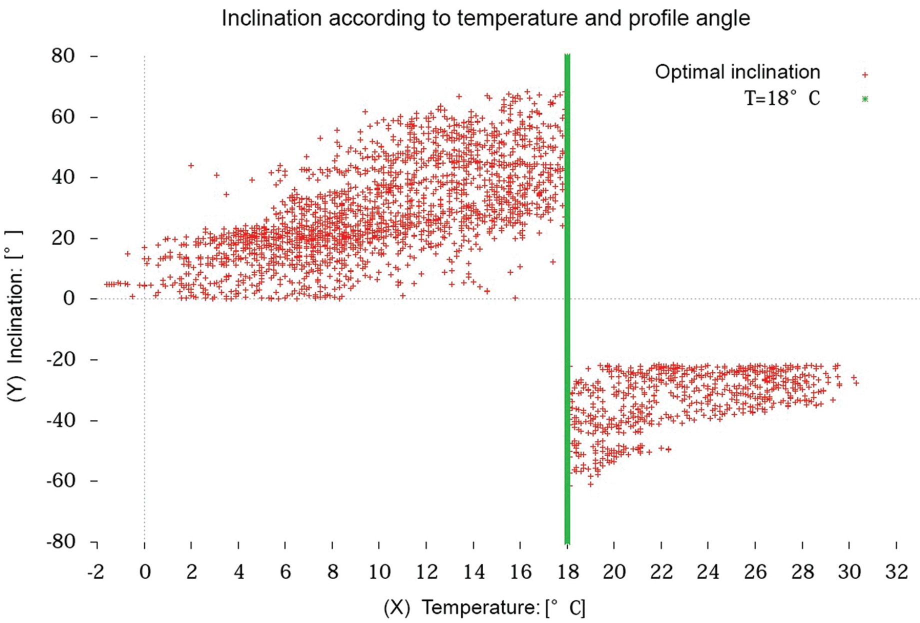
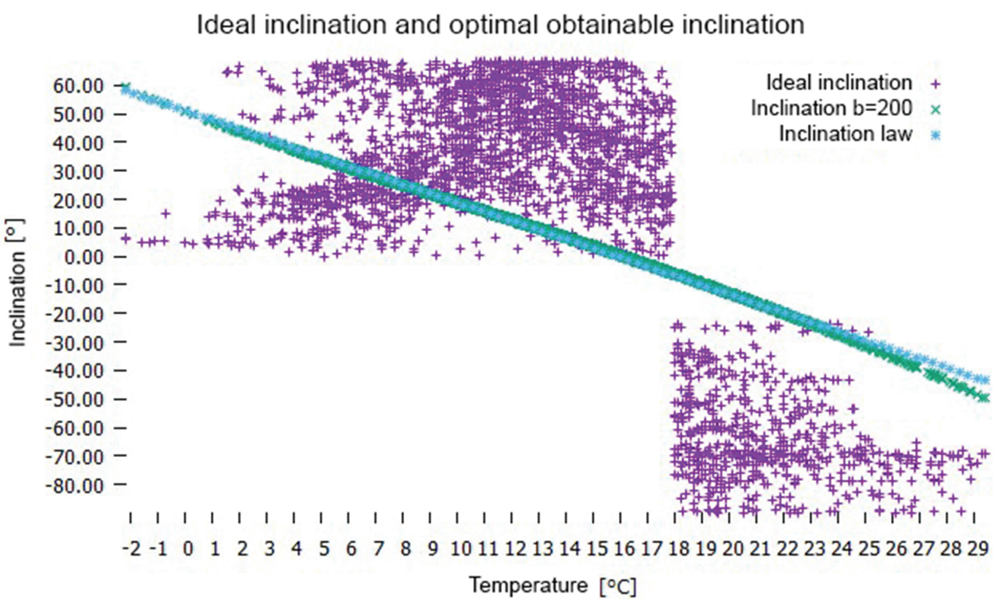


FIGURE 12. Interpolating straight lines, derived from application of the least squares principle to the theoretical distribution of the optimal association between external temperature and slat inclination.



4. POSSIBLE APPLICATIONS

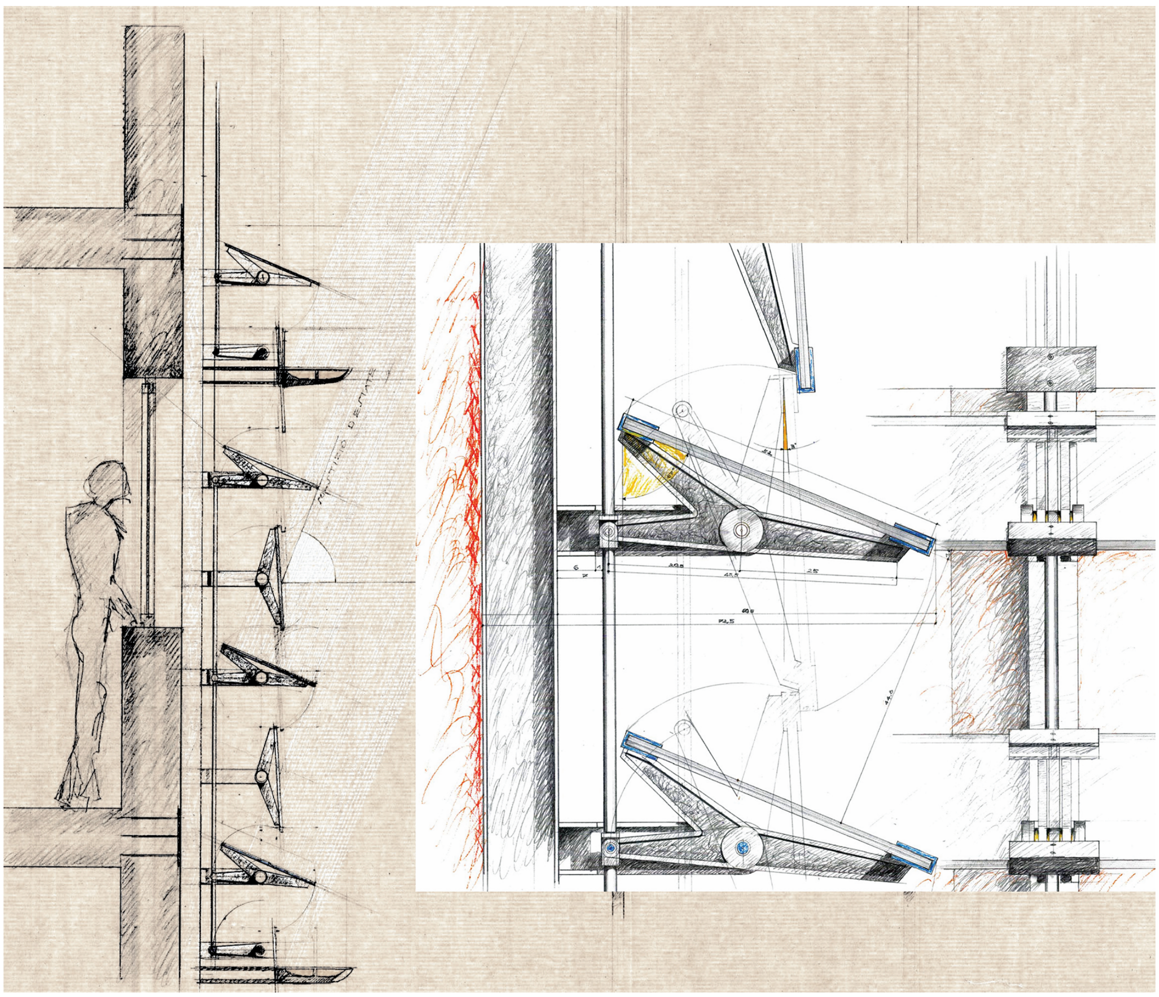
The main field of application of the system is that of "façade systems," including various technological elements such as sunblinds, solar air panels and photovoltaic panels, and air intakes.

The system is built with materials of a limited cost, commonly sold commercially. It should also be taken into account that generally the cost of the external envelope of a building can amount to 15 to 40% of the total cost, while the installed plants make up 30 to 40%. As these two aspects are strictly related to each other, a high-performance façade can bring about significant savings in terms of consumption and operating costs. In some cases, it may enable the installation of smaller-sized systems. Therefore, higher costs of the building envelope may correspond to lower plant system costs.

The basic applications described above may also be revised within the context of more complex technological solutions. The need to ensure the multi-functionality of screening comes from the progressive improvement of architectural envelope systems. It is considered as the main guarantor of internal wellbeing (thermal, visual, acoustic), but also as a fundamental means of characterization of the façades.

In fact, the most recent trends interpret solar shading not only as a passive device, able to protect environments from radiation, but also as an active and dynamic system which can condition the energy balance of the building, also through integration with solar panels.

FIGURE 13. Example of application of the WM system for movement of sunblind elements positioned on a building façade. Diagonal section of a level and elevation of a façade sector, solution with open slats (left). Sections and elevation of the tilting slats. Situation with maximum slats aperture (right).



The benefits to be gained in this case from the installation of mobile screens are:

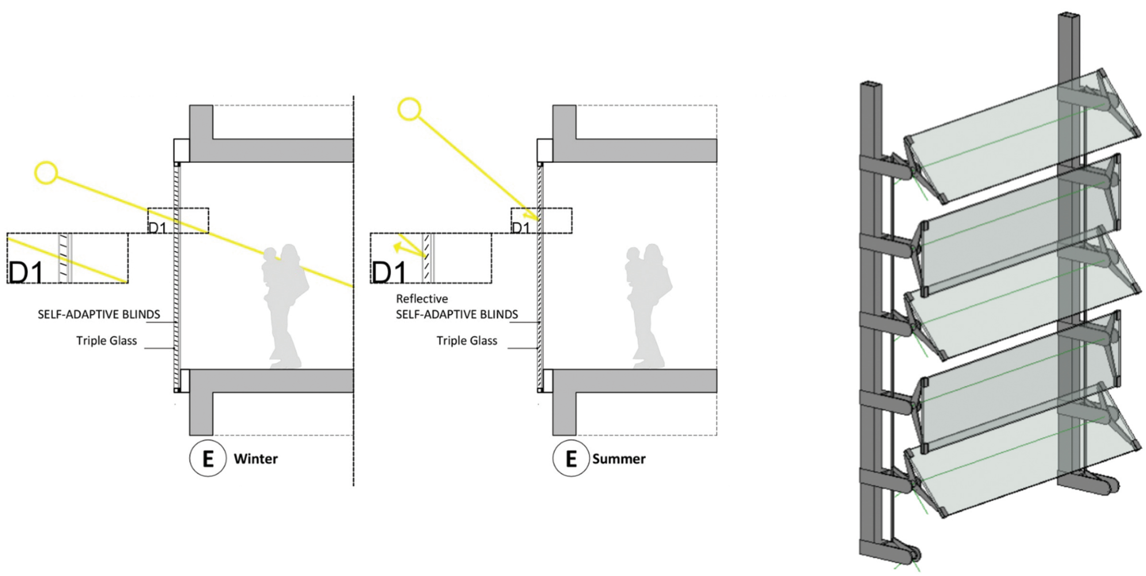
- more efficient collection of solar radiation thanks to adjustable elements able to be positioned approximately in a direction orthogonal to that of incidence of the rays;
- increasing the amount of energy captured thanks to the possibility of adjusting the positioning of the shielding device in relation to the time of day and season;
- ensuring good natural ventilation thanks to the distance between the shielding elements and the space behind.

By way of example, we can imagine façade systems (Figure 14) with fixed and mobile modular elements, transparent, opaque or semi-transparent, in glass or in other materials. The movable screens can be assembled on pivoting supports provided with point or frame connections. The dilating elements can be positioned projecting outwards, in line with the upper or lower level of the windows, or even inside the supporting frames of the structure. The movement multiplication mechanisms and the lever systems suitable for transmitting it to the whole façade can be collected in box-like elements positioned at the extremities of the dilating elements (for example two per floor or two per housing unit).

5. CONCLUSIONS AND POSSIBLE DEVELOPMENTS

The main goal of this research project was the technical-economic feasibility study of an innovative self-adaptive façade system able to orient automatically, without computerized devices or external energy sources (solar panels or solar radiation shielding elements). The proposed study represents the first step of the development process for innovative products currently not available on the market. A preliminary analysis was carried out to estimating the efficiency

FIGURE 14. Example of self-adapting dynamic sunblind system integrated into the façade (left). 3d view (BIM Model) of the WM system for movement of sunblind elements for example positioned on a building façade.



of this proposal. A mathematical model has also been developed to describe and simulate the behavior of the facade system according to the hourly climatic data. The mathematical model takes into account the behavior of all the system's elements. This model was subsequently validated by the experimental results: they show that the mechanisms movements have an almost perfect correspondence with the theoretical data. The possibilities of application to different types of self-adapting façades were assessed and all the theoretical and mechanical elements for the creation of definitive prototypes were defined.

Since the results of the research gave positive feedback, it should now be possible to follow up the experiments by creating prototypes in order to monitor their functioning and to verify and refine the mathematical model. In summary, the possible future developments may therefore be:

- Design, implementation and installation of prototypes in order to refine the behavior with respect to the mathematical model.
- Adoption of a more advanced mathematical model, using programs with finite elements to calculate the coefficients according to the physical-mechanical parameters of the system.
- Optimization of the system in order to increase its overall efficiency also taking into account the effects of the wind.

The research carried out gives ample scope for further investigations and developments with a view to using the system within the context of self-adapting façades or in solar tracking devices. In particular, it will be possible to study: the optimization of the geometry of the dilating elements to maximize the radiative solar contributions, the use of innovative materials with high coefficients of thermal expansion and surface treatments with high solar absorption and low emission, the use of other movement multiplication systems and façade kinematics, and the application of the automation system for ventilation vents for civil, industrial and agricultural buildings.

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