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Interactive Building Structures as Thermal Storage of Solar Energy

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Abstract

Due to the external factors and constant changes as well as the demands of the interior, transparent envelope structures have always been in the focus of research and thus have constantly been tested and subject to various innovations.

Therefore, thermal storage of solar energy in building envelopes by means of phase-change (PCM) materials has been implemented in architectural solutions even more. These materials are substances with latent heat storage, which in the process of melting or solidifying, change their state of matter and release large amounts of energy. These materials are integrated when installing glazing systems, whereas the melting temperature stays within the range by which this process is used for regulating the temperature of the interior thus ensuring the necessary thermal comfort.

Apart from contradictory demands building envelopes are exposed to, when it comes to materialisation (or dematerialisation) of envelope structures, as a result of new trends in shaping and maintaining sustainable development of physical structures, needs arise for new improvements and innovative materials.

This paper discusses advantages of interactive and integrated structures with phase-change materials when compared to conventional methods of materialisation, the principles based on which they function and their characteristics in terms of energy storage and rational energy consumption.

Keywords:	Interactive structures; Integrated glazing systems storing solar energy; Innovative technologies; Phase-change materials

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1. Introduction

Ensuring optimal conditions for the interior aligned with the natural environment and the increasing ecology and energy-efficiency demands are the challenges we have been facing at present. The holistic approach to this problem has resulted in numerous innovative solutions on materialising the envelope structure. This has been especially prevalent when materialising transparent envelope structures. Due to contradictory demands, they represent the most dynamic surfaces, the surfaces introducing, ''changing'' and regulating the flows of energy (e.g. solar energy, heat, sound) and other (inside vs. outside space) interactive demands (water vapour channels, air flow, visual demands etc.) [1].

Dematerialising the envelope structure, the so-called ''skeletionisation'' of massive outer walls reached its peak in the Renaissance and Baroque architecture. Striving for light-filled spaces and allowing architecture and nature to permeate each other put an end to mysticism and was seen as a reflection of the richness of the society and the time of the Renaissance, as well as of the grandeur and glamour of the Baroque era. Light became the key component for defining spatial borders. As new materials were being introduced (e.g. concrete, steel, glass), the needs of the society for new solutions, new constructive dimensions and new aesthetic expressions brought an expansion of transparent structures to architecture and this trend has remained popular until present. For this reason, glass is the essential ingredient in contemporary architecture.

The problems with ''the surplus'' arising after the dematerialisation on the one hand, and the dire consequences of energy-ecology crisis on the other, contributed to the development of all-encompassing and permanent research and innovations to materialise transparent surfaces both when designing them and when offering technological solutions.

Figure 1. Interior: Cordoba, Spain, 785-987 (web)

Figure 2. Crystal Palace, Joseph Paxton, 1851 (web)

Figure 3. A lattice window (mušebak) from the Ottoman period, Sarajevo, Bosnia-Herzegovina

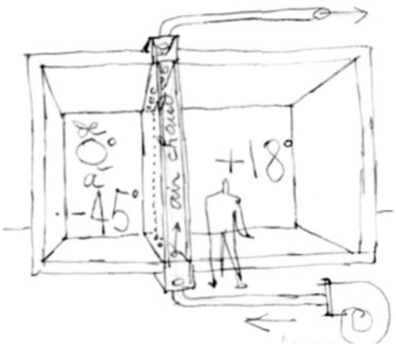


Figure 4. Description of the mur neutralisant by Le Corbusier [2]

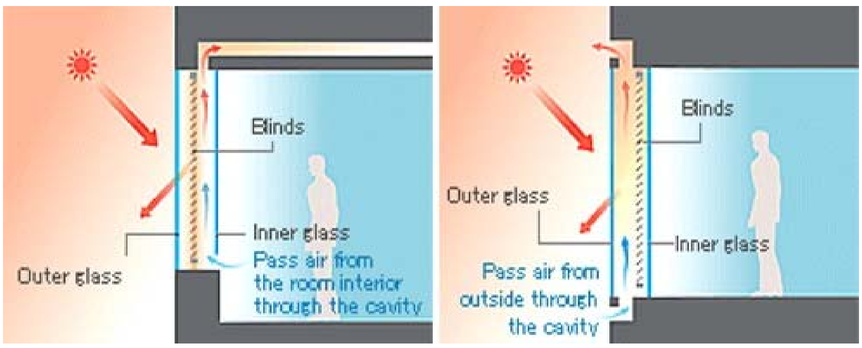


Figure 5. Double layers (web)

2. The course of traditional construction and innovative technologies

What had been for centuries considered an advantage of massive walls has become the major disadvantage of transparent architecture. The comfort of the structure and its climate were at risk, there was too much light and heat, there were losses in energy when it came to both cooling and heating, the acoustics losses, and with the air-conditioned spaces, came the era of the so-called ''sick building syndrome'' (Figure 1 and Figure 2).

Numerous architectural solutions were being sought for the arising problems, such as the sun-protection systems (e.g. blinds, shades etc.), and later, numerous advanced glass-production solutions, thermopane windows and aluminium profiles, thermal bridging, structural and post-structural glass façades etc. Today, we can use transparent envelope structures with a high level of heat, sound and sun protection, low-e multilayer glass systems filled with air or argon gas, or systems from which air has been completely evacuated (i.e. vacuum insulated glass).

What is more, to improve the mechanical features of glass (e.g. brittleness) tempered and enamelled glass were also used. In this way, it was possible to ensure protection from a strike, breakage or fire.

The concept of materialising the ''double façade'' occurred in the last decades of the 20th century. Its roots can be traced back to the principles of traditional masonry and ideas of numerous architects such as Le Corbusier, also known as *mur neutralisant* and *respiration exacte* (the first third of the 20th century). The double membrane with the in-between space that allows the air to circulate naturally is the value ascribed to opening spaces in traditional architecture, which is often aided by mechanical means in contemporary solutions (Figures 3–5).

Apart from ''intelligent'' transparent structures with semi-transparent photovoltaic solar modules (thermochromic, photochromic, electrochromic, liquid crystal glass) whose function is energy management founded on solar energy photothermal conversion of chromic materials or using electrochemical reactions, the transparent envelope structures are now seen as surfaces that may contribute to thermal gains [1].

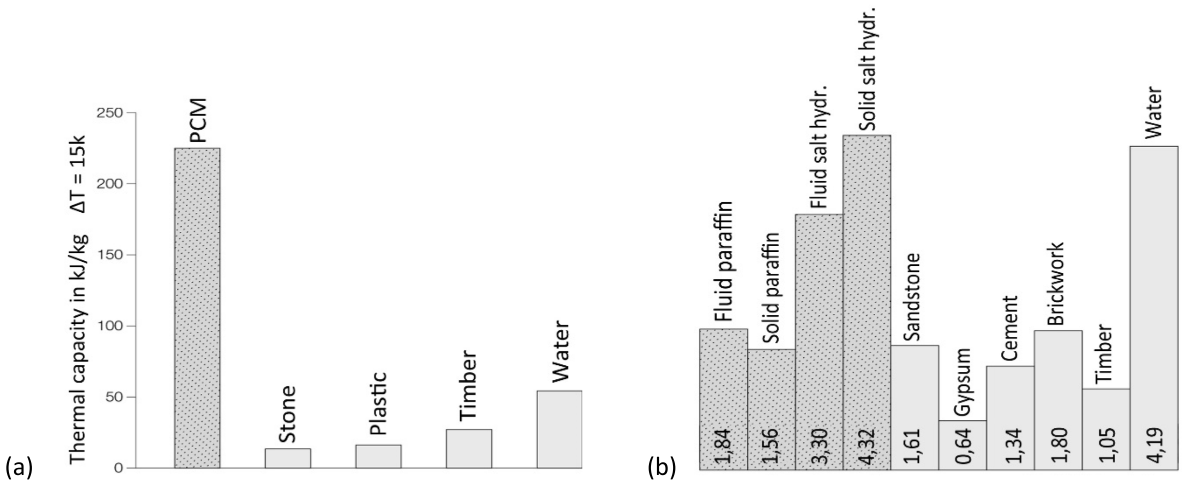
Owing to transparent latent thermal storage capacities (PCM), it is possible to store and emit heat inside a space, which results in stable room temperature. By means of these innovative designs, another function of the transparent structures has been fulfilled. Apart from improving the protection of the structure, the transparent structures act as a medium for energy conversion and storage (heating up and cooling). In this manner, several functional components have been integrated [3].

3. Process of storing solar energy

A traditional method of storing energy was conducted by means of constructing facilities made of solid materials (by means of monolithic architecture or construction). A stable room temperature would be ensured by means of accumulating room temperature during the day, which would then be emitted in late evening hours when the heating was low or turned off. However, the final outcomes found in standard construction materials (wood, stone, brick or concrete), have little significance (Table 1, Graph 1). The thermal storage tolerance is very low. The thermal flux will be transferred within the object in fewer than four hours [6]. This will cause over-heating, the thermal comfort will be disturbed and it will be necessary to activate air-conditioners.

Table 1: Specific heat capacity of some materials. Data based on DIN EN 12524, temperature 20 °C, atmospheric pressure 1 bar

Material	**Density** kg/m3	**Specific heat capacity Cp**, J/(kgK)
Steel	7800	460
Aluminium	2700	880
Concrete	2500	960
Stone	2600–2800	920
Full brick	1800	900
Water	1000	4190



Graph 1. (a) Increased storage capacity through melting enthalpy [5]
(b) Perceptible thermal storage capacity (kJ/L°C) for 1 litre, [5]

The processes of storing and accumulating heat may be conducted in other ways as well. The simplest way is to heat up a certain material stored in a solid or liquid state, which will cause a change in temperature. It is also possible to use latent heat by melting solid materials in the process of changing their state of matter and by means of chemical reactions that allow heat to be released or increased as a result of reversibility.

3.1. Heating up a solid or liquid material

Thermal storage by means of heating up a certain material is founded on the principle that the material stored in a container and having a certain mass and thermal capacity accumulates a certain amount of heat having been exposed to heat which is emitted when the temperature of its surrounding is lower. The amount of the heat stored up by a certain material is expressed as follows:

$$Q = m\, C_{p,v}\ \Delta T \tag{1}$$

where:

Q = the amount of heat (J)

m = mass (kg)

$C_{p,v}$ = specific heat capacity (J/kgK)

ΔT = difference in temperature (K)

The specific heat capacity (Cp – J/kgK) is an important specific feature that is given together with other characteristics of the material. It is defined as the ratio of the heat needed to raise the temperature of a mass (1 kg) of a certain material by 1K while keeping the volume and pressure constant (Table 1) [7]. Apart from heat storage containers containing liquid or solid materials, the so-called Trombe wall as well as rooftop water pools or panels are also used.

3.2. Thermal storage by means of phase–change materials (PCM)

Latent heat storage containers with phase-change materials in the process of changing the matter of state of a certain chemical substance allow for heat to be absorbed or released [8]. The surplus heat is stored when the outside temperature reaches the PCM melting point, which allows for the "cooling" and maintaining optimal thermal conditions inside the structure. For the materialisation of the façade envelope, one can use the PCM materials whose phase transformation ranges from 21°C-27°C, i.e. the temperature necessary for thermal comfort at the interior [9]. The process is reversible if the interior temperature is lower as the accumulated energy is then emitted and the interior heated up.

Based on the state of matter transformations and the phase-change types, there are three kinds of latent heat released:

- In the process of vaporisation i.e. condensation (the transformation of matter from liquid to gas and vice versa);
- In the process of melting or solidification (the transformation of matter from solid to liquid and vice versa);
- In the process of crystallization and re-crystallization (the transformation of the amorphous to the crystalline and vice versa).

Inorganic salts are phase-change materials with relatively high melting points (e.g. combination of sodium nitrate and potassium nitrate (KNO_3, $NaNO_3$), sodium sulphate decahydrate (the so-called Glauber's salt ($Na_2SO_4x10H_2O$). One of the most commonly used thermal storage materials is the so-called Glauber's salt.

New generations of latent thermal storage containers that have proven suitable in construction are produced in the form of granules or water dispersions, e.g.:

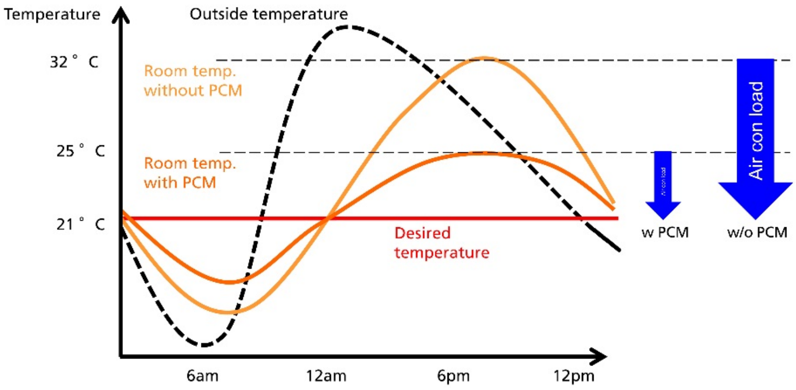
- Inorganic salts hydrates (especially potassium-chloride-hexahydrate ($CaCl_2x6H_2O$) used for thermal storage in the process of materialising transparent envelope structures Cp, J/kgK;
- Organic phase-change materials, the most renowned of which are paraffin wax and various compounds of alkanes (saturated hydrocarbons).

In these materials, the heat accumulation process produces endothermic reactions which dissolve the substance and thus the material is transformed from solid to liquid. The process is reversible, and in the procedure of cooling the surroundings, crystallization occurs and the absorbed energy is released.

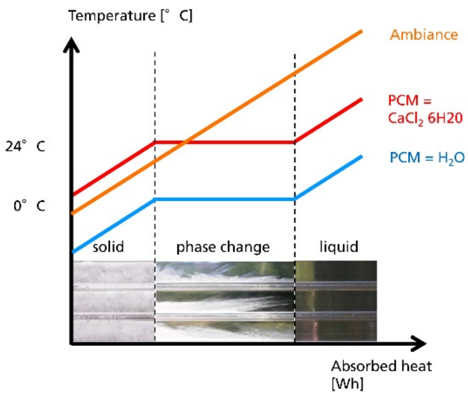
4. Thermodynamic glazing systems with PCM

4.1. Glazing systems with inorganic salts hydrates PCM

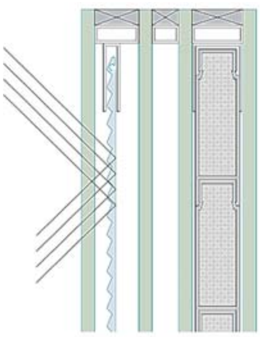
Regardless of the fact that thermal storage capacity when using standard materials is not significant, such an outcome is not found in light or transparent envelope structures. However, far better capacities for thermal storage are achieved in the process of state of matter transformations (Graph 1) when using multilayered glazing systems with integrated phase-change materials (inorganic salts hydrates, Cp – 432 J/kgK) [9].



Graph 2. Temperature oscillations with and without PCM glazing Components (with PCM glazing components reduce necessary cooling power) [6]



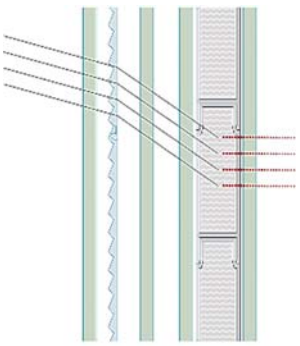
Graph 3: PCM-integrated (potassium-chloride-hexahydrate) glazing systems [6]



Principle:

In summer, when the angle of incidence is greater than 40°, the reflective layer integrated in the first package of the thermopane reflects the sun rays. Measurements: **23-27°C** on the surface for **14-30°C** of the surroundings.
Solar transmittance (g) stays within the range of 6-9%, the PCM components are used as a medium for accumulating solar energy while not allowing the interior to overheat.
U = 0.48 W/m^2K;

PCM façade with salt hydrate in Dmat-Ems, Architect: Dietrich Schwarz, Zurich, 2004



In winter, when the angle of incidence is lower than 35°, the reflective layer integrated in the first package of the thermopane does not reflect the sun rays.
Measurements: **23-35°C** on the surface for **-8 to 4°C** of the surroundings.
Solar transmittance (g) stays within the range of 33-35% which allows for significant solar heat gains accumulated via PCM and emitted towards the interior.
U = 0.48 W/m^2K.

School, Fribourg, Switzerland
Architect: Butikofer de Oliveira Vernay Sarl, 2010

Figure 6. PCM glazing principles and referential structures [10]

By applying phase-change materials in architecture and by integrating them in glazing systems, the oscillations of the outside temperature are neutralised through the process of PCM state of matter transformations. Melting hinders or prevents the temperature from rising above the melting point (18°C–28°C), whereas crystallization prevents the temperature from dropping. During this process, the temperature of the matter remains unchanged (Graph 2 and Graph 3).

By maintaining constant temperature of the interior (thermal comfort), the energy needed to heat or cool a structure is reduced and, at the same time, the harmful gas emissions affecting the natural surroundings. Glazing systems with phase-change materials (potassium – chloride – hexahydrate ($CaCl_2$ * $6H_2O$) hermetically stored in transparent polycarbonate containers and resistant molten glass will reach U = 1.2 W/m^2K and U = 0.48 W/m^2K. The melting temperature remains within 26–28°C. Latent thermal storage containers introduce balance to daily and annual oscillations in temperature, let through the visible part of the spectrum and accumulate the infrared spectrum (Figure 6).

In the process, the translucent model becomes a multifunctional transparent structure that may be implemented when materialising structures of various purposes since, apart from allowing the visible part of the spectrum to go through, high thermal protection, as well as overheat protection is ensured as heat is simultaneously being transformed and stored (Figure 6). The thermal capacity of a PCM (a substance of potassium-chloride-hexahydrate) transparent module is an equivalent of a 25 cm-thick concrete wall, which is the reason why annual expenses for heating and cooling may be reduced [10].

Phase-change materials made of inorganic salts hold a high specific heat capacity, and are, due to their great density, able to store large amounts of energy, their state of matter phases are clearly defined, their thermal transmittance compared to other phase-change materials is greater, they are neither flammable nor toxic and are quite affordable as they are produced without much effort.

4.2. Glazing systems with paraffin wax PCM

The adaptable concept of the "Schüco 2" façade [11] is founded on practical, mobile and multifunctional ''envelopes'' inspired by ''onion layers''. Apart from the transparent module (the triple low-e layer), the aluminium micro-lamels, the non-transparent solar photovoltaic module, the adaptable façade also consists of the non-transparent module with a phase-change-materials-filled honeycomb structure (Figure 7).

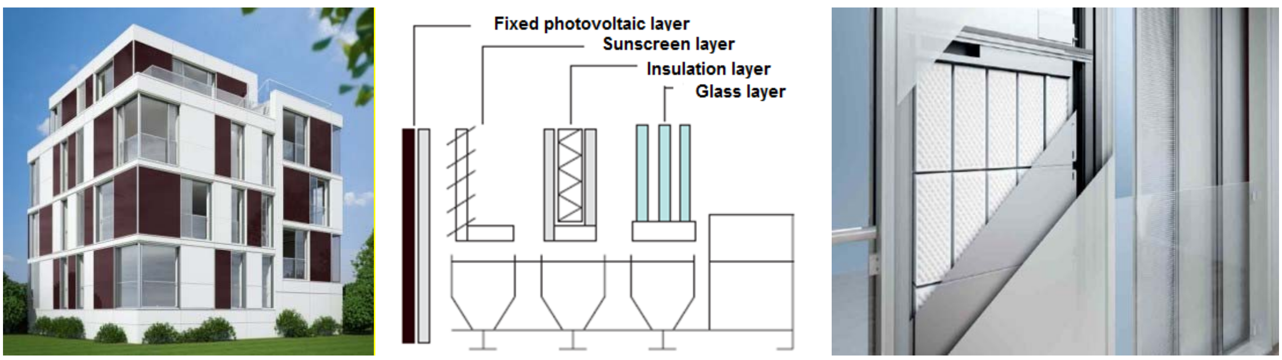
The latent heat storage containers are made of paraffin wax micro-capsules integrated in the acryl glass panels (Figure 7b). The modules are interactive, they interchange and adapt to the user's needs and according to weather conditions (hot-cold, day-night, an extremely cold winter day-an extremely hot summer day, open views-privacy). At the same time, extreme outside conditions are being used in an efficient way.

These systems are highly sophisticated adaptable systems with modern design, aesthetic qualities and dynamic thermal characteristics and varying U values. Mobile isolation panels integrate thermal isolation, the heating and cooling system, as well as the decentralised building ventilation system releasing heat. At night, these systems enhance thermal isolation and offer safety and privacy [12].

The future of such phase-change materials depends on the fulfilment of the demands regarding the specific heat capacity, a greater thermal transmittance, a better transmittance of heat by means of radiation, as well as the intervals and stability of state of matter transformation values which should remain within the range of 21-27°C. What is more, the PCM need to be compatible with other conventional materials, have a certain stable solidity, be corrosion and fire-resistant, eco-friendly, as well as easy to integrate and, at the same time, affordable.

5. Conclusion

Sustainable construction, energy-saving costs and decreasing fossil-fuels dependence are all urgent tasks that the world of today has to address. The necessary awareness and the treatment of a facility as a system of energy which exchanges its energy and matter with its surroundings are the factors that have resulted in numerous innovative solutions, designs and technologies that allow the materialisation of the envelope structure. The principle of neutralizing energy flows and the dichotomy of the interior and the exterior,



(a) (b)

Figure 7. Residential building; Paul Sindram, Schleswig, Germany, 2010 [13]
(a) Modules (b) PCM module implemented in the adaptable façade design

as well as the possibility of keeping the interior temperature constant, has been reinforced by technological advancement, the concepts of multiple layers, and the concepts of multi-functionality and interactivity of envelope structures acting as ''thermal layers''. By implementing phase-change materials integrated into transparent envelope structures, it is possible to store and conserve heat in more efficient ways than by using conventional construction materials.

By means of successfully facing the demands of thermal storage, transparent envelope structures are no longer perceived as ''weak'' panels, but act as massive yet transparent (translucent) walls. As such, they act as specifically structured multilayered membranes interacting with light and the natural surroundings, which is how they ensure that the interior feels comfortable, naturally lit and ventilated. In this way, the solar energy is controlled or turned into electric energy, used for cooling the facility or storing energy. These processes have been possible owing to constant improvement in production, technology, technological solutions and designs, as well as owing to the very processes of glazing and the components or materials integrated in the in-between spaces.

References

[1] Salihbegović, A., Transparentne ogradne površine i savremeni sistemi prirodnog osvjetljenja /Transparent Envelopes and Contemporary Natural Lighting Systems/, Master's Thesis, University of Sarajevo, Faculty of Architecture, Sarajevo, Bosnia and Herzegovina, 2004.

[2] Ramírez-Balas, C., Suárez, R. , Sendra ,J. J. – Future technologies in Le Corbusier's environmental conditioning systems, PLEA2013 – 29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany, 2013.

[3] GLASSXcrystal – The glass that stores, heats and cools / GLASSX AG, http://glassx.ch/fileadmin/_migrated/content_uploads/GLASSX_AG__products_e.pdf

[4] Knaack, U., Klein, T., Bilow, M., Auer, T., Façades – Principles of Construction, Birkhäuser Verlag AG, Basel-Boston-Berlin, 2014, pp. 130–131.

[5] Kaltenbach, F., PCM Latent Thermal-Storage Media – Heating and Cooling without Energy Consumption?, DETAIL 6 (2005), Solar Architecture, pp. 660–665, ISSN 0011-9571.

[6] GLASSX – Glazing with Phase-change Material / GLASSX AG, http://glassx.ch/fileadmin/_migrated/content_uploads/2013_GLASSX_en_ISO.pdf

[7] Keindl, R., Energetika i graditeljstvo: Nove generacije toplinsko izolacijskih materijala /Energetics and Construction: A New Generation of Thermal Insulation Materials/, Professional Training of Certified Engineers & Architects, Course 10, Zagreb Polytechnic College, 2011.

[8] Klein, T., Knaack, U., The future envelope 2: Architecture – Climate – Skin, IOS Press – Delft University Press, Amsterdam, 2010, pp. 48–49.

[9] Kurajica, S., Fazno promjenljivi materijali /Phase-change Materials/, Tehnoeko, 4, (2007), pp. 18–21.

[10] GlassX – Thermodynamic Glazing system / GLASSX AG, http://glassxpcm.com/cms/wp-content/themes/glassx/pdfs/GlassX-Brochure-Web.pdf

[11] Hindrichs, Dirk U., Heusler, W., Façades – Building Envelopes for the 21st Centry, Birkhäuser Verlag AG, Basel-Boston-Berlin, 2010, pp. 15–20.

[12] Salihbegović, A., Adaptibilne ogradne strukture objekta /Adaptive Building Envelopes/, IXth international scientific congress, Non-metallic and inorganic materials, Zenica, Bosnia and Herzegovina, 2012.

[13] Concept 2 – Adaptive Building Envelopes/ Schüco International, KG, http://www.youblisher.com/p/389143-Schueco-Concept-2/