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Building envelopes

Authors:

Assist.Prof. **Silvio Bašić**, PhD. CE
University of Zagreb
Faculty of Civil Engineering
sbasic@grad.hr

Assist.Prof. **Nikolina Vezilić Strmo**, PhD. CE
University of Zagreb
Faculty of Civil Engineering
nvezilic@grad.hr

Saša Marjanović, MCE
sasa.marjanovic@student.grad.h

Subject review

Silvio Bašić, Nikolina Vezilić Strmo, Saša Marjanović

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Buildings exert a considerable influence not only on outside environment, but also on human health, comfort, and productivity. In this interaction, the greatest role is assumed by the building envelope that acts as a filter permitting favourable external influences to enter the building, while rejecting or modifying unfavourable influences. All loads and functions to be assumed by the envelope arise from three significant components and their interactions: external environment, internal environment, and the envelope itself. An objective of modern construction activity is to approach the building envelope issue in a multidisciplinary and integral manner, so as to avoid potential problems while at the same time meeting human needs in an adequate way, at the lowest possible cost.

Key words:
building envelope, external environment, internal environment, construction

Pregledni rad

Silvio Bašić, Nikolina Vezilić Strmo, Saša Marjanović

Ovojnice zgrada

Zgrade značajno utječu na vanjski okoliš, ali i na ljudsko zdravlje, udobnost i produktivnost. U navedenoj interakciji najveću ulogu ima ovojnica zgrade koja djeluje kao filtar koji poželjne utjecaje iz vanjskog okoliša propušta u unutrašnjost, a nepoželjne odbija ili mijenja. Sva opterećenja koja ovojnica mora podnijeti i sve funkcije koje mora zadovoljiti proizlaze iz tri bitne komponente i njihova međuodnosa: vanjskog okoliša, unutarnjeg okoliša i same ovojnice. Cilj je suvremene gradnje pristupiti pitanju ovojnice zgrade multidisciplinarno i integralno kako bi se potencijalni problemi izbjegli, a ljudske potrebe kvalitetno zadovoljile uz što manje financijske troškove.

Ključne riječi:
ovojnica zgrade, vanjski okoliš, unutarnji okoliš, gradnja

Übersichtsarbeit

Silvio Bašić, Nikolina Vezilić Strmo, Saša Marjanović

Gebäudehüllen

Gebäude haben erhebliche Auswirkungen auf die Außenumgebung, aber auch auf die Gesundheit, den Komfort und die Produktivität von Menschen. Eine enorme Rolle spielt dabei die Gebäudehülle, die als Filter die gewünschten Einflüsse aus der Außenumgebung in den Innenraum ableitet und die unerwünschten Einflüsse abweist oder verändert. Alle Lasten, die die Hülle tragen muss, und alle Funktionen, die sie erfüllen muss, ergeben sich aus drei wesentlichen Komponenten und ihren Wechselbeziehungen: der äußeren Umgebung, der inneren Umgebung und der Hülle selbst. Ziel des modernen Bauens ist es, auf die Gebäudehülle multidisziplinär und ganzheitlich einzugehen, um potenzielle Probleme zu vermeiden und die Bedürfnisse der Menschen qualitativ mit möglichst geringem finanziellem Aufwand.

Schlüsselwörter:
Gebäudehülle, Außenumgebung, Innenumgebung, Bau

1. Introduction

Although buildings have a significant impact on the external environment by consuming energy, resources and emissions, hey are also responsible for creating desirable conditions for human health, comfort, and productivity. According to statistics for Croatia [1], energy consumption in construction sector amounts to 48.1 % of the total consumption, followed by traffic with 35.1 %, and industry with 16.8 %. Households represent 62.8 % of the consumption in the construction sector, with most of that energy being spent on heating (Figure 1). When looking at the energy balance of a family home with natural ventilation (Figure 2), it can be seen that the largest part of the energy lost, or as much as 88 %, relates to transmission and ventilation losses through the building envelope, and to losses of the heating system itself, 12 % [2]. Apart from the energy consumption, which has financial implications, the impact of indoor conditions on the health and comfort of people is also very important, especially as people are known to spend 80 % of their time indoors [3].

In this interaction between the external and internal environment, an enormous role is assumed by the building envelope, which acts as a filter that leaks the desired influences into the interior, and repels or changes the undesirable ones. At the same time, the envelope protects other building systems (load-bearing structure, installations, interior areas, etc.) and, in cooperation with them, provides a safe and comfortable environment for the users of the building. Also, visible parts of the envelope (facade) combine two, often contradictory, features - aesthetic characteristics and functional / physical properties of the building [4]. Design of an envelope is a very complex task where several factors need to be considered in order to strike a balance between the level of desired properties and financial cost.

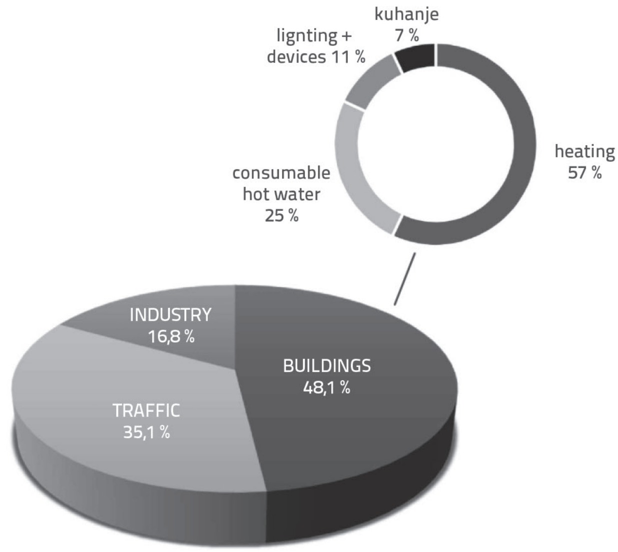

Figure 1. Energy consumption in Croatia in 2013

The envelope itself contains many subsystems composed of numerous components. Each part of the envelope is a three-

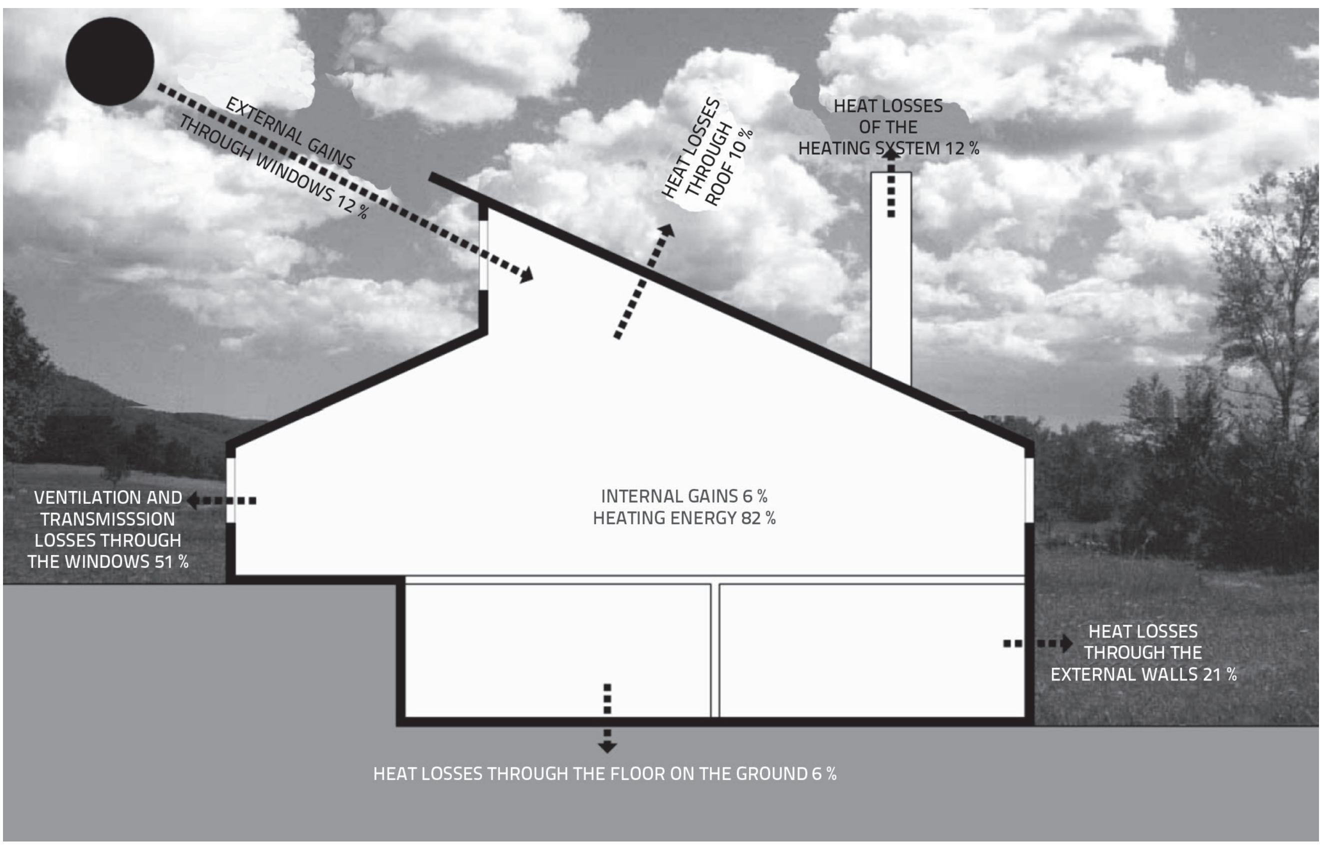

Figure 2. Building energy balance

dimensional, multi-layered assembly of different materials, from the material at the extreme inner face to the material at the outer face of the envelope. Since the envelope represents any part of the building that physically separates the exterior from the interior, the above-ground and underground sections of the envelope can be distinguished (Figure 3). The envelope systems can be divided into:

- Ground floor systems
- External underground wall systems,
- External overhead wall systems including windows and doors,
- Roof systems.

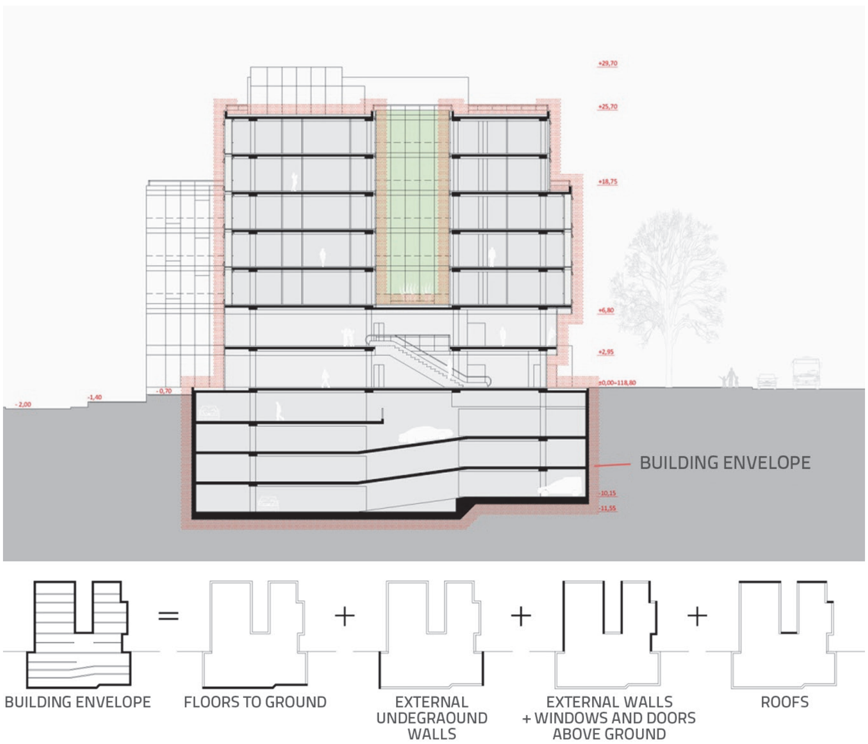

Figure 3. Building envelope

2. Historical development of building envelope

People's needs and demands have grown throughout history, in parallel with the development of society, and buildings have become not only shelters protecting people from natural disasters and enemies, but "containers" for a range of complex activities. Humans need protection from wind, dust, precipitation and, to some extent, from temperature variations, humidity, and air flow, to make them comfortable. They also need security, privacy, noise protection, and a certain level of light, as well as an adequate space for cooking, sleeping, hygiene, and other activities. The main reason for the existence of buildings is to provide adequate space to meet these needs, which is achieved by the envelope as a physical barrier, and by the use of energy [5].

Traditional construction depended on the available resources and technology and on the weather conditions that prevailed in the area (Figure 4). In Europe, for instance, traditional construction is characterized by massive construction, i.e. a thick building envelope, which was the best solution for many reasons: better load carrying capacity to carry roof weight and various loads (such as snow), but also, in terms of energy, heat accumulation in winter, and protection against overheating in summer. In addition, the envelope had good acoustic as well as safety properties due to its large wall thickness and small aperture dimensions. Apart from the plastic processing of the envelope, the shaping of the volume of the building as a whole, and the building material used, it is precisely on this relation of the wall and the opening that the basic stylistic features of the historical periods were founded. In times when there were no suitable technical solutions, openings were treated as weak points of the envelope [6] and their number and size were minimized. As of the moment the importance of designing the envelope as a load bearing (massive) wall changed - using different structural principles, while developing glass manufacturing and window glass installation techniques - the requirements for an increasing proportion of glazed envelope surfaces were increasing. However, these requirements were limited to buildings representative of a particular period (Figure 5).

Figure 4. Traditional shelters

Figure 5. Altes museum, 1830; Neue Nationalgalerie, 1968. (Berlin)

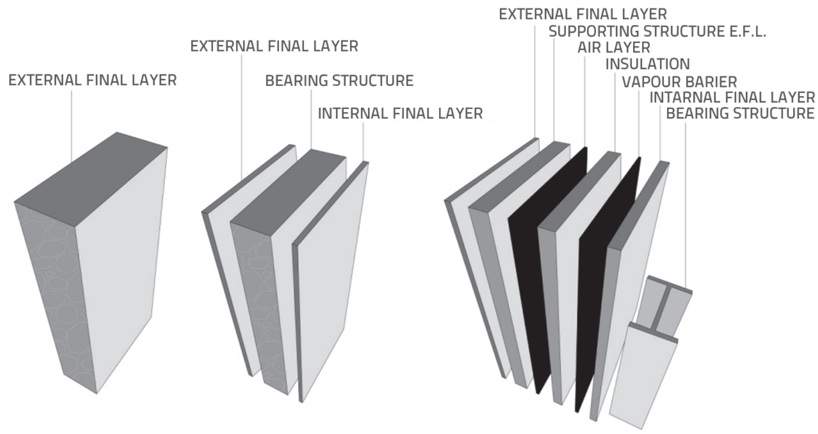

Figure 6. Historical development of the wall

In short, traditional construction is characterized by a single-layer envelope, i.e. a single material that meets all the functions expected of the envelope. Gradually, inner and outer finishes were added to this layer, but their role was primarily aesthetic (Figure 6). It was only with the advent of Industrial Revolution and the introduction of new building materials enabling use of various types of load-bearing structures that the era of contemporary design of building envelopes has began. By abandoning traditional construction and adopting new materials and construction techniques without considering possible consequences, in the second half of 20th century several problems arose in the role of the envelope as a physical control of external influences. There was also an increased need for energy to regulate these impacts. Unlike the building technique used so far, which relied on the experience and skill of the builder, as well as traditionally proven forms of buildings, the newly created situation imposed the need for laws, norms and standards, i.e. for science-based knowledge about desirable properties of interior space (light, climate, etc.).

3. Impacts on envelope

All the effects that the envelope must endure and all the functions it must satisfy come from three essential components and their interrelationships: the external environment, the internal environment, and the envelope itself.

Impacts are events, phenomena, or characteristics affecting the envelope that are associated with gravity, soil, heat, moisture, or air [7]. A distinction can be made between the effects arising from the external or internal environment. In the constant interaction of the envelope with the external and internal environment, the influences are not constant but vary depending on external conditions, as well as on the processes taking place inside the building. The variation may be at day / night intervals, working / non-working days, weekly, seasonal, etc.

3.1. Impacts from external environment

Impacts from external environment are a consequence of climate, nature and its phenomena, and man and his actions (Figure 7). Since external environment is a three-dimensional space with variable mass and energy properties, it is necessary to know average and extreme values of each impact for design. Climate impact values can be obtained from meteorological station data, but the influence of external microclimates is also very important, especially for smaller buildings where this influence is more felt. Different parts of the building envelope are exposed to different external microclimates, such as the influence of adjacent buildings, landscapes, etc.

3.2. Impacts from internal environment

Indoor environments are inhabited, used and very often air-conditioned spaces. These spaces have the function of meeting the various human physical needs that require certain conditions. The conditions are defined by temperature, relative humidity, number of air changes, air quality, etc. Also, the internal environment may be conditioned by certain equipment or occupancy (archives, swimming pools, ice skating rinks, etc.). There may be several indoor environments within each building with different desirable conditions. Inside environments include partitions that must also meet certain requirements, but much less strict compared to those for the building's outer shell.

4. Properties and functions of envelope

Functional requirements that the envelope has to satisfy change with the development of society. In addition to the function of protection against natural disasters and physical protection of

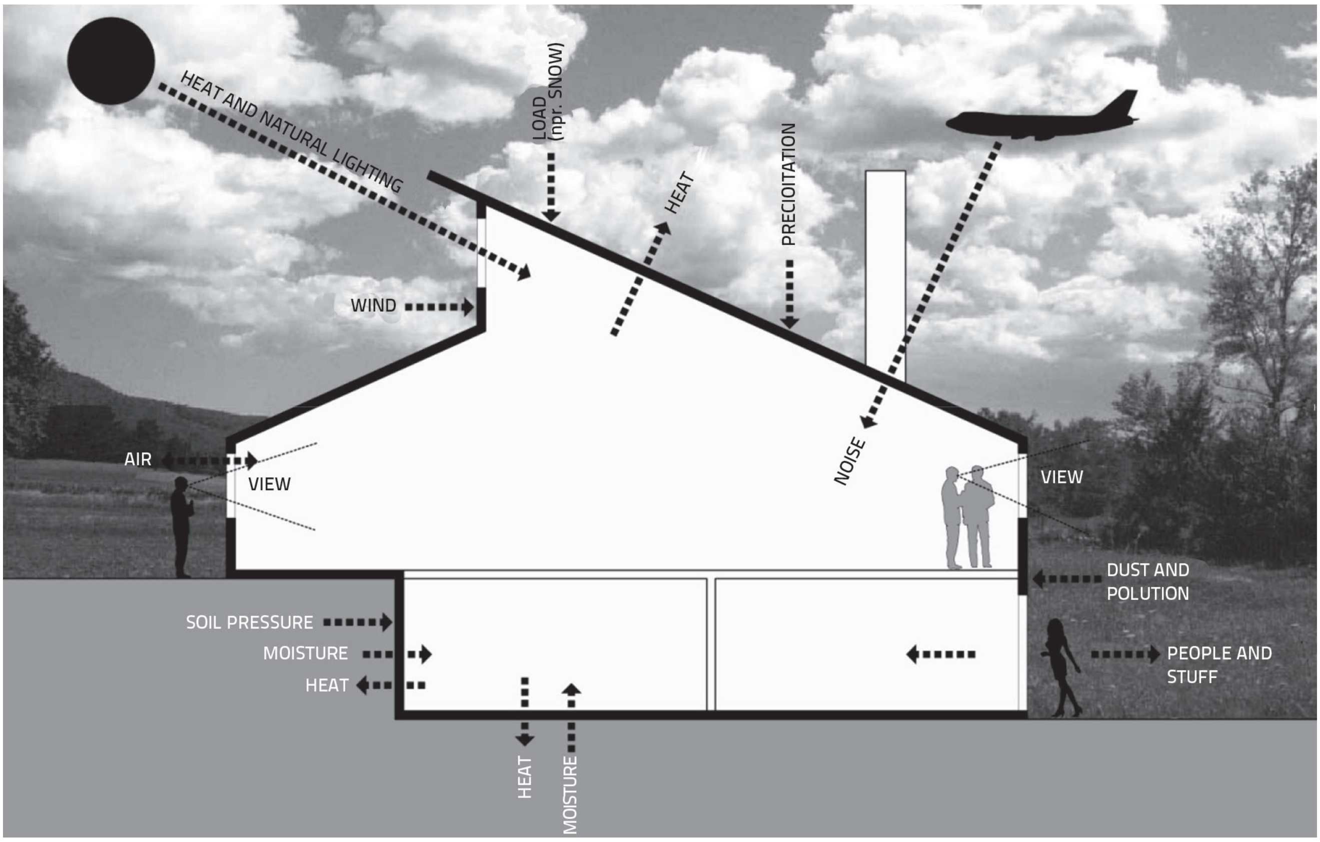

Figure 7. Impact of external environment on building envelope

users, today a far greater number of requests can be distinguished. The application of new technical solutions also causes a change in the aesthetic experience of architecture, which in many respects approaches the sculptural design of buildings and separates further away from the experience of architecture through the relationship between the wall and opening. This approach to envelope design opens up new areas of research arising from the new requirements that are placed before the envelope, and research often goes beyond the reach of individual professions and requires teamwork and close collaboration between different professions. The properties and complexity of today's envelopes can be simplified by a list of functional requirements [8]:

1. Load-bearing capacity: to ensure that the non-bearing wall carries its own weight, and that horizontal loads are transferred to the load-bearing structure.
2. Light transmission: to ensure that the interior space is illuminated in accordance with its purpose.
3. Water tightness: to prevent water penetration.
4. Airtightness: to prevent air penetration.
5. Vapor permeability: to prevent condensation on the interior surfaces when using the space.
6. Stability: to ensure that the envelope adapts to deformations caused by drying, humidification, seasonal or daily changes in temperature and earthquake.
7. Thermal protection: to reduce heat losses that can be caused by radiation, convection and conduction.
8. Noise protection: to prevent transmission of noise (sound).
9. Fire protection: to ensure prescribed fire resistance.
10. Security: to ensure physical protection of users.
11. Maintenance: to ensure easy maintenance, repair, and replacement of worn parts.
12. Feasibility: to ensure construction using available components and achievable technologies.
13. Durability: to provide functional and aesthetic properties over time.
14. Aesthetics: to meet aesthetic requirements.
15. Cost-effective: to ensure that the above requirements are met within the total investment budget.

For each of the above functional requirements, the finished envelope must meet the desired level (or standard) of quality foreseen by the design. These envelope properties can be grouped into four basic function categories [7]:

1. Bearing Function: Resist and transmit physical forces externally and internally, such as lateral forces (wind and earthquake), gravity (constant load, snow), rheological functions (temperature, humidity), shock, wear / abrasion. The capacity of the envelope is therefore its ability to withstand loads that may be permanent and / or mobile, and these should be taken into account at the design stage.

Figure 8. Damage to the envelope as a result of poor control of heat and moisture transfer

2. Control function: manage the mass and flow of energy, i.e. heat, air, humidity, rain, sound, fire, insects, access, etc. This category includes requirements related to climate control affecting the building, as well as the control of the safety of users. In terms of control, the envelope functions as a "building skin" in two ways: it completely blocks certain climatic influences (water, pollution, etc.) while enabling passage of other influences (light, air, heat, sound, etc.) in a controlled manner depending on the needs, desires, and habits of the users. Climate control is primarily aimed at achieving the physical characteristics of the envelope (thermal insulation, vapour permeability, airtightness, sound insulation, etc.) and, if this is not sufficient, desired conditions within the building are achieved by means of appropriate energy resources (lighting, heating, cooling, ventilation, etc.). Both methods of control are important, but it should be emphasized that control by physical characteristics is much less costly, more reliable and efficient and, if the envelope is poorly designed and does not assume its controlling role, deficiencies can not in some cases be compensated for by the use of energy. Therefore, in order to obtain the most efficient and cost-effective building, with as few drawbacks and repairs as possible, it is important to maximize the function of the envelope as a physical barrier, and further limit smaller deviations from the desired conditions by regulating the use of energy.

Security control, i.e. the security function of the envelope, is one of the first reasons why people initially built shelters. Although we no longer need protection from predators and enemy tribes, the envelope's role in protecting against burglars and unauthorized intrusions is very important. People spend large amounts of money to feel safe. As with climate control, safety is primarily achieved through physical characteristics of the envelope, but also through the use of energy, i.e. by applying various sophisticated electrical and electronic systems. Therefore, it is necessary to use materials that have the strength appropriate to the desired level of safety, which is of course related to the very purpose of a particular building. In addition, it is important to take into account elements that are installed in walls and roofs, such as windows and doors, as these are the most common points of intrusion. However, when designing, the most important thing is to keep in mind to reduce the number of intrusion points and hidden views that allow burglars to realize their intent.

3. Aesthetic function: to meet aesthetic requirements for internal and external visible surfaces (colour, texture, reflection, pattern). This group refers to the layer (s) of the envelope that are in direct contact with the external and internal environment. It is important to anticipate the impact of the passage of time on the above layers in order to maintain the aesthetic experience that the designer envisioned. Materials change in different ways, depending on their natural and surface characteristics. For instance, porous materials, such as brick or stone, accumulate dirt and enable organic growth on the surface, while internal chemical reactions can occur in impermeable materials such as metal or plastic. Designers must be aware of these changes when selecting materials and correct details depending on the type of material. Certain changes cannot be completely eliminated, but they can be predicted and controlled - for example by correctly selecting the colour or texture of the surface, but also by the shape of the building that allows for controlled runoff from the facade.

4. Distribution function: to protect and accommodate building services such as electricity, communication, installations, air ducts, gas pipes, roof drains, etc. Also today, the question of using an envelope (in whole or in part) for production of electricity and / or heat required by the building.

4.1. Control of heat and moisture transfer

Despite the large number of the above-listed functions of the building envelope, most of them relate to the control of heat and moisture transfer. The importance of the building envelope, that is, the defects in its design and material selection, are evident from visual inspection of the building (Figure 8).

Possible control methods also depend on the type of heat and moisture transfer. In the case of heat transfer by conduction, the aim is to increase thermal resistance (R) of the envelope, which is achieved by the use of poorly conductive materials (low λ materials), by correct selection and installation of thermal insulation, and by avoiding thermal bridges. In convection heat transfer, most losses can be minimized by reducing air flow and restricting air movement, which is achieved by reducing air cavities between elements, adding convection blocking inserts, and installing air barrier materials. When radiating heat, it is important to reduce the exposure of the envelope to solar

Figure 9. Contemporary envelope design systems: Selfridge department store, Birmingham; a residential town in Marthashof, Berlin; apartment complex Porta nouva, Milan; GSW Business Tower, Berlin

radiation and to reduce transmission of solar radiation. Careful selection of the location and floor plan of the building, good choice of the glazing and control systems, and the use of solar radiation barriers, are quite important in this respect.
The transfer of moisture into and through the envelope takes place from a higher to a lower temperature, it is driven by the degree of heat and / or humidity, and may also be carried by air, i.e. driven by the passage of air into or through the envelope. Unwanted moisture increases heating / cooling load, causes the building envelope to deteriorate, and creates favourable conditions for mould development. To prevent the unintended consequences of moisture transfer, such as chemical degradation and corrosion, decay due to freezing and melting, mould, stains, and damage to the finishes, it is necessary to ensure that moist air does not come into contact and condense on cold elements inside the envelope.
Therefore, thermal comfort within a building is conditioned by the temperature and amount of air movement, humidity, and the temperature of the inner surface of the envelope. Proper design of the envelope i.e. reduced use or avoiding oversized glazing, careful orientation and protection from sun radiation as well as appropriate thermal insulation, can reduce the potentially exaggerated requirements needed in achieving the desired thermal comfort conditions..

5. The origin of modern envelope design system

With the requirements accepted by the adoption of the principles of sustainability and energy efficiency in the building industry, it has become clear that the perception of the building envelope has to be changed, since already at the end of the last century, preconditions were created for changing the envelope design system (Figure 9) thanks to the improvement of the properties of building materials and innovative technical solutions.
An expanded understanding of the requirements that a building has to fulfil implies that they are not static and fixed, but dynamic (variable and transient), resulting in a rethinking of the traditional role of the building envelope solely as the dividing line between interior and exterior space.
The evolution of the envelope, as a focal point of design and innovation in the twentieth century, went hand in hand with advances in engineering and construction, as well as with the development of computing, cybernetics, and artificial intelligence [9]. Increasingly, envelopes are being designed as complex systems of different circuits that are aligned to provide an optimum climate and energy performance. They are increasingly equipped with new and more efficient materials, sensors, self-propelled devices and computers that support automatic control of lighting, air flow and sound emission, heat loss, and indoor air quality.
This new equipment helps, and in some cases replaces, traditional building envelope assemblies. Also, because the sheath is mainly directly exposed to the effects of the sun and wind, it is the most effective place for research and innovation in energy saving and alternative energy production. Its new settings have been redefined so that it is now a part of the whole "organism" of the building with which it is inseparably combined.
In addition to the application of modern technological advances, great potential for the development of smart and intelligent envelopes lies in the use of "smart" materials which, by their physical characteristics, enable the exchange or generation of energy and contribute to the creation of desirable living conditions in a building. Examples of the use of smart materials are already widely available, and include aerogels, micro-encapsulated wax, salt hydrates, films of thermochromic polymers, thermo-bimetals, etc. It is also interesting to apply certain biological systems that use specific capabilities of some plant species in energy production and thus multiple contributors to an energy-efficient architecture. For example, facades with biomass can be used as a dynamic system for darkening and illumination, producing thermal energy from solar energy, and high-quality biomass.
Apart from the use of computer technology and sensors, kinetic or adaptive envelopes can also use physical properties of smart materials, such as bimetals, which, when exposed to a heat source, change their shape, causing the envelope openings to increase or decrease and thus control the brightness level.
Envelopes are increasingly involved in the use of solar energy, i.e. in the process of electricity production. It is common to use photovoltaic cells, but the possibility of harnessing wind energy is also increasingly being explored. When used, wind turbines

become part of the infrastructure of the building itself, which by its design and construction adapts to the installation of wind turbines and their maximum efficiency, whereby the buildings are designed as diffusers for wind turbines or wind turbines are mounted on the roof. In addition, the possibility of integrating small wind turbine modules into the entire surface of the building envelope is being explored, extending the scope so far limited to the roof and edges of the building.

It is important to note that an optimum effect of using smart materials and other envelope systems is often closely related to the specific climatic conditions of the site.

This systematic reflection on the building envelope has fundamentally changed the way architects approach the design of the building and has, over time, eliminated traditional design issues or questions about physical properties of the envelope. Thus, a new discourse has been found within a much broader understanding of the role and characteristics of the envelope. These new parameters have resulted in an increased cooperation between architects and experts from other professions, not only in the field of technical sciences (mechanical engineering, electrical engineering, computer science), but also in the field of natural and social sciences.

6. Conclusion

Throughout the history of construction, man has always had two resources - the physical barrier and the use of energy - to control natural environment and create desirable living conditions. It is this physical barrier, that is, the building envelope, that serves as a filter that leaks environmental influences into the interior, while altering or completely rejecting the undesirable ones. At the same time, the envelope protects other building systems (load-bearing structure, installations, interiors, etc.) and provides, in cooperation with them, a safe and comfortable environment for users of the building. Energy use is sometimes necessary, but it should be emphasized that control by physical characteristics of the envelope is less costly, more reliable and more efficient. If an envelope is poorly designed or constructed and does not assume its controlling role, it is sometimes impossible to make up for the shortcomings even with the use of energy. Also, the envelope combines two, often conflicting features: aesthetic characteristics and functional / physical properties of the building. In assessing an overall behaviour of the building, with its emphasis on the thermal, light and sound protection elements, the envelope is a critical system, and is also a major determinant of the external aesthetic quality of the building - important to owners, architects, but also to the public in general. With the development of society, the functional requirements that the envelope must satisfy have also changed. In addition to the function of ensuring protection against natural disasters and providing for physical protection of users, today we distinguish a far greater number of requests. A thorough understanding of the requirements that a building has to fulfil implies that they are not static and fixed but dynamic (variable and transient), which results in the rethinking of the traditional role of the building envelope solely as the dividing line between interior and exterior space. Bearing in mind the complex issues of the building envelope, and all the factors that must be taken into account in the design, the goal of contemporary construction is to approach the issue of the envelope in a multidisciplinary and integral manner to avoid potential problems, while properly satisfying human needs, with as little financial cost and negative impacts as possible.

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