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Adaptive Box Window, developed with innovative nanomaterial, for a sustainable architecture in the Mediterranean area

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Abstract

A new generation of multifunctional, adaptive and dynamic facades is to be developed in the framework of the research project SELFIE to respond to the EU Directive 2002/91. The aim is to build novel adaptive envelope systems for nZEB to facilitate the exploitation of RES at building scale and simultaneously improve indoor environmental quality both in existing and new buildings. The project focuses on the design, testing and construction of innovative technological systems capable of integrating energy saving smart materials and novel technologies, for buildings located in the Mediterranean area. The Adaptive Box Window elements presented in this paper are designed to be preassembled, modular and adaptive.

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Nomenclature

CABS	Climate Adaptive Building Shell
SELFIE	Smart and Efficient Layers for Innovative Envelope
nZEB	nearly Zero Energy Buildings
ABW	Adaptive Box Window
GDP	Gross Domestic Product
SME	Small Medium Enterprise
RES	Renewable Energy Sources
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
PVB	Poly Vinyl Butyral
PV	Photovoltaic Panel
ICT	Information Communication Technology
PCM	Phase Change Materials
MFG	Mesopourous Foam Glass
IR	Infrared Reflective
LCA	Life Cycle Analysis
DSSC	Dye-Sensitized Solar Cell
TiO2	Titanium Dioxide

1. Introduction

In 2014, European building stock accounted for 30% of the EU's greenhouse gas emissions [1], with a considerable cost effective energy saving potential. As the number of buildings is continuously growing, energy consumption and CO2 emissions will also rise if energy performance minimum requirements are not applied. However, the renewable energy industry is growing rapidly among rising concerns about oil dependence, climate change and the construction industry provided 18 million direct jobs in Europe, and accounts for 9% of our GDP; SMEs contribute more than 70% of the value added in the EU building sector.

Therefore, renovating and retrofitting buildings adds almost twice as much value as the construction of new buildings. Increasing the rate, quality and effectiveness of building renovation will be a great challenge for the coming decades [1]. A whole-building perspective is preferred in new construction or building renovation. The goal in the future market of building construction is a procedure that involves both the building as whole and the approach to the construction process, aiming to show opportunities to improve energy efficiency.

To reach these goals, details about the building envelope's impacts on energy consumption should not be underestimated. In fact, in the current practice, building envelope components are upgraded or replaced using technologies that are often less efficient than the best options available on the market.

The primary focus of the future in the construction market should be on investing in innovation using advanced options. This approach is needed not only to support whole-building approaches but also to improve the energy efficiency of individual building components [2].

2. Climate Adaptive Building Shell

For decades, architects and building scientists have envisioned the possibility that future buildings would possess envelopes that replicate our skin's adaptive response to changing environmental conditions [3]. Advances in materials technology and building automation systems are increasingly imitating the intelligent response of human behavior and of our own skin to environmental stimuli in active envelopes, thus allowing to regulate energy flow through a building's thermal barrier in a controlled manner that benefits energy reduction and occupant comfort.

The building envelope could be defined as a technological interface between indoor and outdoor environment. It is able to satisfy many aesthetic and physical functions that determine most of the energy consumptions of the building itself. Traditional building envelopes are developed as “static systems”: they have limits to the quantity of energy savings that can be realized [4] and they are unable to take advantage of favorable outdoor conditions that would consistently benefit the indoor environment; they hinder the occupants’ abilities to modify the envelope to their needs. With seasonal variations, shifting weather patterns, and occupants' ever-changing comfort and energy needs, static envelopes cannot provide consistent climate control without HVAC assistance due to hourly changes in the weather, suggesting the need for dynamic controls [5]. Moreover, the target of the Energy Performance Directive of Buildings 2010/31/UE [6] and the Energy Efficiency Directive 2012/27/UE [7] on the energy performance of buildings, the rising cost of fossil fuels in recent years, the high emissions and tiny air pollution particles, led us to the development of new façade systems. An appropriate envelope is, in fact, the main element in the field of sustainable building design [9].

In order to follow the national legislative contest and supported by European directives, the Italian Ministry of University and Research and the regional administration of Tuscany have funded a research project named SELFIE. It aims to increase the energy savings of constructions in Mediterranean climate areas, focusing on summer comfort, and developing and testing innovative envelope solutions according to the innovation technologies developed by national and local companies. Furthermore, the SELFIE aims at increasing the knowledge on energy performances and technological features of adaptive envelopes, such as CABS and ABW, that are able to change their architectural configuration and their energy features in order to respond in real time to the climatic conditions [3].

In the last decade, adaptive envelopes have shown a significant technology evolution thanks to the possibility to integrate smart materials and building management systems. For their technological features, CABS can rely on multifunctional highly adaptive systems, where the physical separator between the interior and exterior environment (i.e. the building envelope) is able to change its functions, features or behavior over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance [9]. Furthermore, CABSs offer the potential for energy savings without a need for compromising comfort levels thanks to the opportunity to transform indoor spaces again into ‘mediated’ rather than ‘manufactured’ environments [10]. Finally, this type of envelope, if developed like ABW, could be used for the renovation of existing buildings in order to add new volume that could be used like living space or loggias and balconies, to allocate space to stairs and elevators, or to integrate other distribution elements.

For these reasons, the ABW shown in this paper has been developed like CABS with the objective to cover three distinct research domains:

1) Design (conceived and engineered for flexibility and modularity, targeting full customization to specific refurbishment requirements),

2) Materials (use of emergent micro and nano-materials and processing techniques in the functionalization of building parts for improved technical and functional performance) and

3) Engineering systems (i.e. integration of advanced control and monitoring systems for a smart behavior of the building envelope).

Particular attention was also paid to architectural aspects, considering that the aesthetical issues constitute an important barrier against a broad implementation of some energy efficient technologies in refurbishment projects [11].

3. Experimental program: the applied research work

The design on ABW was developed adopting an inductive and systemic methodological model that allowed building a research work based on consequential moments of analysis. Each work phase was defined by a distinct research methodology approach, linked to appropriate tools in order to deepen the knowledge phase.

The references for the research work were the analysis of a building envelope’s performance and the innovation technologies that allowed developing the change from “building closing” to “façade” and then to “dynamic and smart envelope”. Therefore, the specific research objective was to develop a smart bow window, realized with high performance to satisfy the temperate climatic data, to be integrated into the residential recovery buildings in order to improve their energy performance.

In the first research phase the state of art was analyzed with all the references on dynamic envelopes and intelligent materials; several case studies with innovation technology characteristics in the building envelope were collected and best performance requirements were identified. The results were collected in a dynamic and innovative building façade catalogue. The second phase of the work was characterized by the definition of the concept of an innovative façade component, starting from the development of functional, technological and performance details, which was applied on a residential building case study to verify its architectural effectiveness.

4. The analytical phase and the definition of the state of the art

The analytical phase was focused on the knowledge of the state of the art to define the technological characteristics of dynamic envelopes located in a temperate climate. Industry company and designers have been involved in order to build a scenario of case studies and to describe what features must be chosen to guarantee the indoor comfort and, at the same time, a significant reduction of the building energy consumptions, also in the summer months. The analysis showed trends in the façade systems realized in the Mediterranean area in the last decade. The transparent double skins have dynamic external layers realized with mobile shading devices or sliding panels to reduce overheating in summer; mobile solar shades are always integrated in the buffer zone of the double skin façades to regulate the daylighting inside of the building. Smart materials and/or PV panels are used to increase the thermo-hygrometric performances, in particular in the summer months and ICT has a crucial role to enable demand-response, real time energy management and integration of intermittent renewable energy sources.

These analyses of the technological characteristics and the definition of the energy performance of the adaptive facades chosen as case studies, were necessary to identify a reference model for the development of the SELFIE façade concept.

The classification of the geometric features of these envelope systems as well as the definition of their thermo-hygrometric characteristics had also enabled us to define quantitative data that were used in the meta-design phase and to understand what technical elements to adopt and how to combine them in the façade system to achieve high physical performances also in terms of thermal inertia.

The technological features defined in this first research phase and used to design the SELFIE ABW prototype were those related to:

- *Geometric configuration*: we have decided to develop a modular bow window since it can be integrated into an existing façade system and it guarantees an easy installation and maintenance;
- *Natural Ventilation*: the size of the façade module (height and depth) ensures a good ventilation of the adjacent spaces;
- *Mobile Shading device*: integrates PV lamellas into the box windows in order to optimize the lighting of indoor space and reduce the overheating phenomena.

5. The ABW concept

The ABW prototype, as first research result, can be integrated into the renovation of an existing building in correspondence of balconies, door and/or window located in the external wall of living spaces (Fig.1). They will provide the following performances:

- *Reduction of energy consumptios and CO2 gas emission*. The ABW, in fact, were designed to decrease the energy losses during the winter and overheating phenomena during the summer, thanks to the integration of innovative nano and smart materials in the transparent and opaque elements (PCM and glass with PVB). All the materials used were chosen for their LCA performance so to decrease also the environmental impact of the whole system.
- *Wellness and health.* The possibility to use photocatalytic paints and nano materials within the opaque panels, allows to reduce internal air pollution due the presence of occupants or for the use of toxic glue, formaldehyde or other harmful materials.
- *Energy production.* In the ABW, innovative DSSC PV cells were integrated to produce and use renewable energy in situ with the aim to decrease the whole energy consumptions of the building.
- *Reduction urban pollution*. The use of Photocatalytic paints and nano materials to realize also opaque modules of the ABW components, will actively contribute to the CO2 and/or other chemical pollutants reduction.

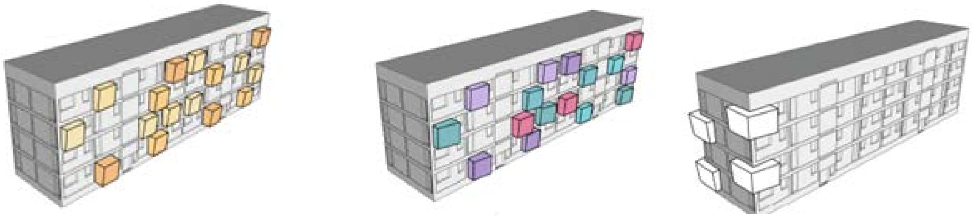

Fig. 1. Example of ABW integration in a deep renovation of an existing building

- *Management of buildings consumptions*. An integrated energy management system will be embedded in the ABW components frames, so as to guarantee a smart control of energy flows inside the building envelope and to ensure a "dynamic configuration" of the panels that allows to change their energy performance; in function of the external climatic conditions and of the indoor comfort required. Consequently, the multiple combination of the ABW panel components assures an aesthetic modulation of architectural envelope.

The ABW was realized as modular elements with a size of 90.0 cm x 140.0 cm, that can be assembled, with six different geometric configurations in two module typologies (Fig.2):

- *The "filter module"* characterized by opaque surfaces built with tiles of honeycomb, a porous ceramic material, charged with TiO2 material, able to activate with visible light a purification effect of outdoor air;
- *The "greenhouse module"* realized with a transparent module in PV panels DSSC, to produce renewable energy, ensuring a good architectural integration.

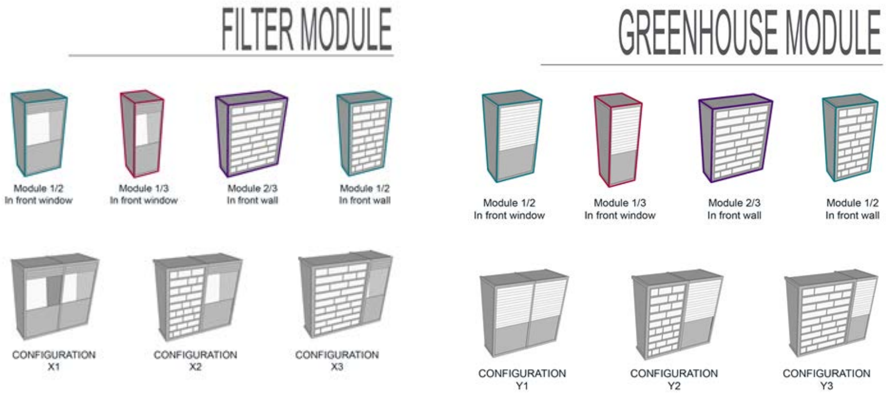

Fig. 2 Analysis of the configuration for the two modules ABW.

In detail, the ABW has been designed as a unitized bow window system that allows an easy installation on the building site. The modular components can be placed in this technological frame with different geometric configurations, different types of materials and different colors in order to guarantee the customization of the whole façade system. As previously stated, the ABW consists of fixed and mobile parts (opaque and transparent), which can be operated through automatic or manual controls to regulate the air temperature and air quality inside the building during the whole year and to increase the natural ventilation during the summer months.

Furthermore, the dynamic façade ABW is designed to achieve a good performance in terms of:

1) <u>Structural safety</u>, ensuring: Mechanical Resistance to static, suspended and dynamic (the wind and/or seismic actions) loads; Shock resistance; Fire resistance; Deformation resistance; Contact safety.
2) <u>Indoor comfort</u>, through the control of the following parameters:
   - *Air permeability*, providing a good implementation of sealing layers, finish coatings and vapor barriers.
   - *Water tightness*, planning adequately junction points to avoid water infiltrations inside the panels.
   - *Thermal transmittance*, decreasing thermal bridges and monitoring the temperature of the indoor surfaces. In particular the transparent SELFIE modules will have a U value at list of 1,2 W/m2K;
   - *Hygrothermal insulation*, choosing materials and technological solutions to control the interstitial and superficial condensation phenomena to improve the thermal and mechanical proprieties of the façade system.

- *Daylighting and solar protection*, guaranteeing integration of shading devices and nanomaterials in the glass panels to regulate the incident rays on the transparent surfaces.

3) Maintainability: the choice to use modular elements will enable repairing (with isolated action of maintainability) the facade system without changing the global performance of the façade.
4) Functioning, guaranteeing to the users to manage the façade also in absence of an automated system of control.

6. Conclusion

The ABW is only one of the façade concepts developed in the frame of research SELFIE, for this reasons we do not have data on simulation results or any numerical estimations on its energetic impact/performance. We hope to find a financing program to develop also a prototype and test it in the test cell of our University in the future. In any case, this research shows how it is possible to develop technological innovation in synergy with companies, providing the opportunity to promote improvement in the building construction sector as well, thus expecting an integrated approach, taking into account the energy, environmental, financial, and comfort related aspect.

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