Università degli Studi di Ferrara
DA Dipartimento Architettura Ferrara
Universiteti POLIS

Smart Architecture

Supporting the design of transparent building components towards the improvement of building envelope performance

Candidate: Valentina Frighi
DA Supervisor: Prof. Giovanni Zannoni
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DA External expert: Prof. Fabio Conato
Cycle XXXII

International Doctorate in Architecture and Urban Planning

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Università degli Studi di Ferrara

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UNIVERSITETI POLIS

INTERNATIONAL DOCTORATE IN ARCHITECTURE AND URBAN PLANNING

Cycle XXXII

IDAUP Coordinator Prof. Roberto Di Giulio

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Supporting the design of transparent building components towards the improvement of building envelope performance

Curriculum Architecture/ IDAUP Topic 1.3 - *Innovative technologies and materials for industrial, building and structural design*
(Area 08 – SSD: ICAR/12 - Technology of Architecture)

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(Years 2016/2019)

To Claudio and my parents, who always believed in me and made everything possible
A Claudio e ai miei genitori, che hanno sempre creduto in me e reso tutto possibile

To my Sofino, who made everything better
Al mio Sofino, che ha reso tutto ancora più bello

Smart Architecture

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ABSTRACT

The growing awareness about issues related to environmental sustainability and energy consumption reduction of the built environment has led to a shift in building process and technologies.
In this framework, the greater attention is addressed towards building envelope as major responsible for building energy efficiency so as for the internal environmental comfort of end-users.
Besides, interests of various disciplines have been directed not only to the production of sustainable architectures but even towards a new generation of energy-efficient, interactive buildings, defined *smart buildings*, capable of reacting to the continuous variability of the surroundings and the ever-changing needs of end-users.
In the context here depicted, fenestration systems have been identified as one of the major responsible for buildings' behaviour towards the external environment (it has been appraised that windows are accountable for about the 60% of the whole building energy consumption).

From these considerations descend the choice to deal with **glazed components**, under the opportunities research offers in this field due to still existing shortcomings related to the specific role they play within building envelope systems.
Indeed, it is evident that fact that glass is still the building component that needs of the most implementation in terms of performance – presenting issues that cannot be resolved only resorting to materials' innovation – but that is, at the same time, a material with great potential, due to its intrinsic ability in reacting to external stimuli.
Therefore, the main objective of the present research is to provide a solution to the existing lack of guidance about how existing glazing technologies could be profitably integrated into buildings in a way that maximises their performance.
So, after investigating the world of the smart building envelopes, as the latest goal of contemporary architectural and technological research – developing a characterization of them through the creation of a supporting database of smart architecture – the present work exploring the role that transparent building components play in this framework, classifying existing glazing technologies and providing a systematic methodology to assess their building integration potential.
The final aim of this research was to design a **decision support tool(box)** for architects, to inform and create new design possibilities, providing an insight into the application and design of smart building envelope systems and understanding role and potentialities of transparent building components within this specific framework.
Such toolbox is composed of three separated tools: *i*) a balanced scorecard, *ii*) an assessment matrix and *iii*) the smart windows configurator, final achievement of the dissertation. It is conceived as a sort of open matrix for compiling and quantify options for decision making support towards the conscious and effective integration of transparent building components within advanced and innovative building envelope systems, bridging the gap from current practice thus supporting further research and development activities.

KEYWORDS | building technology; building envelope; smart building; transparent building components; smart windows; decision-support tool.

ABSTRACT (ITA)

La crescente consapevolezza delle problematiche legate alla sostenibilità ambientale e alla riduzione dei consumi energetici del costruito ha recentemente determinato un cambiamento anche nei processi e nei metodi costruttivi, concentrando l'attenzione di utenti e operatori di settore nei confronti dell'involucro edilizio, individuato quale principale responsabile dell'efficienza energetica e del comfort ambientale interno degli edifici.
Parallelamente, gli interessi delle varie discipline coinvolte in tali processi sono stati rivolti tanto alla produzione di architetture sostenibili quanto nei confronti di una nuova generazione di edifici, intelligenti ed efficienti, capaci di interagire con la continua variabilità dell'ambiente circostante e con le esigenze sempre in mutamento dei loro utenti finali, i cosiddetti *smart buildings*.
In tale quadro di riferimento, gli infissi, e, più in generale, i componenti trasparenti di involucro, rimangono i principali responsabili del comportamento termo-ambientale dell'edificio nei confronti dell'ambiente esterno (è stato stimato che le finestre sono responsabili di circa il 60% del totale consumo di energia di un edificio).
Da queste considerazioni discende dunque la volontà di concentrare l'attenzione della presente ricerca nei confronti dei **componenti trasparenti di involu**cro, in virtù delle opportunità offerte dalla ricerca in questo campo per via di limiti ancora esistenti legati al loro ruolo specifico all'interno dei sistemi di involucro.
È evidente infatti come essi costituiscano ancora i componenti che necessitano della maggiore implementazione in termini di prestazioni – presentando criticità che tuttora non riescono ad essere risolte contando unicamente sulle caratteristiche intrinseche del materiale che li compone, il vetro appunto – ma che, allo stesso tempo, presentano un grande potenziale, dovuto alla loro capacità di reagire e interagire con gli stimoli esterni.
L'obbiettivo principale del presente lavoro pertanto, è quello di compensare l'assenza di linee orientative per l'integrazione dei suddetti componenti all'interno dei sistemi di involucro, in modo da massimizzarne le prestazioni.
A valle di un'analisi nel dominio dei cosiddetti *smart buildings*, quale ultima frontiera della ricerca architettonica e tecnologica contemporanea – strutturatasi in un database per la loro caratterizzazione sistematica – la tesi esplora il ruolo svolto dai componenti trasparenti di involucro nell'ambito di sistemi edilizi complessi, classificando le tecnologie esistenti e fornendo una metodologia per la valutazione comparata di prodotti differenti, al fine di valutarne la potenziale integrabilità.
Scopo finale della ricerca è la **messa a punto di uno strumento di supporto decisionale** rivolto all'informazione e creazione di nuove possibilità progettuali di sistemi di involucro intelligenti, comprendendo il ruolo e le potenzialità che i componenti trasparenti di involucro rivestono all'interno di questo specifico dominio.
Tale strumento si compone in realtà di tre selementi separati: *i*) una *balanced scorecard*, *ii*) una matrice di valutazione (*assement matrix*) e quello che viene qui definito come *iii*) "configuratore di *smart windows*", vero e proprio risultato applicativo del presente lavoro.
Tale configuratore è stato concepito come una sorta di matrice aperta per la compilazione e la quantificazione di diverse opzioni tecniche e prestazionali relative alle diverse tecnologie investigate, al fine di fornire un supporto decisionale verso un'integrazione consapevole ed efficace dei componenti trasparenti all'interno di sistemi di involucro edilizio complessi, colmando il divario rispetto alla pratica corrente e supportando eventuali future attività di ricerca e sviluppo.

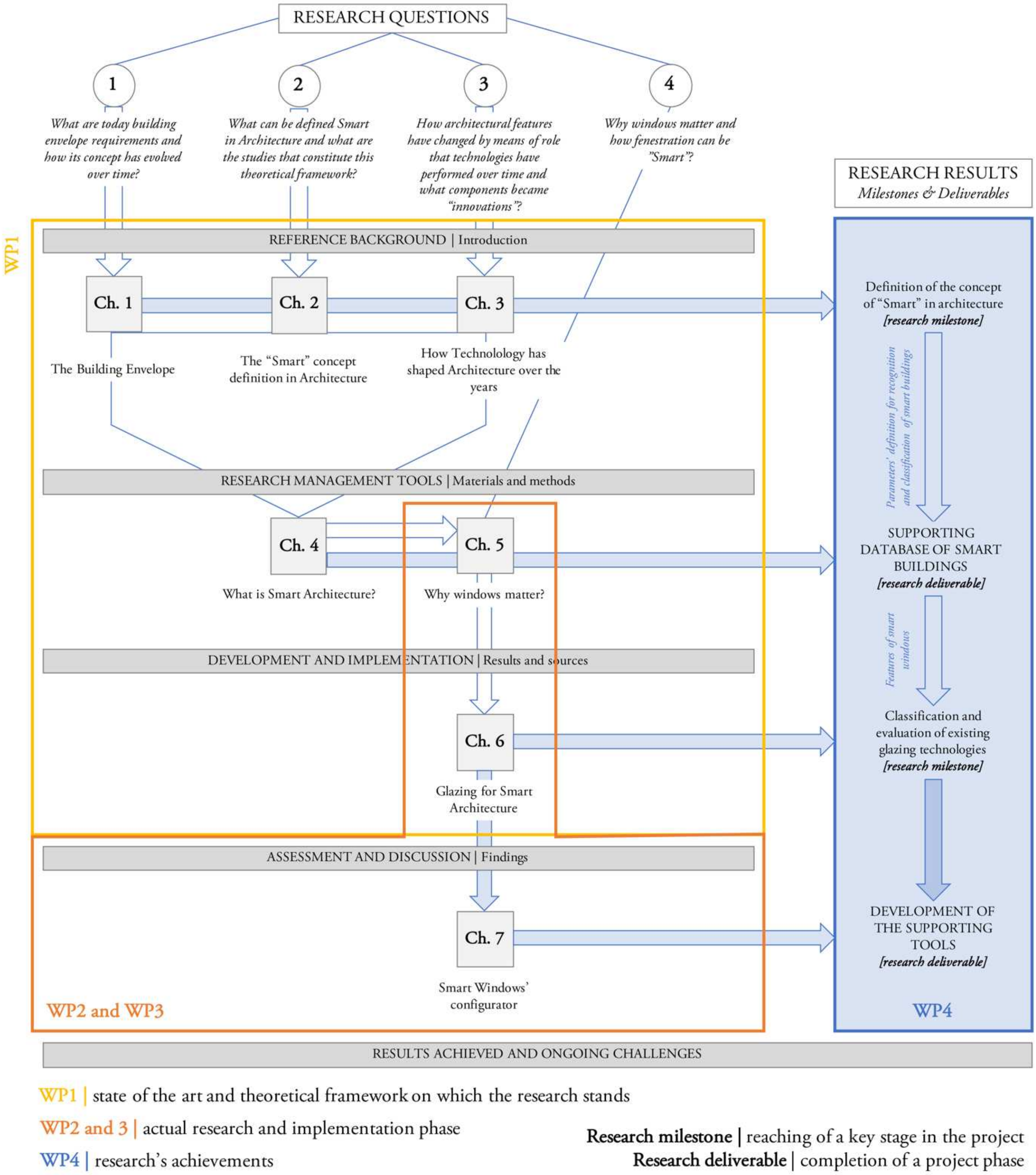

Fig. 01 – Synoptic scheme of the research

FOREWORD

REFERENCE BACKGROUND | Introduction

1. The Building Envelope

The first chapter gives preliminary definitions about what a building envelope is, analysing the evolution of its conception over time according to different emerging needs.
Indeed, as a consequence of new human needs that emerged overtimes, as well as of the emission of stricter regulations in terms of energy efficiency, building envelope and – with it – building materials, components and systems, have evolved accordingly, towards a new generation of smart materials and products able to properly face these new emerging issues.

Chapter subdivision

1.1. Definition of building envelope systems

1.2. The evolution of building concept: needs and wants

1.3. New requests for building materials, components and systems

- 1.3.1. Influencing factors
- 1.3.2. Building envelope requirements

2. The "Smart" concept definition in Architecture

In this second chapter, efforts are aimed to define what can be called "Smart" in the architecture domain and what are the studies that establish the theoretical framework on which this scope is based on.
Although this theme constitutes a quite young field of research within the broad area of technologies for architecture, as well as literature on it is such heterogeneous and – in general terms – lacking recognized agreed definition, the will is to define what the term "Smart" could sense within this domain, paying particular attention toward the role that Internet of Things and Industry 4.0 logics play in this context.

Chapter subdivision

2.1. The "Smart" concept: different definitions, several meanings

2.2. Internet of Things and ICTs for Smart Buildings

3. How Technology has shaped Architecture over the years

This chapter deals with the modifications which occur overtimes in Architecture's features by means of the role that technology – and technological evolution of building materials, components and systems – has performed to properly respond to the continuous emerging needs. So, after a brief description of what Architecture (and especially building envelope, as the main structure that made it up) has become thanks to the new available technologies, new application possibilities of materials and technologies for "Smart" Architecture are here presented.

Chapter subdivision

3.1. Technological innovations for new architectural languages

3.2. The CABS: reconciling the multiple-performance in a holistic way

3.3. Smart Advanced Technologies: innovation and experimentation

RESEARCH MANAGEMENT TOOLS | Materials and methods

4. What is Smart Architecture?

In this chapter a sample of case studies – chosen within buildings that show particular forms of innovations, according to with different predetermined criteria – has been analysed to understand the role of the abovementioned technologies within them, investigating the positive contribution given to the architecture in its whole as well as how the adoption of such advanced technologies has innovated building practices as well.
An additional benefit of this systematic characterization has been the recognition of common patterns among strategies adopted in such systems, mapping them while identifying unexplored concepts, useful for further development.

Chapter subdivision

4.1. Case-studies definition: selection and classification

4.2. Case-studies: assessment criteria and parameters' definition

4.3. Factsheets

4.4. Lessons learned

5. Why windows matter?

Since the analyses conducted so far has enlightened the fact that the great majority of the technical solutions investigated addresses transparent building components, this chapter focuses on the importance that windows have within the whole building system – considering their specific role, design and features – due to, both, their symbolical meaning as well as the very performance implementation they still need.

Chapter subdivision

5.1. The role of glazed components

5.2. Windows' design features

- 5.2.1. Characteristics of glass products
- 5.2.2. Glass' general properties
- 5.2.3. Window panes
- 5.2.4. Frames, spacers and other devices

5.3. Glass' energy performance features

- 5.3.1. Introduction to light and color
- 5.3.2. Reference parameters for windows' performance evaluation

DEVELOPMENT AND IMPLEMENTATION | Results and sources

6. Glazing for Smart Architecture

With this section starts the actual implementation phase of the dissertation. In the sixth chapter, in particular, an in-depth state-of-the-art about glazing for Smart Architecture (the so-called "Smart Windows") has been developed, dividing the technologies based on their

development status, recognizing more traditional technologies and systems and advanced technologies, with a final focus on emerging solutions.
For each kind of technologies, a commercial product representative of the category (if available) will be analyzed to understand its strengths and weaknesses and establish its potential in the current context.

Chapter subdivision

6.1. Smart Windows technologies

6.2. Passive | Static glazing technologies

- 6.2.1. Tinted
- 6.2.2. Reflective
- 6.2.3. Selective
- 6.2.4. Low-Emissive
- 6.2.5. Vacuum Insulated
- 6.2.6. TIM
- 6.2.7. Self-cleaning
- 6.2.8. Heating
- 6.2.9. Photovoltaic

6.3. Active | Dynamic glazing technologies

- 6.3.1. PCM
- 6.3.2. SPD / LCD
- 6.3.3. OLEDs
- 6.3.4. Electrochromic
- 6.3.5. Thermochromic
- 6.3.6. Thermothrophic
- 6.3.7. Photochromic
- 6.3.8. Gasochromic
- 6.3.9. Electrochemical
- 6.3.10. Electrothermal

6.4. Emerging solutions

- 6.4.1. Bio-adaptive glasses
- 6.4.2. Heat Insulation Solar Glass system
- 6.4.3. Air sandwich device
- 6.4.4. Vacuum tube window technology
- 6.4.5. Water-flow window
- 6.4.6. Solar pond window
- 6.4.7. Self-sufficient smart window
- 6.4.8. Electrokinetic pixel window technology
- 6.4.9. Elastomer-deformation tunable window

6.5. Brief comparison and critical reasoning

ASSESSMENT AND DISCUSSION | Findings

7. The Smart Windows' Configurator

This section is the actual "heart" of the thesis work thanks to the development of a toolbox to compile and quantify options for decision making, supporting the inclusion and design of transparent components within complex building systems.

This will be achieved through the set-up of a systematic methodology to asses building integration potential of transparent building components through a balanced scorecard and an assessment matrix.
Then, the final item of such toolbox, the so-called "Smart windows' configurator" will provide strategical addresses to inform the design of transparent building components, thus create new possibilities providing a holistic qualitative evaluation framework to gain insights into the degree of fulfilment of smart windows requirements.

Chapter subdivision

7.1. The Tool(box)
- 7.7.1. Balanced scorecard
- 7.7.2. Assessment matrix

7.2. SWC's structure and workflow

7.3. The configurator

RESULTS ACHIEVED AND ONGOING CHALLENGES | Conclusions

APPENDIX I | Related research projects

In the first appendix, existing research programs related to the topic under investigation have been analyzed. The aim was twofold: from one side to recognize interests currently active within both the scientific community and industrial and productive sectors; and, from the other, to map their distribution along with Europe, understanding their diffusion and dividing them according to their research areas and main purposes.

APPENDIX II | Smart materials for smart applications

In this second appendix, following descriptions and consideration made within Chapter 3, new materials and technologies for smart applications in Architecture are presented.

APPENDIX III

This last appendix presents the relationship between window and wall, recognized as one of the most challenging interfaces within the whole building envelope system under the multiple interactions among heterogeneous components that occur in it.
This scope has not been deepened in its whole as a part of the research nor has been deeply investigated due to its extents, but anyhow it has been recognized as a crucial theme to ensure that performance related to the specific technical elements under investigation – the windows – keep unchanged in the transfer from the conceptual phase to the implementation phase.
Indeed, the aim of this "digression" is to attract interest in the importance of correctly design such relevant interface, trying to overcome actual criticalities among off-site phase and real on-site performance.

Chapter subdivision

Critical interactions: the case of window-wall interface
1. The window-wall interface
2. Functional surfaces of the fenestration system

Installation and setup operations for a job well done (*La regola dell'arte*)
1. Window's position within the wall
2. Fastening typology
3. Primary and secondary joints' insulation

REFERENCE BACKGROUND | Introduction

Introduction to research topic and building of the theoretical framework on which the present research stands.

1. The Building Envelope

- Preliminary definitions about what a building envelope is.
- Analysis of the evolution of building envelope concept over time.

2. The "Smart" concept definition in Architecture

- Definition of what can be called "Smart" in architecture domain.
- Investigation on what are the studies that establish the theoretical framework on which this scope is based on.

3. How Technology has shaped Architecture over the years

- Description of what Architecture has become thanks to the new available technologies.
- Presentation of materials and technologies for "smart" Architecture application possibilities.

RESEARCH MANAGEMENT TOOLS | Materials and methods

This second section of the dissertation goes more in depth into the research topic, by identifying materials and methods for further development of the work.

4. What is Smart Architecture?

- Case-studies' analysis to understand the role of "Smart" technologies within them;
- Systematic characterization of Smart Architecture, mapping them while identifying unexplored concepts, useful for further development.

5. Why windows matter?

- Reduction of the field of analysis to transparent building components.
- Focus on the importance that windows have within the whole building system, considering their specific role, design and features.

DEVELOPMENT & IMPLEMENTATION | Results and sources

With this section starts the actual implementation phase of the dissertation thanks to the elaboration of results gathered from previous analysis that produced sources for future progresses.

6. Glazing for Smart Architecture

- Development of state-of-the-art about glazing for Smart Architecture.
- Analysis of commercial products representative of the technologies investigated, to understand their strengths and weaknesses and establish their potential in the current context.

ASSESSMENT AND DISCUSSION | Findings

This section is the actual "heart" of the dissertation which explains findings of the present research.

7. Smart Windows' configurator

- Set-up of a systematic methodology to asses building integration potential of transparent building components through the development of a balanced scorecard and an assessment matrix.
- Compilation and quantification of options for decision making, through the development of a Smart Windows' configurator.

RESULTS ACHIEVED AND ONGOING CHALLENGES | Conclusions

This section concludes the work, taking stock of all the achieved results and paving the way towards future challenges.

Fig. 01 – Synthesis of research structure and chapter subdivision

FOREWORD
Research theme and statement of the scientific problem

Specific challenge

The growing awareness about issues related to environmental sustainability and energy consumption reduction of the built environment has led to a shift in building process and technologies.
In this framework, the greater attention is addressed towards building envelope, as major responsible for building energy efficiency as well for the internal environmental comfort of end-users.
Coupled with the advancements in technological progress, this has produced the desire to obtain materials and components with ever more high-performance that very quickly led to the replacement of the so-callable "traditional technologies" with new "advanced technologies", equipped with unconventional features and sometimes related to scientific branches and industrial sectors completely different from building technology, aimed at increasing performance of building materials and components thus reducing building energy demand and its environmental impact as well.
Besides, thanks to the rise of the automation as well as the availability of new processing and production techniques, interests of various disciplines have been directed not only to the production of sustainable architectures but even towards a new generation of energy-efficient, interactive buildings, defined *smart buildings*, capable of reacting to the continuous variability of the surroundings and the ever-changing needs of end-users.
In the context here depicted, fenestration systems have been identified as one of the primary responsible for buildings' behaviour towards such external environment (it has been appraised that windows are accountable for about the 60% of the whole building energy consumption); for this reason, the possibility to profitably include advanced transparent building components within such complex systems allows to imagine a new generation of innovative envelope models, capable to adapt to the variability of the external environment and to reduce building's energy requirements while constantly meeting end-users' changing demands.

Scope

After understanding how the relationship between advanced materials, technology and Architecture has become a key driver for innovative building design concepts, **the present research aims at investigating the world of the smart building envelope**, as the latest goal of contemporary architectural and technological research, **and**, within this framework, **the role that transparent building components play,** exploring them and defining new approaches to implement their building integration potential.
The analysed resources included traditional technologies as well as advanced and emerging solutions, to help in conceiving optimized window systems able to significantly contribute to the whole building performance, thus optimizing energy savings during all seasons without affecting building aesthetics or functionality.
The choice to deal with glazed components to set up an approach to improve their performance is determined by the opportunities that research offers in this field, due to many related shortcomings by virtue of the specific role they play within the building envelope.
Indeed, it is evident that fact that glass is still the component that needs of the most

implementation in terms of performance – presenting issues that cannot be resolved only resorting to materials' innovation – but that, at the same time, it is the material with the greatest potential due to glass' intrinsic ability in reacting to external stimuli.
So, recent breakthroughs in materials science seem now able to open up a range of possibilities for architects and professionals to influence designs as far as glazing is concerned.
Therefore, the present research aims to provide a solution to the existing lack of guidance about how existing glazing technologies could be profitably integrated into buildings in a way that maximises their performance. At the same time, reasoning on transparent building components and their interfaces open possibilities of work at 360° on Architecture, because it allows to potentially intervene at all the design scales and on different housing scenarios.
Thus, the development of strategical addresses for building application of (transparent) systems and components with smart features play a significant role in recent efforts aimed at bridging the gap from current practice, towards meeting future energy-saving targets, becoming useful tools for the building sector able to support further research and development activities.

Research objectives

The main objective of the present research is to **provide a solution to the existing lack of guidance about how existing glazing technologies could be profitably integrated into buildings in a way that maximises their performance**.
So, after investigating the world of the smart building envelope, as the latest goal of contemporary architectural and technological research, the present work **aims at design a decision support tool(box) for architects**, to inform and create new design possibilities, providing an insight into the application and design of smart building envelope systems and understanding role and potentialities of transparent building components within this specific framework. In the light of demands for ever-increasing building components' performances, not always attainable with traditional design and technological skills, the will of this research is to move towards the field of advanced technologies for architecture, by investigating the existent link among "advanced materials and technologies" and "traditional technologies", aiming at inform design through the creation of new possibilities, providing a holistic qualitative evaluation framework to successfully include transparent building components within complex building systems.

Other related objectives are:

- to define the concept of "*Smart*" in Architecture, understanding how innovative technologies has 'shaped' Architecture over years offering technological answers to current critical needs [*research milestone*];
- to provide a systematic characterization of existing examples of smart buildings, through the development of a supporting database, mapping adopted strategies and recognizing common patterns within a sample of theoretical case studies, as a first stage to evaluate current and future trends in the context of building envelope to help further development of high-potential innovative building components [*research deliverable*];
- to collect and present state-of-the-art commercially available Smart Window products, classifying existing glazing technologies and assessing their building integration potential [*research milestone*];
- to develop a "Smart Windows' Configurator", to compile and quantify options for decision making support towards the conscious and effective integration of transparent building components within advanced and innovative building envelope systems [*research deliverable*].

Fig. 01 – Office buildings in Amsterdam, Van Heeswijk

Methodology and research implementation

The doctoral research has been organized in four phases – structured as **Work Packages** – to fulfil the objectives identified within the end of the PhD course.

WP1 – Advancement beyond the state-of-the-art

WP1 – Advancement beyond the state-of-the-art	**Duration**: month 1st to 10th
General objective: To implement the research topic through the conduction of an intense desk literature review to build the research's theoretical framework.	
Tasks: • To investigate the specific role of the building envelope (performing reference background analysis, defining requirements of actual building envelope systems as well as building technologies' role over time). • To define how building envelope concept changed over time and how it gathers these modifications in the relationship among technological performance responses of building materials/components and architecture. • To reduce the research domain to transparent building components, investigating transparent materials' properties, type of products under development and types of building components mature on the market. • To analyse existing research programs to understand what kind of interests are active within the scientific community and what kind of advanced products have already been developed.	
Milestones and Deliverables: • [**M**] Definition of what the term "smart" senses, relating it not only to buildings in themselves but also to the whole contributors in the creation of smart Architecture, in the broad sense of such definition. • [**M**] Organization of on-the-market-available transparent building components. • [**D**] Development of a best-practices catalogue based on the research programs investigated.	

The first phase (which took, approximately, from the 1st to the 10th month of the research) concerned the implementation of the research topic through the conduction on an intense desk literature review.

Starting from the understanding that human needs evolved over the years, and, consequently, that technological responses of building materials and components have progressed accordingly, the specific role that building envelope performs in this process has been investigated, analysing how this concept has changed over time and how it gathers these modifications in the relationship among technological performance responses of building materials/components and Architecture.

So, the first analysis about performance requirements and influencing factors which act on building envelope has been made; then, a definition for such a new building envelope concept has been provided, identifying opportunities given in this context by ICTs and Industry 4.0 logics.

Broadening the overview of the research towards building envelope domain in its whole, it has been recognized that, as a consequence of such modifications, even building materials and products have been evolved towards a new generation of *smart* products, able to properly face the new emerging issues.

So, a preliminary result from this first investigation-phase was the definition of what the term "smart" could sense in this domain, relating it not only to buildings in themselves but also to the whole contributors in the creation of smart Architecture, in the broad sense of such definition.

Other activities related to the construction of such a theoretical framework concerned:

- reference background analysis;
- definition and requirements of actual building envelope systems;

- definition of building technologies' role over time.

Within this phase, a reduction of the research domain to transparent building components has been made; starting from the fenestration as a complex system, it has been investigated classes of technical elements and technologies on-the-market-available.
The activities concerned the investigation of the properties of transparent materials, type of products under development and types of building components mature on the market – both in their basic as in their most advanced forms.
An organization and cataloguing of the on-the-market-available technologies has been done, analysing them under several points of view. Besides, existing research programs (ongoing or just concluded) has been investigated to understand what kind of interests are active within the scientific community and what kind of advanced products have already been developed.
The activities of this WP has been conducted through a documental investigation and with the acquisition of data, mainly through websites and participation in conferences, seminars and workshops on relevant topics, as well as through interviews and meetings with research centres and experts in the field.

WP2 – High-performance technologies definition

<table>
<tr><th>WP2 – High-performance technologies definition</th><th><u>Duration</u>: month 9th to 24th</th></tr>
<tr><td colspan="2"><u>General objective</u>: To develop further implementations and critical analysis of the information collected.</td></tr>
<tr><td colspan="2"><u>Tasks</u>:
• To define common terms and parameters to compare and classify the different technologies identified.
• To collect a selection of case studies to investigate the specific role that transparent building components play within complex building envelope systems.
• To perform a second-level analysis on transparent building components.
• To implement the best-practices analysis.</td></tr>
<tr><td colspan="2"><u>Milestones and Deliverables</u>:
• [M] Development of technical and assessment sheets to allow a synoptic comparison between examined products.
• [D] Organization of case-studies' collection in a matrix that resumes all the levels of classification employed, providing a systematic characterization of smart buildings for future trends in design, mapping strategies adopted in such systems, recognizing common patterns and identifying unexplored concepts, to help further development of high-potential innovative smart building components.
• [D] Development of an evaluation matrix of transparent building components to define their main properties and understanding their actual applications and potentialities in the smart buildings' viewpoint.</td></tr>
</table>

The second phase (which took about from the 9th month of the present research up to the 24th month) regards further implementations and critical analysis on the information collected. It was about the definition of common terms and criteria to compare and classify the different technologies identified.
As a result, a catalogue of the technologies previously identified has been developed to compare products with different characteristics. This collection provides the reader with valuable information to assess the energy performances' feature of such technologies, evaluating at the same time their strengths and weaknesses along with their experimental and research status; moreover, their presentation in a comprehensive table allows for a synoptic comparison between examined products.
As cross-cutting activities among this two first phases, an overview in the wide scope of so-called smart buildings' domain has been made, through a collection of theoretical case-studies

to investigate the specific role that transparent building components play within such complex systems.
The case-studies (over 50 buildings have been examined) have been selected among recent buildings representative of the above-mentioned evolution that showed particular forms of innovations, according to criteria that include environmental sustainability and energy efficiency.
Their selection is a result of a rigorous and extensive literature survey, collected from different sources such as scientific publications, websites of companies or building components' manufacturers as well as architecture magazines and scientific journals, online and in their printed version. It does not intend to be comprehensive of the multitude of realizations ascribable under the given definition of what a smart building could be; instead, it would study and evaluate existing examples and concepts of smart technologies for the building envelope, gaining an overall understanding of them, thus providing a general overview within their state-of-the-art, developing knowledge about materials and technologies commonly used, understanding their strength and weaknesses and trying to comprehend which of them can "shape" new architectural languages by virtue of their abilities to solve present and future critical issues.
This analysis has allowed collecting the above-mentioned case-studies in a matrix that resume all the levels of classification employed, providing a systematic characterization of smart buildings for future trends in design, mapping strategies adopted in such systems, recognizing common patterns and identifying unexplored concepts, to help further development of high-potential innovative smart building components.
This first, preliminary result can be useful in approaching design problem of smart systems, contributing in defining how existing materials and technologies can be incorporated in their design as well as desired properties and features can be obtained through the most suitable configurations. Moreover, it has produced an important framework in which the present research stands, equipped with interesting possibilities for further developments.
Besides, this activity underlined once again the significant role that fenestration play in building energy efficiency and internal environmental comfort as well; it is worth mentioning indeed, the fact that almost the totality of technological innovations and solutions adopted in the case-studies investigated addresses transparent components. The reason is twofold: from one side, due to the symbolical meaning they have within the building envelope; while from the other, because they are components that still need of a very implementation in their performances.
Therefore, these considerations have been added to the desk literature review conducted so far on currently available glazed technologies.
For each category of transparent building component technology identified, the second level of analysis has been done through a performance comparison of one product per category (where available) in order to acquire specific technical data to which refer to, defining its main properties and understanding its actual applications and potentialities in the smart buildings' viewpoint.
During this investigation, other valuable information and specifications were presented, related not only to the performance features of glazed components but also to their geometrical, morphological, dimensional and architectural control within the whole building envelope.
Further, an evaluation matrix has been used to summarize this assessment.
Finally, best-practices analyses already done, concerning existing – ongoing or just concluded – research programs, has been implemented. Since almost the beginning of the research indeed, national and international most relevant research projects (coherent with the research purposes) have been investigated, to understand what prototypes have been developed and

what interests are active within both the scientific community, as well as in the industrial and productive sector.
In this WP, in particular, a further systematization of such data has been made, trying to mapping the distribution of such research along with Europe and to divide them according to their research areas and main purposes. This has produced a catalogue of "best-practices" suitable for different reading levels, endorsing once again the chosen specific research topic since the almost totality of such researches address glazed facades' consumption reduction, plus other complementary issues related to comfort/privacy purposes and others.

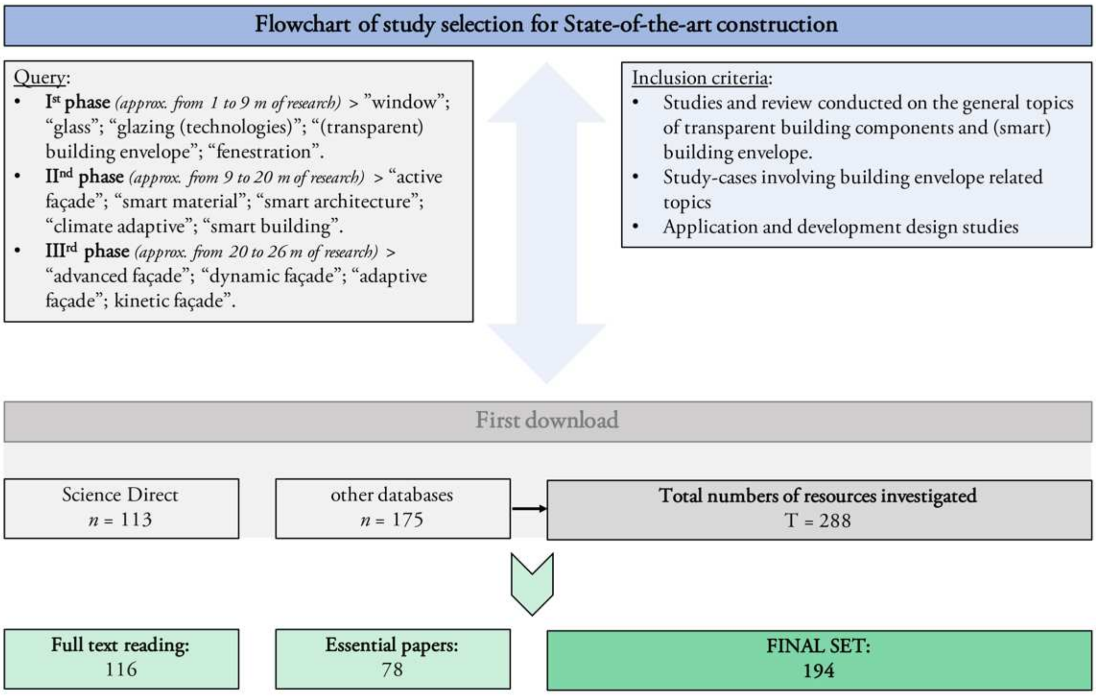

Fig. 02 – Flowchart of studies selection for state-of-the-art construction: in the first blocks has been reported the "keywords" used for the investigation phase conducted on online databases as well as the inclusion criteria adopted for selecting literature considered relevant for the present dissertation. Afterwards, a further selection has been made, identifying the final set of literature which has constituted the base on which the present work stands.

WP3 – Assessment and validation

WP3 – Assessment and validation	Duration: month 22nd to 32nd
General objective: To develop a toolbox for supporting the design strategies of transparent building components within complex building envelope systems.	
Tasks: • To elaborate data gathered so far in a complex matrix. • To develop tools able to orient actions needed to overcome the simplification of traditional components.	
Milestones and Deliverables: • [D] Development of a balanced scorecard able to group requirements of building envelope previously identified and correspondent actions needed to respond to research's questions. • [D] Development of an assessment matrix, to systematize abovementioned requirements with the research objectives. • [D] Compilation of a Smart Windows' configurator to quantify options for decision making, supporting the design of transparent building components towards the improvement of building envelope performance, fostering their conscious and effective integration within advanced building envelope systems.	

The third phase of the research, which started at approximately the 22nd month, has been the investigational one. It has been concentrated on the development of a toolbox for supporting the design strategies of transparent building components within complex building envelope systems.
This phase started with the elaboration of data gathered so far in a complex matrix; besides, a balanced scorecard will group the requirements of building envelope previously identified and correspondent actions needed to respond to research's questions.
A further matrix, defined assessment matrix, has been developed to systematize such requirements with the research objectives. These two tools flew into the so-called "smart windows' configurator", which – starting from the initial situation of every transparent building component under investigation (basically its behavior towards each requirement identified), will recommend in general terms what kind of actions need to be undertaken to overcome the simplification of traditional components.
The final aim of this toolbox is to compile and quantify options for decision making, supporting the design of transparent building components towards the improvement of building envelope performance, fostering their conscious and effective integration within advanced building envelope systems.

WP4 – Dissemination and exploitation

WP4 – Dissemination and exploitation	Duration: month 1st to 36th
General objective: To disseminate achieved results within the scientific community.	
Tasks: • To organize and systematize the work done so far.	
Milestones and Deliverables: • [D] Draft of the PhD dissertation. • [M] Production of scientific publications in proceedings and technical journals.	

The fourth and last phase has started since the beginning of the research due to the need of disseminating the obtained results within the scientific community through publications in technical journals and participation in conferences and forums on related topics.

Then, during work progress, and especially during the second year of the research, the need to organize and systematize the work done so far has raised; so, the development of the draft of the PhD dissertation – even if in a preliminary phase, has started to encounter its final round during the last months of the third year.

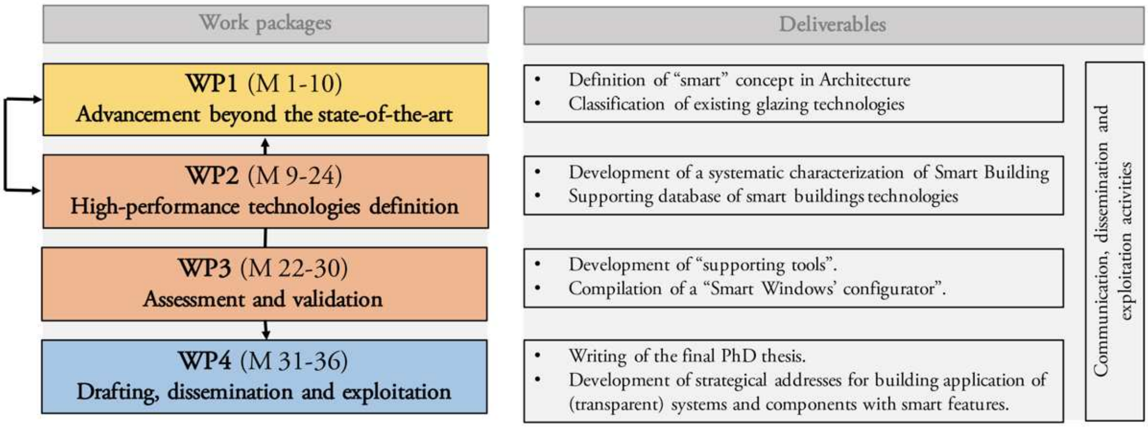

Fig. 03 – Structure and relations among Work Packages and synthesis of related deliverables

Expected results

The main expected result concerns the development of a tool(box) for approaching design problems in complex building envelope systems, primarily to reduce critical issues related to design and inclusion in such systems of transparent components.
This achievement will be delivered through the development of strategical addresses for the application in building systems of material and components with *smart* features, focusing the attention towards transparent components. Such a report will be aimed at researchers in the field and professionals to give an overview of how the products investigated could properly work thus improve the performance of the whole system, helping them in developing new solutions to the problem of designing and constructing sustainable smart buildings and supporting them in deciding on the most pertinent further researches and development activities.

Stakeholders involved and main target audience of the research

Several categories of potential stakeholders have been identified:

Industries

- Companies, producers of innovative and traditional building materials and components for building envelope;
- Construction companies and installers, building contractors and workers in the building sector.

Universities | Scientific community

Research centres | Private researchers

High-level professionals and workers in the building sector

- Architects
- Engineers
- Trade associations
- Others

Wider audience

End-users of the building process are becoming more and more aware of the indiscriminate use of energy and natural resources required by existing buildings and of the consequences that this process entails in environmental and economic terms; for this reason, also citizens can be interested in discover technological solutions able to reducing consumption and improving building performances more sustainably.

International interests in the present research

Since years, the European Community has allocated funds to support EU policies, through the publication of specific calls and program guidelines. Starting from the FP5 before, and, after, with the FP7, H2020 and now the incoming Horizon Europe (FP9), such actions aim to give actuation to European policies within different thematic areas, through the cooperation among different countries.

Due to the continuous revisions witnessed by European directives in terms of energy efficiency, the **building sector is one of the leading areas** within which concentrate and propose new research projects, intending to propose new initiatives and approach to find out hard-working solutions able to solve the still open questions.

Within such domain, the EU-28 has recently underlined the relevance of some aspects, such as the reduction of greenhouse gases emissions, the decarbonisation of the building stock, the improvement of buildings energy performance as well as the development of national strategies for building renovation that takes into account their "smartness level". Within these general frameworks, other relevant sub-topics have been pointed out, as the importance of undertaking research measures aimed at bringing innovation in the field, through the development of advanced materials[1] or, again, of developing multifunctional materials, suitable for multi-purpose demands.

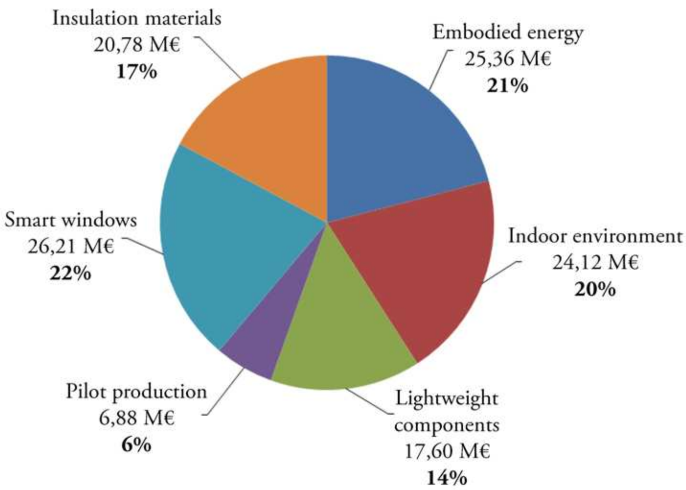

Fig. 04 – Distribution of EU research projects' topics within the domain of façade materials.

According to data recently collected about EU research projects in the domain of building sector (especially regarding façade materials), emerged that one of the key areas is that of **smart windows and glazing materials in general** which means that the object of the present research stands in line with EU policy priorities as cross-cutting topic able to align and organize the efforts between stakeholders and academia to initiate new research projects in the area of smart, innovative facades.

[1] Source: SET Plan 2011/2014, IEA Technology Roadmap 2013.

To endorse this statement thus enrich the reference framework on which the present work stands, a recognition of EU research projects (ongoing or recently concluded) on topics research-related has been done. Such analysis has been performed recurring to factsheets specifically developed that report all the information found regarding each project – including project's coordinator, start date and end date and partners' list – plus a brief description of the activities carried out within them (or expected, if the project is still ongoing), in addition to a specific "box" designed to point out and quickly recap project's connection with research's objectives. A sample of the factsheet is presented in the following pages while the whole catalogue has been indexed as an appendix at the end of the work (see ***Appendix I***).

The analyzed projects have been assigned with a progressive ID that takes into account also the programme under which they have been funded (**A** – for FP5, **B** – for FP7 and **C** – for H2020) as well as their status (**c** – if the project is already concluded, or **o** – if the project is still ongoing) (e.g. B-c-01 means that the research project has been funded under the FP7-EU Programme, that it is already concluded and that it is the first project analyzed in the progressive order).

Moreover, a brief classification regarding purposes and research areas among which research projects fit has been provided.

The result is a catalogue of "best practices" suitable for different reading levels which endorsed once again the research questions on which the present work is based since the almost totality of such researches address glazed facades' consumption reduction.

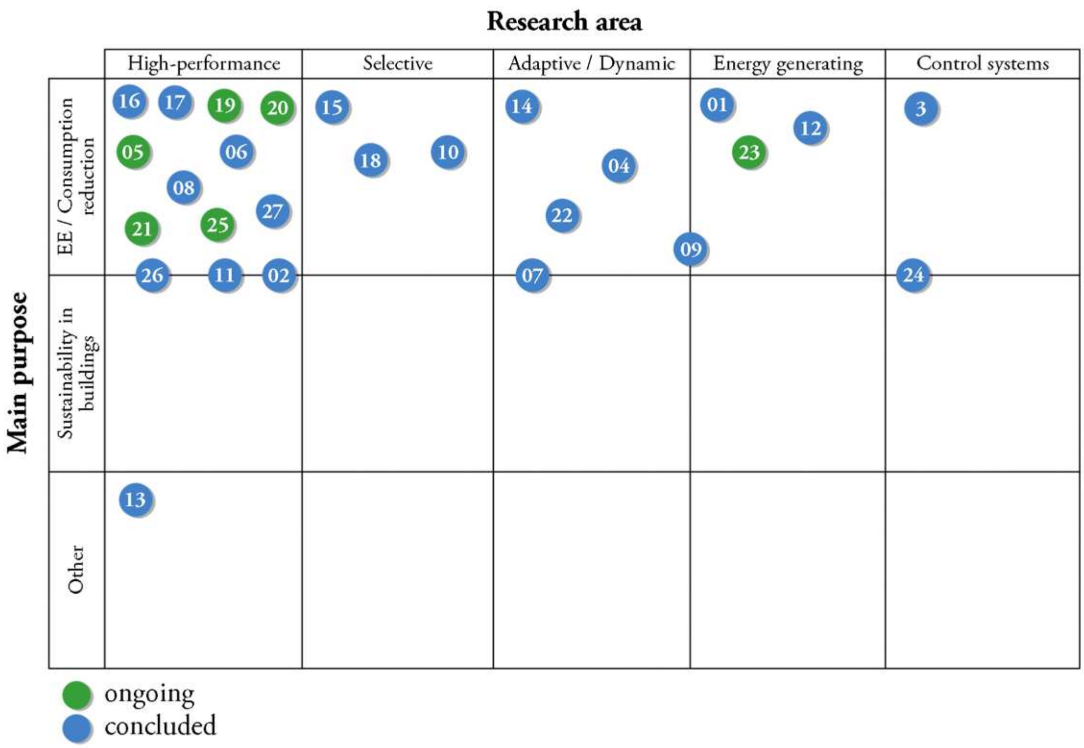

Fig. 05 – EU research projects map: distribution of main purposes and research areas of the research projects under investigation. For specific about each of them see Appendix II.

The EU research project analysed are:

01) B-c – **BIPV – PCM – COGEN. A Novel BIPV – PCM Heat and Power Cogeneration System for Buildings,** (2012-2014), United Kingdom
02) B-c – **CLEAR-UP. Clean buildings along with resource efficiency enhancement using appropriate materials and technology** (2008-2012), Germany
03) B-c – **CLIMAWIN. An intelligent window for optimal ventilation and minimum thermal loss** (2010-2012), Denmark
04) B-c – **EELICON. Enhanced Energy Efficiency and Comfort by Smart Light Transmittance Control** (2014-2017), Germany
05) C-o – **EENSULATE. Development of innovative lightweight and highly insulating energy efficient components and associated enabling materials for cost-effective retrofitting and new construction of curtain wall facades** (2016-2020), Italy
06) B-c – **FLUIDGLASS. Solar Thermal Glass Facades with Adjustable Transparency** (2013-2017), Liechtenstein
07) B-c – **GRINDOOR. Green Nanotechnology for the Indoor Environment** (2011-2016), Sweden
08) B-c – **HarWin. Harvesting solar energy with multifunctional glass-polymer windows** (2012-2015), Germany
09) C-c – **LaWIN. Large Area Fluidic Window** (2015-2017), Germany
10) A-c – **LCDAYLIGHT. Liquid crystal techniques and daylight systems** (2003-2004), France
11) B-c – **MEM4WIN. Ultra-thin glass membranes for advanced, adjustable and affordable quadruple glazing windows for zero-energy buildings** (2012-2016), Austria
12) C-c – **ML System. Heatable, integrated photovoltaics with insulated glass units** (2015-2015), Poland
13) B-c – **NECSO. Nanoscale Enhanced Characterization of Solar selective coatings** (2013-2016), Spain
14) B-c – **SmartBlind. Development of an active film for smart windows with inkjet method. Application to a building envelope component: autonomous smart device** (2012-2015), France
15) B-c – **SolarGain. Low cost switchable reflective polymeric solar heat gain control films for energy efficient smart window applications** (2011-2014), United Kingdom
16) B-c – **SOLPCM. Solar Collector and PCM Thermal Façade for Low Carbon Buildings** (2014-2016), United Kingdom
17) B-c – **WINSMART. Smart, lightweight, cost-effective and energy efficient windows based on novel material combinations** (2012-2016), Denmark
18) C-c – **WISER. The energy saving and burglar proof window that breathes for enhanced indoor comfort** (2015-2016), Poland
19) C-o – **BRESAER. BREakthrough Solutions for Adaptable Envelopes in building Refurbishment** (2015-2019), Spain
20) C-o – **P2Endure. Plug-and-Play product and process innovation for Energy-efficient building deep renovation.** (2016-2020), Netherlands
21) C-o – **HEART. Holistic Energy and Architectural Retrofit Toolkit** (2017-2021), Italy

Research program's short name and progressive identifier

BIPV – PCM – COGEN B-c 01

Full name and extended description

A Novel BIPV – PCM Heat and Power Cogeneration System for Buildings

Credits and general information

CREDITS

Project ID	298093
Country	United Kingdom
Coordinator	University of Hull, UK
Funded under	FP7 - PEOPLE
Started in	2012-12-07
Ended in	2014-12-06
Contact information	Xudong Zhao

[Relation to the current research] Developing of an innovative building materials employable in façade able to obtain a benefit in cutting carbon emission by means of its high-energy potential.

Relation to the current research

Project's brief-descritption

[Project description] The project BIPV-PCM-COGEN aims at developing a novel BIPV (Building-Integrated PhotoVoltaic) façade module that can be used to replace conventional building materials in several parts of the building envelope.
The specific objectives of the project are: **1)** to design a conceptual BIPV module and the associated heat and power co-generation system, using a PCM slurry; **2)** to develop a computer model to optimize the configuration of the BIPV/PCM system and to predict its energy generating performance; **3)** to construct and test a prototype of a BIPV/PCM system and to validate the above-mentioned computer model using the experimental data; **4)** to carry out economic, environmental and regional acceptance analyses.
Through this project has been developed: **1)** a new BIPV structure and a dedicated PCM slurry (able to overcome the difficulties associated with existing BIPV systems); **2)** a design for a conceptual PCM-slurry adapted to the BIPV module; **3)** a computer model to optimize the configuration between the PCM-slurry and the BIPV module and predict its operational performance; **4)** the construction of a prototype of a BIPV – PCM – slurry energy system and its validation.

Purpose	
Consumption reduction	■
Sustainability in buildings	
Comfort and privacy	
Reduce costs	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	■
Control systems	

[Notes]
1 The slurry is a mixture of micro-encapsulated PCM particles and water, with variable concentration determined through the experimental tests, that transfers heat away from the back of the PV modules to increase their efficiency. Dedicated heat exchangers transfer heat energy from the PCM slurry to a refrigerant used to ventilated the building and provide heat and hot water for domestic uses; any excess is stored and returned to the system on demand.

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22) C-c – **InDeWaG. Industrial Development of Water Flow Glazing Systems** (2015-2019), Germany
23) C-o – **ENVISION. ENergy harVesting by Invisible Solar IntegratiON in building skins** (2017-2022), Netherlands
24) C-c – **TransFlexTeg. Large area transparent thin film thermoelectric devices for smart window and flexible applications** (2015-2018), Portugal
25) C-o – **IntelGlazing. Intelligent functional glazing with self-cleaning properties to improve the energy efficiency of the built environment** (2016-2021), United Kingdom
26) C-c – **FIBGLOW. High insulating fiberglass window and curtain wall profiles** (2015-2015), Italy
27) C-c – **Q-Air. Sustainable Prefabricated Glass Façade with Performance Exceeding State-of-the-art Glass Façades** (2017-2018), Slovenia
28)

Research's future developments

Glazed components and, more in general building components with potential *smart* features are certainly the most promising in the current sceneries of building materials, under their ability to properly face current (and probably future) regulations requirements in terms of energy consumption, respecting the surrounding environment towards more responsible and sustainable development.
Glass indeed constitutes an essential material to equip architecture with functional and aesthetic features such as those related to thermal comfort, light and occupants' health as it provides vision, air ventilation and acoustic comfort through the envelope.
Also thanks to technical evolution that allows greater and brave new shapes, glazed applications in current building practising are continuously increasing so as a windows-to-wall ratio. However, technical limitations and shortcomings related to glazed application in different climatic context require an update of transparent building envelope components to increase the energy efficiency of the whole building stock accordingly to what claimed by in force regulations.

Fig. 06 – Apple Store Fifth Avenue, NY.

So, this upgrade seems possible only shifting from static to dynamic systems to equip building components with the ability to self-regulate (heat, light and air) flows from outdoor to indoor, acting as an interface able to continuously adapts to changing conditions (Perino & Serra, 2015).
For these reasons, future developments should combine possibilities introduced by the 4th Industrial Revolution and materials advancements to create new concepts thus develop building envelopes able to integrate multiple functionalities and obtain self-sufficient systems in terms of energy consumption. Smart building envelopes domain indeed is far from being saturated and mature due to its challenging as a result of the increased use of innovative technologies.
Additionally, other possible research's future perspectives are those addressed at deepening problems concerning the proper design of building envelope's interfaces, as contact points among the conceptual design phases and the implementation, actualizing ones. The way towards this direction has started to be paved within the insight done in Appendix I but certainly susceptible to be greatly expanded and implemented with further analyses and considerations.

<u>**Research development's scheme**</u>

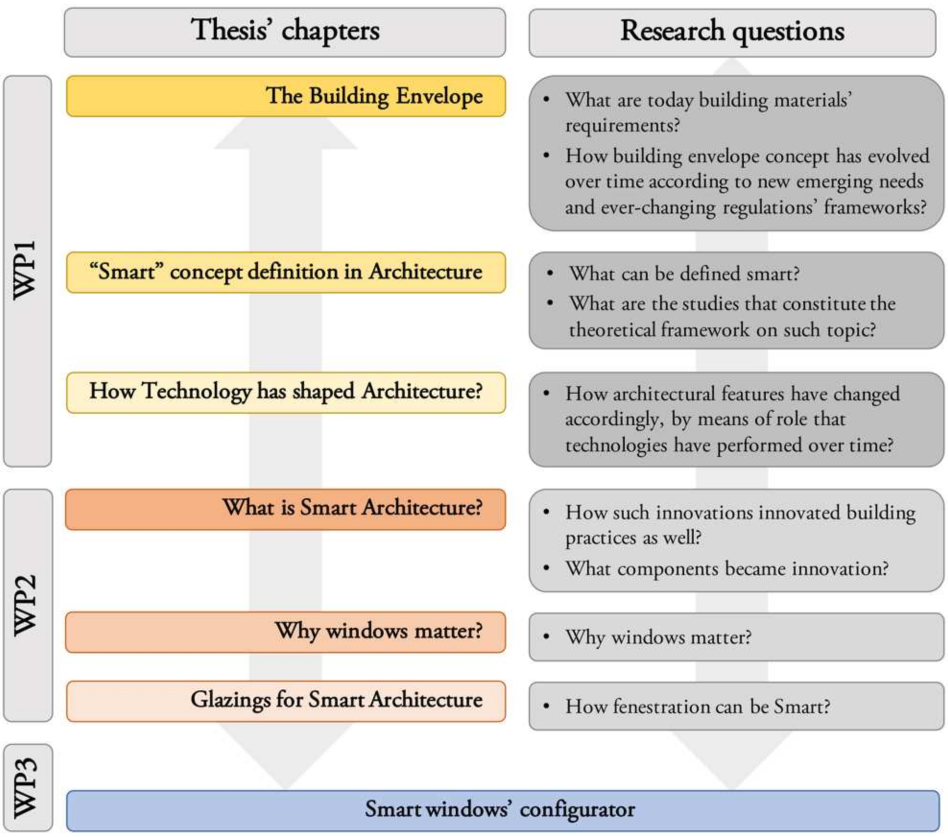

Fig. 07 – Research development scheme. For each chapter of the present dissertation are here presented research questions on which they are based on and to whom they try to give a response, to reach for the development of the final achievement of the work: the so-called "smart windows' configurator".

List of abbreviations and acronyms

BAMS	Building Automation (and) Management Systems
BAS	Building Automation Systems
BAT	Building Automation Technologies
BIPV	Building Integrated Photovoltaic
BMS	Building Management Systems
EC	Electrochromic
ETC	Easy-to-Clean
GC	Gasochromic
HVAC	Heating, Ventilation and Air Conditioning Systems
ICT(s)	Information and Communication technology(ies)
IGU(s)	Insulated Glass Unit(s)
IoT	Internet of Things
LCDs	Liquid Crystals Device(s)
Low-E	Low-Emissivity
NZEB(s)	Net- *or* Near- Zero Energy Building(s)
OLEDs	Organic Light Emitting Diode(s)
PC	Photochromic
PCM	Phase Change Materials
PV	Photovoltaic
SC	Shading Coefficient
SHGC	Solar Heat Gain Coefficient
SIC	Sound Insulation Capacity
SPDs	Suspended Particle Device(s)
SWC	Smart Windows' Configurator
TC	Thermochromic
TIM	Transparent Insulating Materials
TT	Thermothropic
UCG	User Generated Content
UV	Ultraviolet
VLT	Visual Light Transmission

REFERENCE BACKGROUND
Introduction

REFERENCE BACKGROUND
1. The Building Envelope

After the emission of stricter regulations in terms of building energy efficiency, the scientific community and productive sectors as well have increased their interest towards building envelope, as the element on which act to properly face current requirements.

1.1. Definition of building envelope systems

The building envelope can be defined as the main division element between environmental factors and end-users' needs, entrusted with the task to regulate interactions among inside and outside.

It is made up by the external structures (closures)[1] that delimit a building and its task is to act as a complex and selective filter to guarantee constant comfort conditions of inhabitants. Through the casing indeed, environmental and technological parameters to be kept in consideration during the whole design and construction process must come to a balanced synthesis, able to blend different and sometimes juxtaposed needs.

So, as Fitch (1975) stated[2] in his main work (*op. cit.)*, building envelope – due to the high variability of influencing factors[3] that act on it – should be imagined not as a simple barrier but as a «permeable and selective membrane», able to admit, reject and filter each of the factors that act on it.

First conditions for the development of the modern concept of building envelope were introduced by R. Bahnam in 1969, in his "The Architecture of the Well-Tempered Environment[4]" (*op. cit.).* In this work, he recognized the role that building envelope has in maintaining determined comfort conditions, controlling and modeling interactions and exchanges that occur among inside and outside, reacting to environmental variability and minimizing thermal losses during the winter period, while limiting temperature increasing in summer.

Therefore, it is clear that building envelope has to be able to respond to certain performance requirements, established by the in-force regulations – according to different application contexts – but depending on the degree of variability of external boundary conditions, as well as on specific needs of buildings' intended use.

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[1] Italian regulations define external structure or closures «the whole technological units and technical elements of a building system that have the function of separate and conform its internal spaces in respect of the outside». Basically, they are composed by walls, roof and slab on the ground. [Definition taken from the document "Allegato n.1" of the "Decreto Assemblea Legislativa n. 156/2008", and further modifications and implementations.

[2] Fitch, J. M. (1975), *American Building: The Environmental Forces that shape it* (op. cit.).

[3] With the term "influencing factors" (Conato and Cinti, 2014) can be defined environmental and design features that characterize the setting of a single architectural project, resulting into restrictions and conditions to which building envelope has to respond in terms of performance by means of the properties of the layers and/or skins that compose it. Factors of influence can be divided into fixed factors, unchangeable over time, given from the contextualization of the casing in a specific environment – to which it has to respond with steady performance – and variable factors, with characteristics and attributes changeable over time.

[4] Bahnam, R. (1969), *The Architecture of the Well-Tempered Environment* (op. cit.).

Furthermore, acting as a thermal barrier, building envelope plays a central role in regulating indoor temperatures and determining the whole system consumptions, being in this way responsible for their control and reduction.
For these reasons, it must be conceived as a complex and fine-tuned system within which each component contributes to the definition of building's global performance.

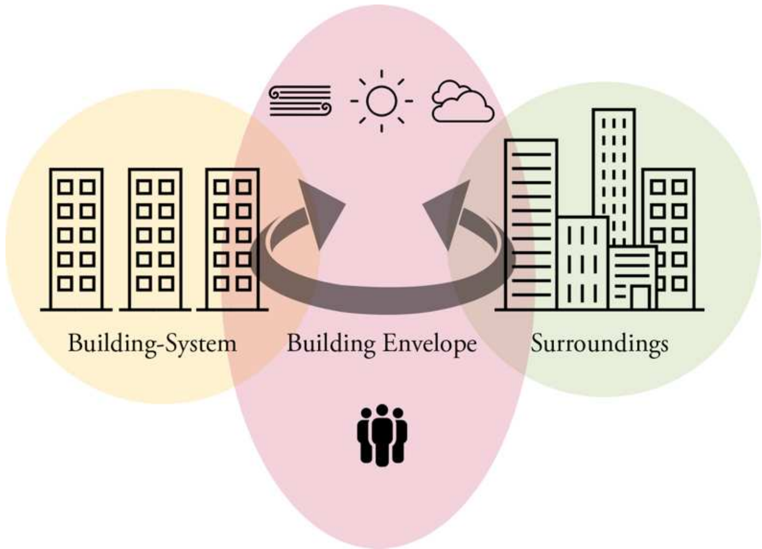


Fig. 01 – Building envelope's role in joining the building system's needs and interactions with the surroundings.

Main functions that a building envelope has to perform can be resumed as follow:

- **support function**, aimed at providing structural support against loads and forces; although building façade and structures are very often detached, the envelope has anyhow the task to support its weight as well as other building components;
- **exchange-control function**, aimed to prevent undesired fluxes between inside and outside. Even if a wide variety of climatic and thermodynamic phenomena influence the behavior of a façade, the parameters to which a building envelope has to act are basically: temperature, air pressure and humidity, whose variations are caused by energy transfer phenomena as a consequence of external dynamic conditions.
- **aesthetic-finishing function**, to make building attractive while performing the other two functions.

So, to promptly practice the three above-mentioned functions, an effective building envelope has to actively interact with the environmental surroundings, exploiting site's opportunities as well as positive influencing factors while reducing boundary's weaknesses, favoring the use of renewable energy sources and employing sustainable materials.

To give a schematic overview of what are the parameters that building envelopes must take into account, according to the previous subdivision, it can be said that an efficient and effective building envelope has to:

- **passively control solar incident radiation,** interacting with it to avoid undesired overheating during summer while maximizing solar heat gains in winter season;
- **enhancing daylight,** reducing artificial lights' needs;
- **modulate and control natural ventilation,** to increase passive cooling in hot seasons thus ensure a good level of indoor air quality;

- **deal with thermal mass storage and energy transfer**;
- **guarantee an appropriate thermal insulation level**, controlling heat transfer through it;
- **guarantee an appropriate acoustic insulation level**;
- **guarantee the hygrometric-air level modulation and condensation control**.

Additionally, essential requirements are water and wind tightness, maintenance and repair facilities as well as fire safety.
Therefore, typical design needs that building envelopes have to fulfil, can be ascribable to six main families, which summarize the abovementioned features, that are the following:

THERMAL CONTROL	ENERGY PERFORMANCE	INDOOR AIR QUALITY
VISUAL PERFORMANCE	ACOUSTIC COMFORT	INTERACTION AND CONTROL

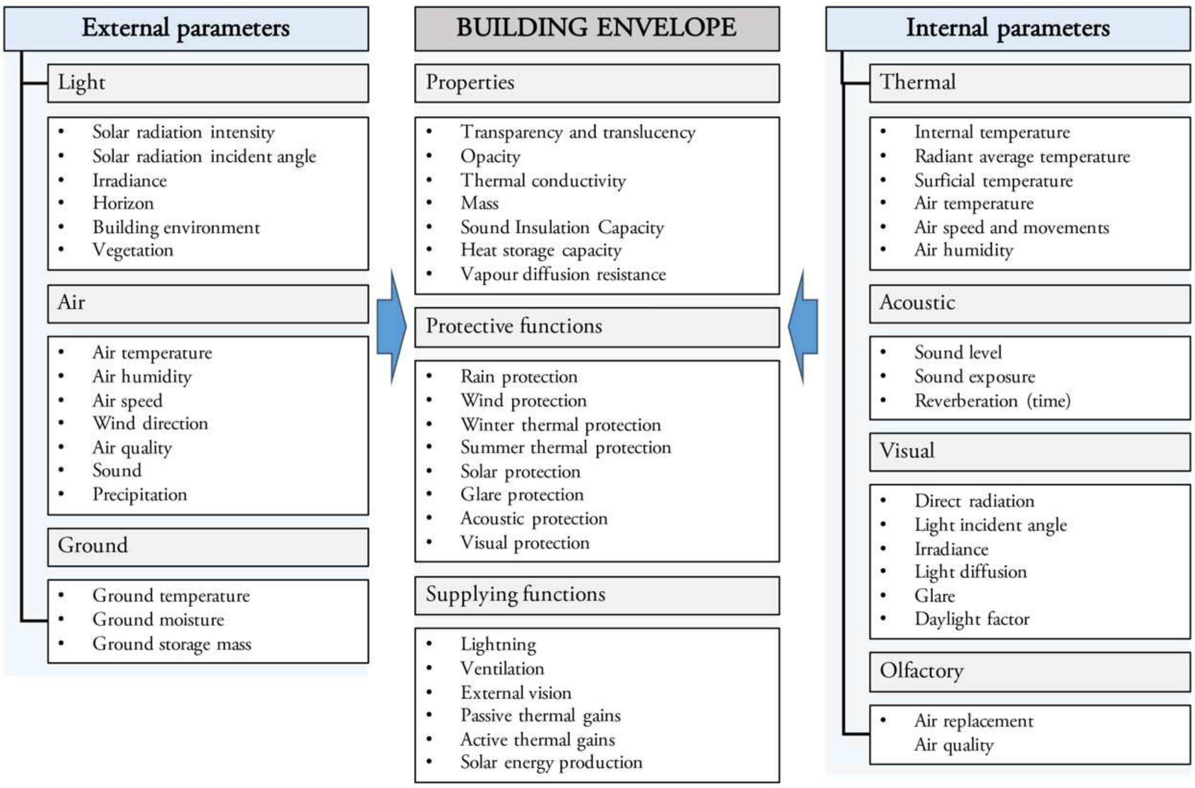


Fig. 02 – Synoptic framework of external and internal influencing factors, features and functions of building envelope.

1.2. The evolution of building concept: needs and wants

«*The design of the building envelope has to address a wide spectrum of issues, ranging from the technical performance of the individual materials and the nature of their assembly to the visual appearance and propriety of the resulting building form*»
(Bob Allies, introduction to Lovell, J. (2010), *Building Envelopes. An Integrated Approach*, Architecture Briefs, Princeton Architectural Press).

Building concept and, with it, features and requirements of building envelope systems, has incredibly changed over the years. If once, buildings were only less more than a shelter, now they have become the space in which we spend most of our everyday life, working and living.
So, on the basis of what kind of activities they host, they have to be promptly designed in both terms of layout as in performance terms.
A building envelope indeed can be considered efficient if able to successfully respond to all the "design needs" identified in the previous paragraph; this means considering that surrounding influencing factors in actual application contexts are too often randomly changing.
For this reason, this condition must be satisfied resorting to a dynamic interface, continuously interacting with external climatic conditions, able to respond to external stimuli as well as to the needs of end-users.
So, to manage the complexity of multiple factors that influence its behavior, a building system should make use of different and complementary contributions and to continuous interactions among components that made it up.
Therefore, if once building envelope was conceived only as a "monolithic" shell, now it has to be designed as a **set of layers** (much lighter than in the past) equipped with specific tasks to mediate external climatic conditions with people's internal comfort perception through their cooperation. Clearly, it follows that the overall quality of a building is largely related to the technological features of its closures; for this reason, modern building envelopes have to be intended as advanced systems that must consider at the same time architectural and urban constraints, structural performance, energy efficiency and indoor environmental quality as well.
So, following the energetic and environmental questions, as well as the advent of new dynamics that radically changed project's demands, it seems no longer possible to rely only on building envelopes with static performance – although high in their absolute values – to adequately respond to the needs of a constantly changing context, but we should aim at developing technological solutions suitable for the increasing complexity of current application's sites, able to adjust and to adapt to the continuous variations that occur in such a contemporary society. Thus, everything seems to lead to the adoption of "dynamic" devices and systems, equipped with greater possibilities thanks to their adaptation capacities.

1.3. New requests for materials, components and systems within the building envelope

1.3.1. Influencing factors

As a filter between the internal environment and external surroundings, building envelope must be appropriately designed to respond to the application context in which it will be inserted. Indeed, on a building, and especially on its envelope – made of opaque and transparent parts – act different external factors and agents, definable as **influencing factors**.
Influencing factors can be distinguished among **fixed factors** and **variable factors** as well as between **external factors** and **internal factors**, depending on the application context to which they refer. Fixed factors are those that are unchangeable overtime – coming from the specific geographic context – while variable factors are those with transitionary features.
As one can imagine, all the influencing factors affect human comfort in multiple ways, even if factors from which comfort depends mostly are basically function of the geographic context, such as the climatic area, orientation, site's morphology, outdoor temperature and humidity, wind and precipitations as well as the relationship with other buildings (able to determine different amounts of solar radiation) and so on.
By virtue of the fact that each building site is necessarily exposed to different factors, every façade should have a customized typological, technological and performance arrangement to optimize the potential interactions among climatic features and energetic issues, although it is clear that it is not a feasible alternative in current building applications.
For this reason, the will to include in architecture the dynamic dimension of nature has emerged, leading building envelope to establish continuous interaction with constantly changing boundary conditions.

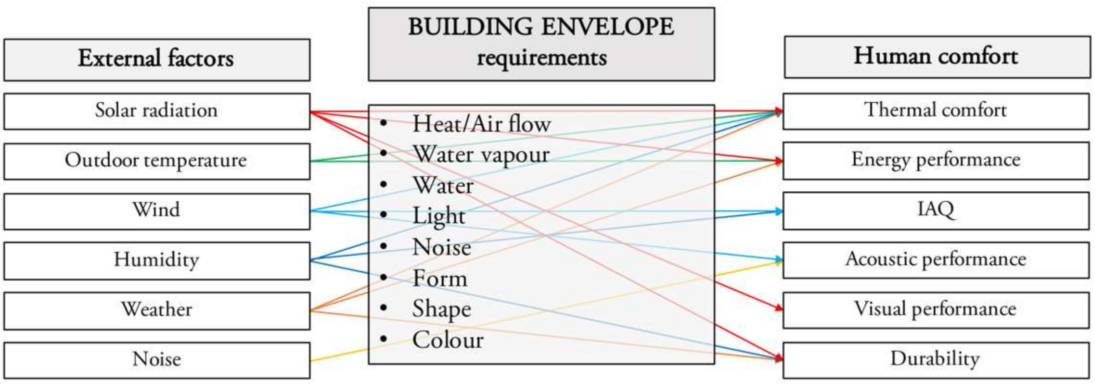


Fig. 03 – Building envelope requirements in the relationship between external factors and human comfort needs.

1.3.2. Building envelope requirements

The abovementioned influencing factors to which building envelope has to appropriately respond, have been basically substantiated in **parameters** and **requirements** that have to be fulfilled to ensure the internal environmental comfort of a building and, consequently, its correspondence to current regulations and end-users' needs.

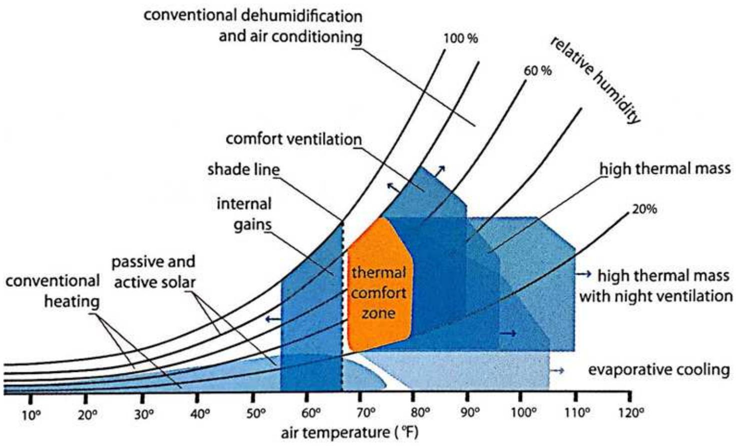


Fig. 04 – Psychrometric chart that shows the effectiveness of different design strategies in extending the potential comfort zone.

The **internal environmental comfort** is defined as one of the seven "classes of building needs" stated within the UNI norm 8289:1981[5] as the «condition in which a human being is satisfied towards the environment that surrounds him». It expresses a neutrality condition and it is completely personal, being largely influenced by physiological subjective factors (such as metabolism, ages, clothes, physical activities, etc.), not quantifiable, and by other factors (such as temperature, humidity, airspeed, etc.) that, on the contrary, are countable environmental parameters.

External environmental perception is obtained through the processing of a set of thermal, visual, acoustic, olfactory and psychological inputs, filtered and altered due to an individual sensitivity which is, in turn, influenced by heat-exchanges (for conduction, convection and radiation), by the body-metabolism and by the evaporative processes determined by breath and skin perspiration.

Italian regulation defines five different classes of needs related to comfort: 1) thermo-hygrometric comfort, 2) visual comfort, 3) acoustic comfort, 4) olfactory comfort and 5) psychological comfort, whose establishment is related to specific requirements[6].

The variables depending on the external and internal climatic conditions that affect buildings' thermo-hygrometric comfort are:

- the **air temperature**, measured in °C;
- the **internal air relative humidity**, expressed in percentage, which is the expression of the ratio among the vapors' quantity within a mass of air and the maximum amount that that mass is able to contain, at the same temperature and pressure conditions;
- the **average radiant temperature**, expressed in °C and calculated as the mean value among internal walls' temperature, ceiling and floor included;
- the **airspeed**, expressed in m/s.

Although, as previously said, physical parameters that influence the environmental comfort are subject to a personal perception, minimum requirements' values that indicate a general and commonly shared accepted comfort conditions are stated (generally on a statistic base) in national or international norms.

[5] UNI Norm 8289:1981 - Edilizia. Esigenze dell'utenza finale. Classificazione.

[6] Intended as the translation of a specific need in factors aimed at define comfort conditions within a building organism (from: UNI NORM 8989:1981)

Seasonal comfort conditions		
Variable	Winter season	Summer season
Operating temperature	20-24 °C	23-26 °C
Relative humidity	30-70%	
Airspeed	0,15 m/s (22°C)	0,17 m/s (24°C)

Tab.01 – Seasonal comfort conditions coming from the recommendations included in the UNI EN ISO 7730 for a person in a sedentary state or under light physical activities.

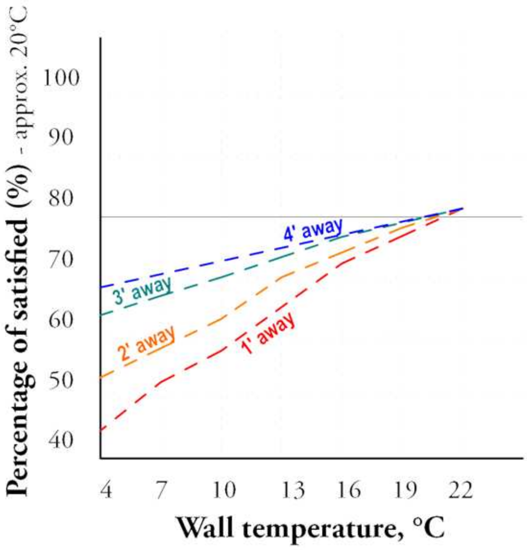
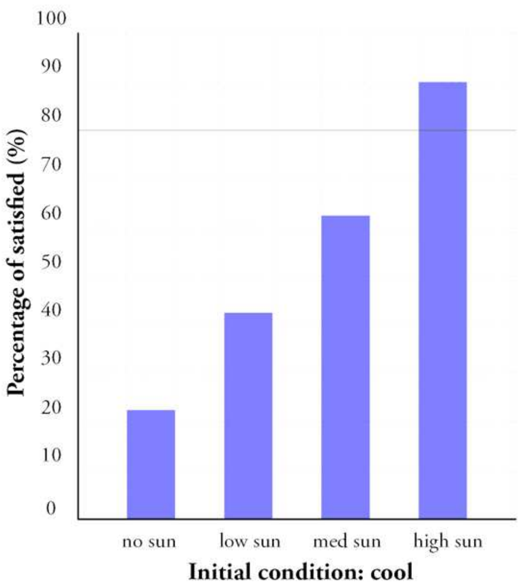


Fig. 05 – Trend of human comfort (in terms of percentage of satisfaction) in relation to the proximity to a cool surface.



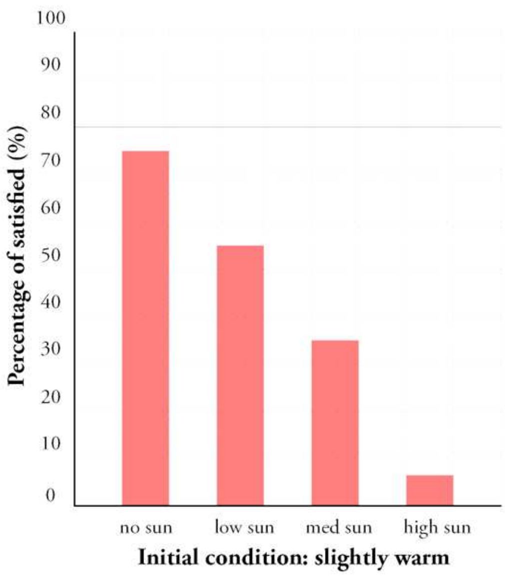


Fig. 06 – On the left: the relationship among human comfort (in terms of percentage of satisfaction) and Winter Solar Gain, while on the right: the same relationship in respect to Summer Solar Gain.

Requirements that building envelope has to fulfill can be briefly divided into two categories, that are:

- **mandatory requirements**, that means those defined by local, regional and national regulations we are obliged to respect to ensure a minimum level of performance;
- **discretionary requirements**, that can be reached exceeding the previous ones with advanced design options or construction practices, promoted to improve as much as possible the performance of building system.

Among such groups, we can make one more subdivision, by distinguishing requirements on the basis of the main field to which they pertain. So, we can talk about **technological requirements**, intended as those that comprise all the issues whose control is entrusted to the building envelope and whose minimum values to be respected are generally defined by regulations. They concern energetic, visual and acoustic issues and, more in general, all the requirements of technological nature, even if specifically directed towards plants or other specific parts of the system.
On the other hand, we can recognize **typological requirements**, that have to be satisfied mainly through spaces' disposal within the building in relation to the external environment (orientation, wind, sun, …). They basically concern user-related issues, both in terms of layout and enjoyment of the spaces as well as in control and management terms.

So, to fulfill both the above-mentioned requirements, a well-designed, efficient and effective building envelope has to:

- ensure the comfort within confined spaces during juxtaposed seasons;
- guarantee a correct thermal and acoustic insulation level of its opaque components as well as the correct installation, in order to avoid thermal bridges that could compromise its performance;
- provide an appropriate number of openings, properly treated and shaded in order to maximize positive solar-heat-gains during cold seasons whole avoid overheating during hot seasons;
- adopt effective ventilation strategies;
- make use – as far as possible – of renewable sources for energy production purposes;
- exploit building automation strategies to optimize operation modes and functioning of the whole building system, even according to end-users' habits.

Last but not least, it has to consider the continuously evolving relationship among architecture, men and environment.

To give an overview of what are in details the major requirements that building envelopes have to satisfy, as well as the relative reference parameters that as to be controlled during the whole process, they are here briefly described, divided into the two recognized categories.

Technological requirements

As stated above, technological requirements attain mainly comfort perception[7] within buildings, both from a thermal as from an acoustic point of view.
They are strictly related to material properties, form and fabrication that compose the building envelope and basically can be grouped under the energetic and acoustic definition.

[7] Human comfort sensation within confined spaces is verified when the internal temperature is comprised between 24 and 25 degrees during summer, and among 18 and 22 degrees during winter. Clearly, this perception depends on a subjective sensation (caused by variables such the metabolism, the clothes level and the degree of physical activities).

Energetic issues

Energetic issues comprise parameters and requirements that mainly pertain to thermal and thermo-hygrometric control that has to be guaranteed by building components.

For transparent component, in particular, energetic issues are significant and mostly influenced by incident solar radiation, that determines phenomena able to increase undesired thermal loads within rooms (such as the greenhouse effect) and consequently serious challenges to deal with.

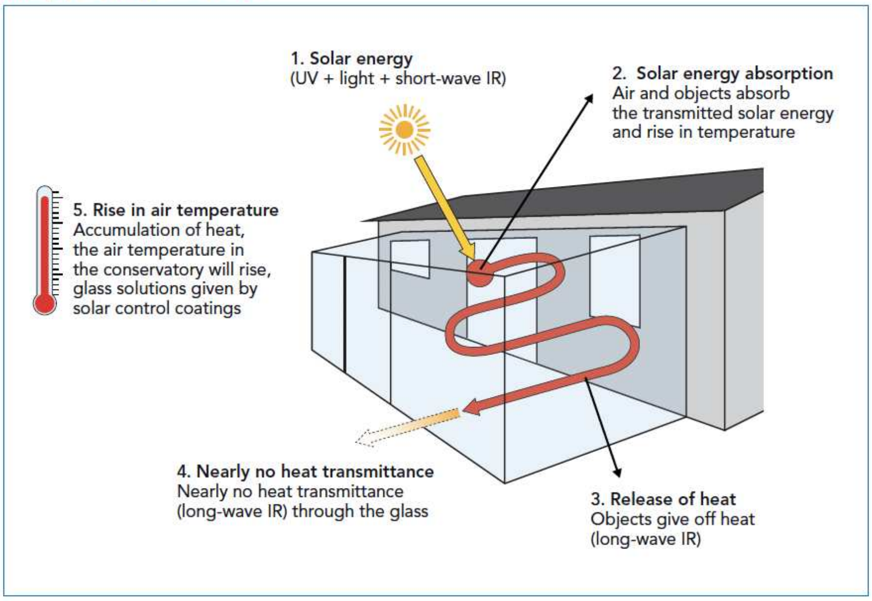


Fig. 07 – The greenhouse effect.

Materials and components' ability to retain heat and to tackle temperature's peaks – in other words, their thermo-energetic behavior – is expressed through physical parameters such as thermal transmittance, thermal resistance, heat conductivity[8], heat capacity[9] and specific heat, thermal lag and frontal mass, for opaque layers.

On the other hand, as anticipated before, the definition and description of the energy performance of transparent components is quite more complex due to the fact that they can interact with incident solar radiation; for this reason, they have to be described in terms of both thermal and optical parameters.

[8] The heat conductivity or thermal conductivity (λ [W/m°K]) represents the insulation performance of a material, and it is expressed through its ability in transmitting heat. The lower is the value of the heat conductivity the better will be the heat insulation performance of the material.

[9] The heat capacity [J/K] of a material expresses its ability in storage heating to further release it to the surrounding environment. This feature is particularly important during summer season due to the reduction of thermal heating loads during the whole day thank to the attenuation and delay of heat entering in rooms; on the other hand, during winter, this ability allows to diminish building's internal thermal fluctuation.

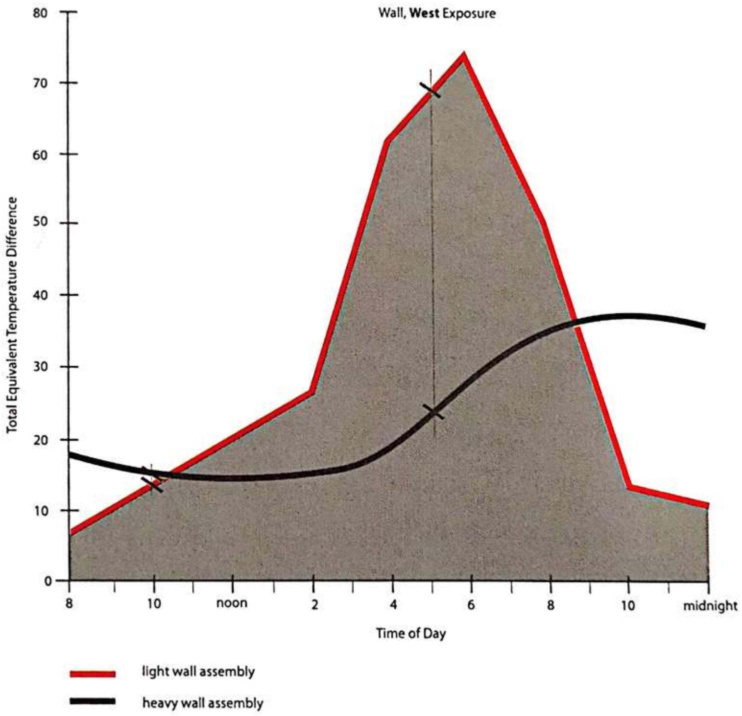


Fig. 08 – Diagram that indicates the temperature variation in both light and heavy envelopes for a west-facing façade, St. Louis, Missouri.

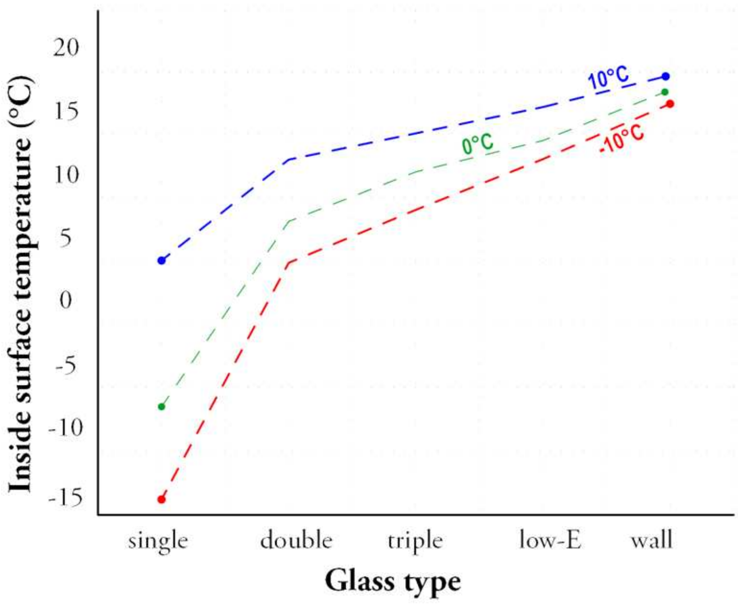


Fig. 09 – Diagram that shows the relationship between glass type and outdoor temperature trend with internal surface temperature variations.

The energy performance level of a building envelope is currently evaluated, in Italy, on the basis of its correspondence to the requirements established in regulations, which, in turn, descend from European Directives in terms of energy efficiency.
Up to now, the key laws that cover the reduction of buildings' energy consumption, thus result in parameters and requirements that have to be respected, are the **2010 EPBD** (Energy Performance Buildings Directive) and the **EED 2012** (otherwise known as EPBD Recast) even if significant are the update proposed by the Commission in 2016 to promote the use of smart

technology in buildings[10], as well as the agreement reached on such update at the end of 2017 about the addition of a series of measures to the current Directive «aimed at accelerating the cost-effective renovation of existing buildings. There will also be updates to provisions on smart technologies and technical building systems» […] (EC, 2018, available at https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings).
The last Directive in chronological order is the 2012/27/UE that, among other measures, establishes the national goals of energy efficiency to be respected.
Italian regulations adopted the last European directives with different legislative measures; the **D. Lgs. n. 102/2014** in particular (with further modifications and integrations), constitutes the acknowledgement of the EED 2012/27/UE which establishes a framework for the promotion and enhancement of energy efficiency towards national energy savings' goals within 2020.
The **D. I. of the 26th of June 2015**[11] instead, also called "Minimum Requirements Decree" is the one that completes the implementation of the EPBD 2010/31/UE, occurred with the **L.G. n. 63 of the 4th of June 2013**, that first introduced the directive by modifying the previous **D. Lgs. n. 192/2005** which in turn implemented the old European Directive 2002/91/CE.

For opaque envelopes, the energy requirements that have to be fulfilled – according to the previously mentioned regulations – are:

- the **thermal transmittance**, or U-value, expressed in W/m^2K, that changes according to the climatic zone[12];
- the **frontal mass**, intended as the mass for surface's unit of the opaque wall, expressed in kg/m^2 and fixed in a minimum value of 230 kg/m^2. This parameter has been introduced to avoid energetic evaluation only under stationary conditions, trying to simulate the energetic behavior of the wall even in dynamic conditions, thus trying to limit the effects of external temperature variations within confined spaces;
- the **thermal periodical transmittance** (Y_{IE}), expressed in W/m^2K and intended as the ability of an opaque element in displacing and attenuate the thermal flux that passes through it in a day. It basically quantifies the inertial capacity of a component, that means its ability in diminishing internal temperature variations if compared to external one during the summer season, as well as to store heat during the day to further release it gradually during night. This value has to be lower than 0,10 W/m^2K and it is strictly connected to the frontal mass of the component.

One of the parameters that influence most the energetic behavior of a building is the **amount of natural light within rooms**, coupled with its correct balance with the artificial compound.
Basically, if a building has correct morphology, dimension and position of its opening, we can say that it will be able to maximize the natural lighting supply.

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[10] On the 30 of November 2016 the Commission proposed an update to the Energy Performance of Buildings Directive to help and promote the use of smart technology in buildings and to streamline the existing rules. The Commission also published a new buildings database – the EU Building Stock Observatory – to track the energy performance of buildings across Europe. More information and materials about are available at the following link:
https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition

[11] The last Decree in chronological order that deals with energy efficiency issues, so far.

[12] In 1993, the D.P.R. n. 412 introduced the classification of municipalities in six climatic zones, on the basis of the values of the annual heating degree days.

However, to ensure lighting comfort, the natural compound has to be accurately designed according to the type of activities and use of spaces, exploiting even the reflected and diffused light components and resorting to particular devices if necessary.
Such requirements are clearly ensured exclusively by the presence of transparent building components, for which Italian in force regulations establish different parameters if compared to opaque ones. First parameters are those aimed at ensuring a correct level of natural lighting within confined spaces, expressed through the **average daylight factor**, defined in the D. M. of the 5th of July 1975, which established minimum residential standards as well as the threshold for average daylight factors, according to the destination of use. For residential rooms the average daylight factor is fixed at 2%; it is expressed in percentage as the ratio among the average illuminance of a confined space, given by natural light, and the external illuminance on a horizontal surface, exposed to the vaulted sky, without any obstruction, in an overcast condition.
Other parameters involved in the definition of the environmental comfort related to transparent building components are those connected to the amount of light passing through the glazing, thus means to the selective/reflective ability of the glass employed. Unfortunately, these values (transmission coefficient, solar heat gain coefficient or light to solar gain ratio), are too often a prerogative of designer and technicians' best practices because they are not always taken in consideration in regulations, although the D.L of the 26th of June 2015, defines a parameter that must be controlled in new buildings, defined as the ratio among solar equivalent summer area and the area of the net surface:

$$A_{sol,est}/A_{sup\ utile}$$ [13]

The first parameter takes into account glass' features, shading systems, shading coming from external bodies or objects and orientation and it is calculable following a formula stated within the Decree[14], while the second expresses the area of the net glazed surface. It has been established that this parameter has to be less or equal than 0,040.

Acoustic issues

Speaking about technological requirements cannot avoid mentioning acoustic issues. The acoustic well-being of a room indeed is a fundamental parameter to guarantee the proper development of activities within it.
The acoustic quality of an environment does not depend only on the presence or not of a disturbing-sound source but also from many other factors, function of the environmental features of the surrounding, of the level of eventual background-noises as well as from constructive and technological building's features.
So, if on one hand correct design and installation of building components has to be properly done to control such issue, on the other, even the correct arrangements of rooms within the building – that must occur after the evaluation of the presence of actual or potential sound sources thus predisposing, if needed, protected view for sensitive uses and/or exploiting distribution spaces as buffer spaces – can help for the achievement of an adequate comfort level.
The evaluation of acoustic comfort happens referring to the sound level, that means in relation to a maximum threshold of acceptable noise that does not disturb a person within the environment.

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[13] The first parameter takes into account features of glass, shading systems, shading coming from external bodies or objects and orientation and it is calculable following a formula stated in the Decree (see Appendix A, Paragraph 2.2).

Sounds indeed spread in air or through materials with different speed, according to two different mechanisms:

- via air transmission, when sound spreads freely in the air without facing solid barriers;
- via structural transmission, when sound spreads through solid structure by means of elastic vibrations.

In addition, in building components it is necessary to distinguish among direct transmission, which happens when sound energy transmission occurs only through the considered components, and flanking transmission, which happens when the transmission is through structures near the one considered.

Among Italian regulations, the reference document for acoustic issues in buildings is still the Decree of the 5^{th} of December 1997, which establishes performance that buildings must achieve in relationship to **acoustic insulation,** among different residential units, toward outside as well as flanking.

Acoustic insulation is defined as the difference among the average sound pressure values between adjacent rooms: one room in which is located the sound source and the receiving room, in which is located the receiver; such value is not an intrinsic property of building components, instead it depends by:

- the acoustic properties of single components;
- the mechanical properties of bearing structures;
- the acoustic absorbing features internal surfaces' materials, that determine the sound reflection within the two environments.

In the D. L. 5/12/97 minimum values that building components have to respect have been established according to buildings' destination of use. For residential buildings, the maximum value for façades standardized acoustic insulation is established at 40 dB.

Typological requirements

Environmental comfort in confined spaces is strongly related to rooms' layout within buildings, both in relation to the functions that take place in them as towards climatic and micro-climatic external conditions.

Therefore, spaces' arrangement must take into account needs related to thermal, lighting and acoustic comfort as well as towards activities carried out within them.

Even building orientation must be carefully considered, in order to maximize solar positive contributions where necessary while passively act on heat-losses by means of buffer spaces towards disadvantageous views.

So, diversified thermal regimes that occur at various orientations, due to different daily irradiation conditions, must, therefore, be reflected by the internal distribution of environmental units.

To generally resume common best practices, we can say that on north orientation, temporary environmental units and buffer spaces that can protect main rooms from external thermal variations can be located; on south orientation, long-term main environmental units, that require high thermal and light comfort should be appropriated, while on intermediate orientations (east/west) long-term secondary environmental units, used for a particular time of the day, would be fine.

All the above-mentioned questions must be considered even in relationship to new ways of life, habits and family settlement of end-users, far from being static over time due the constant transience and fluidity of such VUCA[15] reality.

[15] VUCA is an acronym used to describe or reflect on the volatility, uncertainty, complexity and ambiguity of general conditions and situations (source: Wikipedia, the free encyclopedia, https://en.wikipedia.org/wiki/Volatility,_uncertainty,_complexity_and_ambiguity).

2.1. The "Smart" Concept: different definitions, several meanings

«You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete».
R. Buckminster Fuller, 1895-1983

Even if the idea of "smart" is far from being newly born, since that it takes, in its basic form, inspiration from nature, where all living organisms possess stimulus response abilities, the application of this concept to the architectural field is quite recently, having appeared in literature only at the end of the last century to define materials and components with unconventional features or selective and specialized performances, opposite to traditional ones. However, due to the multitude of existing definitions about what **smart**[1] senses, coupled with the fact that, especially in architecture, this concept appears still fluid, Addington and Schodek, formerly in 2005, recognized that it can be employed without a precise definition of its meaning, because it appears surprisingly difficult.
So, today, the **smart feature** in the architecture's domain is generally associated to **materials and technologies highly-engineered**, **able to respond in an intelligent way to the context in which they're inserted if subjected to external stimuli**, as well as to **vary their properties, change their structure and/or form or to assume different functions** (Drossel et al., 2015).
Thus, referring to smart materials and technologies means speaking about something with an advanced and sometimes dynamic response, by its nature juxtaposed to "traditional" materials and technologies, generally equipped with mainly static performances.
Nevertheless, it has to be said that there is a very fine line that divides "smart" materials from "conventional" materials (Bogue, 2012; 2014) because a lot of existing materials can «react or respond to some stimulation» (Oliveira et al., 2018, p. 270) so to behave in a smart manner;

[1] See, for instance, the definitions provided within: Addington and Schodek (2005), *Smart Materials and New Technologies for the architecture and design professions*, Oxford: Elsevier Architectural Press, such as:

Chapter 1, pg. 1, «Defined as "highly engineered materials that respond intelligently to their environment'", smart materials have become the "go-to" answer for the 21st century's technological needs».

Chapter 1, pg. 3, «Smart materials are often considered to be a logical extension of the trajectory in materials development toward more selective and specialized performance»; and, again, [Smart Materials] «their properties are changeable and thus responsive to transient needs».

Chapter 1, pg. 4, «Whereas standard building materials are static in that they are intended to withstand building forces, smart materials are dynamic in that they behave in response to energy fields».

Or, again, the following:

«smart materials and structures are those objects that sense environmental events, a process that sensory information, and then act on the environment» Kroschwitz, J. (1992), *The Encyclopedia of Chemical Technology*, New York: John Wiley & Sons.

«Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled manner by an externally applied field value, such as stress, temperature and electric or magnetic fields. This behavior is reversible and consequently enables these materials to fulfill actuation and sensing functions in one component», Drossel, W.-G. et al. (2015), Smart^3 – Smart Materials for Smart Applications, paper presented at *CIRP – 25th Design Conference Innovative Product Creation* and published in CIRP 36 Procedia 211-216.

this is even more true in architecture, where buildings' global performance largely depends by the overall behaviour of a set of heterogeneous components.
So, in the specific field of technologies for architecture, **different interpretations of such concept seem possible**, that go from the single building material to the component – in which heterogeneous materials and products relate each other in a "smart" way – up to the building envelope system in its whole, in which different components work together to provide a dynamic and tailor-made performance response, according to the variability of boundary conditions.
Therefore, the "smart" concept has not to be intended only as the integration of different or unconventional features in a given material, component or system, but it can also be attributed to the intelligent application of something within building system in its whole or, again, to the intelligent management of a complex organism such as the building one.

Fig. 01 – Berkshire Residence, Olson Kundig (2014), Berkshire, Massachussets (USA). Private residence designed as low-tech smart home, symbolic of the smart definition here provided. In this project indeed, facades can transform without recurring to advanced technologies but just employing a complex system of cranks and levers.

So, it is clear that, especially in the specific domain under investigation, several and complementary definitions of the concept of "smart" seem possible and suitable for the different application-scales that mark out building process.
Accordingly, such idea led to the definition of smart buildings as systems able to adapt, in a responsive way, not only to the variability of the boundary conditions but even to the continuously evolving needs of their end-users. Casini[2] (2016) indeed, defines a "smart building" the evolution of a "Nearly Zero Energy Building" in which to the high and static performance of employed materials and technologies, the possibility of dynamically control building's environmental parameters depending to the variation of external or internal conditions, is added.

[2] Casini M. (2016), *Smart building. Involucro 2.0* (*op. cit.*)

Fig. 02 – The Smart building concept as the evolution of the concept of sustainable building, passing through the NZEB building.

So, a smart building is not only an edifice that make use of building automation technologies – definition which sounds as rather reductive – but it is a building equipped with technological solutions able to provide high performance in terms of comfort, energy efficiency and environmental sustainability, capable of dynamically interact with the surrounding and to acquire data and information useful for optimize its functioning, thus correct possible inefficiencies.

Despite of such quite common agreement, literature on smart buildings is quite lacking, especially regarding the formulation of a precise shared definition, as each author emphasize certain issues over others.
A definition that seems suitable for the present research is based on the performance that an architecture must ensure to appropriately respond to actual standards though its envelope, that basically can be resumed as follow:

- heat-insulation control;
- acoustic control;
- sun protection, during hot seasons;
- daylight control and active shading, when needed;
- maximization of SHG, during cold seasons;
- active air and ventilation control;
- energy production, through renewable sources;
- indoor air quality control;
- passive design strategies and exploitation of site's resources;
- reports and data on real performance, during operation time;
- self-adjustment capabilities based on users' feedbacks or predetermined input sceneries.

Evidently, this entails the adoption of new, efficient building materials and components as well as of Information and Communication Technologies (ICT) to perform monitoring and controlling functions[3], such as, for instance, temperature sensors and heat detectors, light-level detectors, movement and occupancy sensor, smoke and gas detectors, status-sensors (e.g. IAQ, open windows, breaking sensors, etc.).

[3] OECD (2009), *Smart Sensor Networks: Technologies and Applications for Green Growth*, available at: DSTI/ICCP/IE(2009)4/FINAL)

2.2. Internet of Things and ICTs for Smart Buildings

The rapid development in Information and Communication Technologies created, over the last decade, the technical basis for the current implementation of the Industry 4.0; this refers to the transformation from automated to intelligent manufacturing that determined the networks' extension to real objects and things[4], allowing new unconventional and interesting possibilities even in architecture.

Indeed, the applications of building sensors and wired objects, as well as their coupling with smarter control systems, are forming the basis for smart buildings that generally make use of such technologies to optimize construction, monitoring and management costs[5]. Examples of smart controls are promising and reporting significant savings: from 10% from simple controls up to 60% for the most advanced[6].

	HVAC	Lighting	Shading	IAQ	Switching devices	Security and safety
Temperature and heat detectors	✓		✓			✓
Light level detectors		✓	✓		✓	
Movement / Occupancy sensors	✓	✓		✓	✓	✓
Smoke and gas detectors	✓			✓		✓
Status sensors	✓	✓	✓	✓	✓	✓
Glass break sensors						✓

Tab. 01 - Smart Buildings' automation technologies.

Since, in recent years, the management of building systems has become ever complex – by means of new dynamic and variable controls of high-performance building – the domotic market has increasingly spread, especially in the residential sector, where ICTs are constantly growing.

One of the projections, among others, expected that by 2020 more than 50 billion devices will be connected each other and to the cloud[7], lowering costs and efforts by taking advantages of powerful cloud-based data analytics. This will progressively result in estimated savings of up to 150 Mtoe (1,745 TWh) per year by 2028 (Casini, 2016) that means the 22% of all buildings' energy consumption and the 9% of total final energy consumption of the entire European Union.

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[4] The so-called Internet of Things, that is – in other words – the connection of almost all types of devices into a network through the web, often without the interference of man. IoT should be not treated as an independent technology but as a combination of many technologies and aspects that complement each other (Andrzej Magruka, *The most important aspects of uncertainty in the Internet of Things field – context of smart buildings*, Operational Research in Sustainable Development and Civil Engineering - meeting of EURO working group and 15th German-Lithuanian-Polish colloquium (ORSDCE 2015), published in Procedia Engineering 122 (2015) pp. 220 – 227)

[5] Talon and Strother (2017), among others, estimate that the adoption of Building Automation Technologies or Building Automation Control Systems would allow to obtain within 2028 a saving of more than 150 MToe (the equivalent of 17.455x108 KwH) per year.

[6] Lindera L. et alii (2017), "Big Building Data - a Big Data Platform for Smart Buildings", paper presented at the CISBAT 2017 – International Conference Future Buildings & Districts Energy Efficiency from Nano to Urban Scale, Lausanne, and published on Energy Procedia 122, pp. 589-594.

[7] OECD, *Smart Sensor Networks: Technologies and Applications for Green Growth, 2009.*

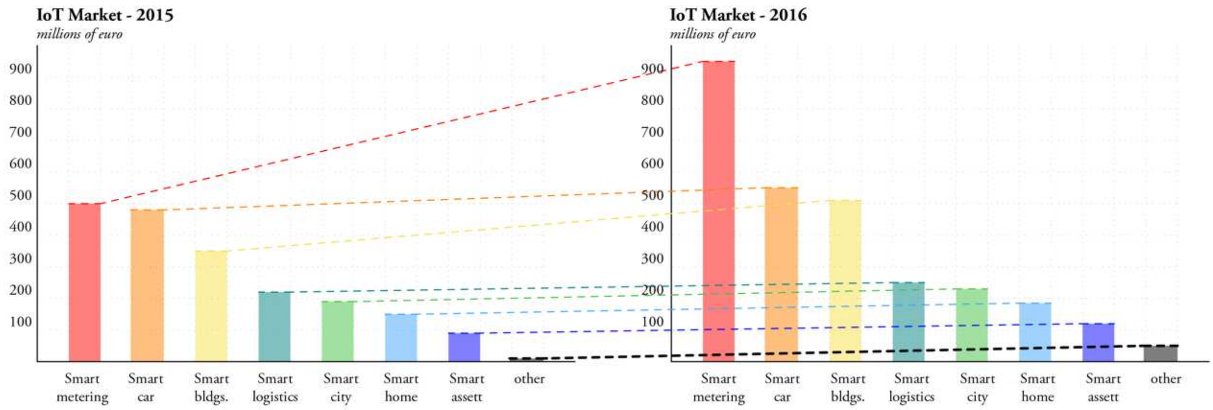

Fig. 03 – IoT Market's growth forecasts.

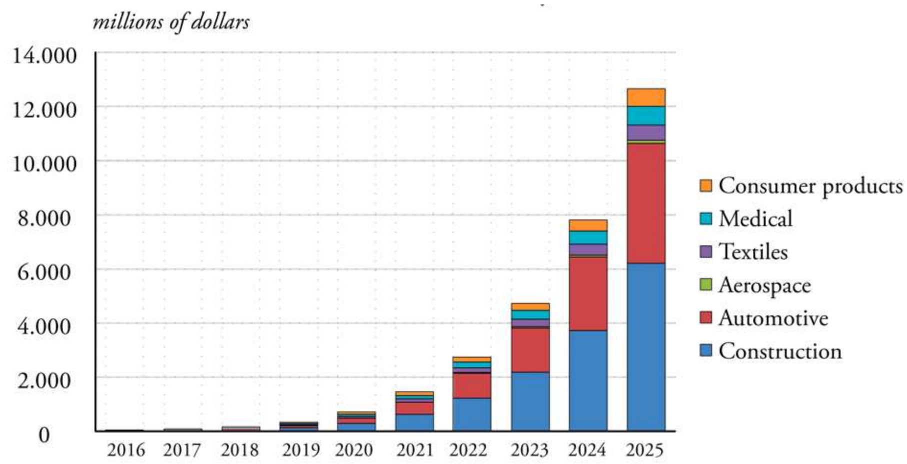

Fig. 04 – Forecast of Smart Multifunctional Materials.

The value of IoT is not only in enabling technologies but rather in the value that collected data can provide to make processes more efficient, reducing cost and managing things and people in a complex environment.

Most of the actual widespread technologies are currently based on advanced ICT systems and make use of shared integrate data models, such as the above-mentioned cloud technologies.

With the general "cloud" term, it is intended a technology «that allows organizations to outsource data storage, communication, and/or processing»[8] which comprises «consumer and business products, services, and solutions delivered and consumed in real-time over a network»[9].

Cloud-based solutions are easy to deploy, able to collect and process data from anywhere at any time, deliverable to any user platform and easily scalable and expandable.

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[8] Leblond S. and Shoumi S., Schneider Electric – White Paper 998-2095-11-05-15AR0, Rev 0.

[9] Talon C. (2013), *The impact of Cloud Computing on the Development of Intelligent Buildings*, IDC, Energy Insights.

Cloud terminology	Definition
Public Cloud	"Multi-tenant environment" where the computer resources used are shared with other tenants. A Public Cloud is cheaper than a Private Cloud but gives the user no control over the actual systems.
Private Cloud	Defined as "Single-tenant environment" in which each client has systems and hardware dedicated to their applications. This costs more than a Public Cloud but provides greater control over technologies uses and ownership of security.
Hybrid Cloud	Environment that combines both Public and Private Cloud resources. In a Hybrid cloud, the Private Cloud is reserved for sensitive data and applications while the Public Cloud is used where possible to reduce costs.

Fig. 05 – Definition of Cloud terminology.

As result, clouds are ideal platforms for building management and automation because they can gather a great amount of data about HVAC, lighting and energy, collected from different buildings and at regular intervals, that can be further employed to implement same systems in new and improved applications of them.

Clouds that group building data on real consumption are still not so widespread because of the complexity of collecting and gathering such a variety of data. Having a meaningful sample indeed means to collect data about a lot of different parameters (representative of the specific features investigated) for an enormous period, which implies a huge quantity of information to be collected, gathered and systematized to be further re-used for any kind of activities.

Existing datasets on building uses are no more than a set of ten; they assemble information that goes from building energy consumption to building occupations, temperature, relative humidity and so on. Furthermore, datasets generally involve commercial and business buildings while residential ones are much less frequent; the reason why data about the residential stock are scarce depends on the complexity to acquire them due to the heterogeneous of properties and on the scarce availability of users in making their home accessible to install measuring devices.

Moreover, all of the abovementioned information, to have significant and scientific reliable results, would be put in relationship with estimated and real consumption data, not always available.

Current most significant datasets are certainly those promoted and developed by the U.S. Department of Energy[10], such as the BPD (Building Performance Database), the nation's largest dataset of information about the energy-related features of commercial and residential buildings. This database combines a lot of data collected by different institutions and bodies to make them available to the public.

Another significant attempt is those made within the European Project ODYSSEE-MURE[11], coordinated by the French agency ADEME[12] and supported by the Intelligent Energy Europe program, that involves the national energetic and environmental authorities of the 28 European countries, as well as Norway, Switzerland and Serbia, and to which has taken part even ENEA. It is a dataset, adopted by the European Commission as statistic fundamental for energy policies, that collects energy consumption and energy efficiency as well as CO_2 indicators using two complementary databases: ODYSSEE and MURE, that contains policies

[10] Available and consultable at: https://energy.gov

[11] http://www.odyssee-mure.eu (The access to the database is free for all EU Ministries, Concerted Action EED, EED Committee Members and EU Universities as well as reserach centers for non-commercial uses and via subscription for other users).

[12] Agence De l'Environnement et de la Maîtrise de l'Energie (Agency for the environment and the energetic management)

and measures of energy efficiency and their impact since the ‘80s. Meaningful of the abovementioned complexity is the sample disclosed by Italy: 85 provisions of which 65 are actually in force, a clear expression of the great amount of data to be collected and, at the same time, to be respected over time.
In addition to the ODYSSEE-MURE database, six data-tools have been developed to monitor market-penetration signs of progresses of a selection of energy-efficient technologies and practices, to identify drivers responsible for the variation of energy consumption to further compare and benchmark the energy efficiency and performances of countries.
In this direction are even going research centers and units, urged by the EC; proof of what claimed is the ongoing EU-funded project ExcEED[13], coordinated in Italy and aimed at «establish a robust and durable return of knowledge mechanism, collecting actual buildings energy performance data, and providing information to designers, energy managers and policymakers».

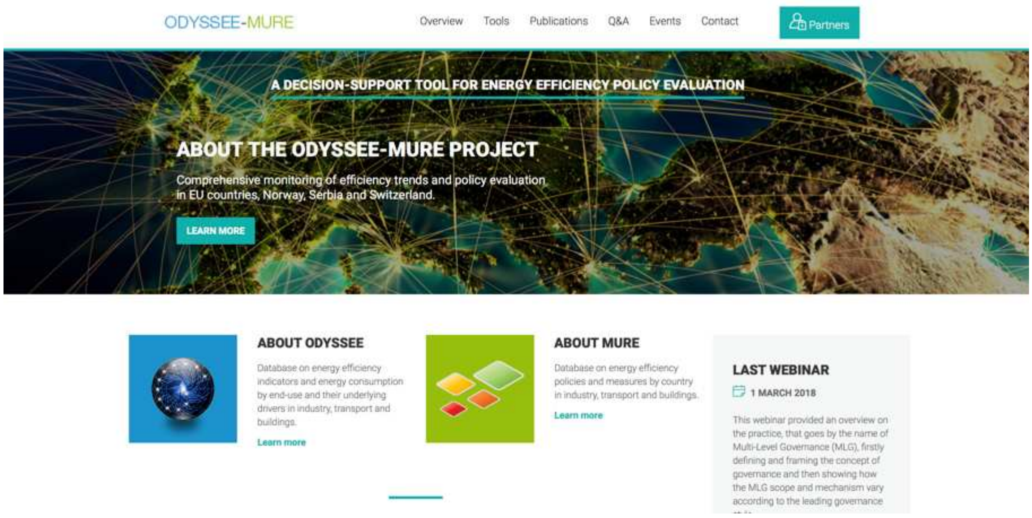

Fig. 06 – ODYSSEE-MURE website homepage [available at: http://www.odyssee-mure.eu]

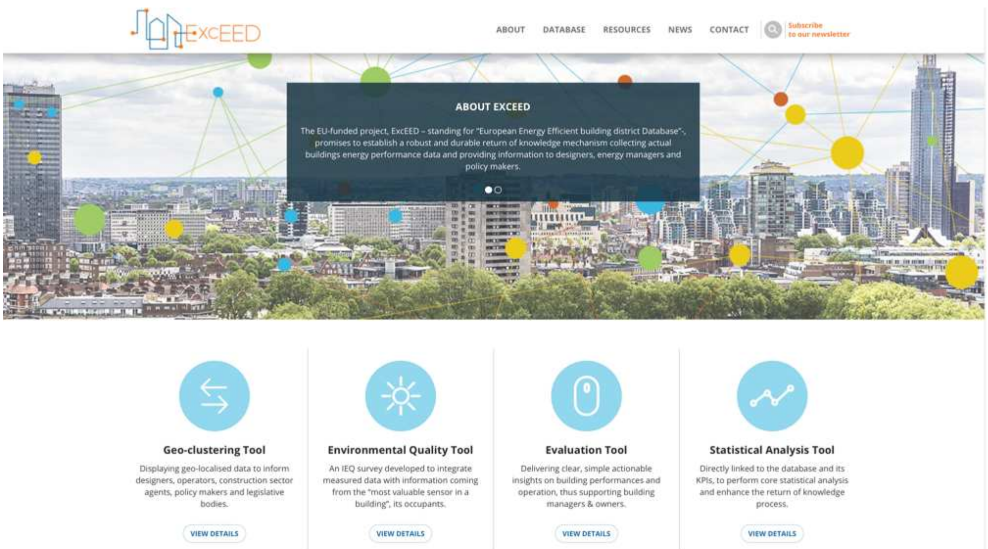

Fig. 07 – ExcEED project’s website homepage [available at: http://www.exceedproject.eu]

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[13] European Energy Efficient building district Database.

As we saw so far, building envelope constitutes the element through which buildings establish a "dialogue" among external environment and end-users' needs; which means it can be considered the "place" in which the various performance issues come to a balanced synthesis thanks to the technological responses of materials and components that made it up.
However, through the incredible modifications that building envelopes suffered over time, due to the changes occurred in ways of living and human habits as well, we can say that the different technological innovations – that evolved accordingly – have performed a significant role in shaping Architecture, leading to the production of buildings with formal and expressive values destined, in turn, to change, in a continuously evolving relationship among evolutions and experimentations.

3.1. Technological innovations for new architectural languages

«It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change».
Charles Darwin, 1809 - 1882

Since the firsts human lives' forms have appeared on earth, building envelope constituted a shelter to protect its occupants from external actions of every kind. A sort of constant among the different forms of dwelling that succeeded over time is the fact that it always tried to exploit positively the environmental context of reference, producing organisms whose formal and technical-constructive features interacted (more or less) coherently with the surroundings.
However, the concept of building envelope intended as we do right now takes his origin from Bahnam (1969) work, in which he introduced the concept of the "well-tempered environment". Analyzing the history of Architecture indeed, Bahnam recognized three main "environmental control models", each of them associable with a building envelope type and with its specific features.
The first model identified was the "**conservative**" model, characterized by an environmental control that makes use of massive walls with lack of openings to reduce heat losses in a cold climate, as well as over-heating during hot periods; the second model was the "**selective**" model, suitable for hot-humid climate because – differently than the previous one – it exploits favorable external conditions within confined spaces, such as natural lighting for passive heating. The third and last model instead, was the "**regenerative**" model, spread where buildings have inadequate mass – being only a barrier among internal and external – thus the environmental control is entrusted to technological systems.
Such evolutions, although with some variations, have produced over time several examples of artifacts, able, in a more or less effective way, to interact with their context. This has generated a sort of shared approach to exploit positive common features, reducing the impact of negatives factors to determine "efficient" buildings behavior.
The design choices that have resulted from this approach, coupled with the evolution and modification of structural systems determined by progress' advancements, shaped in history certain distinctive features of Architecture. So, if early building envelopes were formed on the

main features of available materials[1] and technologies, progressively, the production of new tools, the discovering of new materials as well as the improvement of construction techniques led them to evolve in a direct relationship with housing conditions, allowing to recognize distinct building elements or techniques as characteristic of a precise point in time, being significant examples of the period that generated it.
In addition to as such representative buildings, even traditional houses are in a certain way significant of the characteristics of the place in which stand, of the climate and the resources available, thanks to the design strategies adopted as well as to the materials employed, according to the approach explained before.

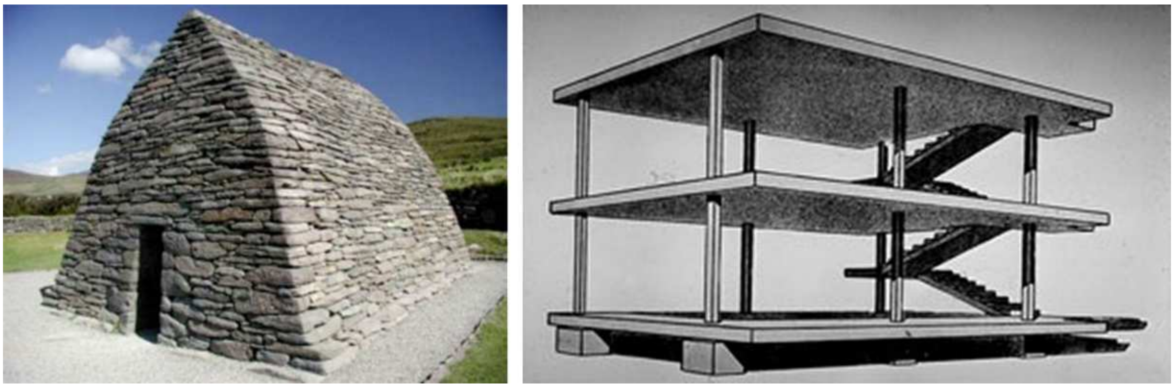

Fig. 01 – On the left, traditional massive buildings; on the right, Le Corbusier's Domino House.

However, it is only with the advancement of the technological progress that characterized the years among the 19th and the 20th centuries that architectural languages underwent a real revolution, due to the introduction of new industrial processing techniques and materials – as reinforced concrete, glass and steel – that allowed the realization of ever more light and transparent casings, in contrast with ancient and strongly massive load-bearing structures.
In the post-war period, science and engineering promoted limitless possibilities for progress and advances in material science profoundly altered the nature of the architectural design. Following this enthusiastic tendency, Architecture became universal, detached from a precise application context and inspired only by trends and materials as well as by technologies' possibilities.
Besides this "flattening" of the architectural features, new requirements have been flanked to ancient primary needs, due to new emerging ways of life.
This has resulted in an acceleration of the ageing of a great number of recent buildings, making them inadequate towards specific environmental requests. This is the reason why, to overcome this issue, robust use of technological systems began, making in a short time the model so-defined unsustainable, due to the large use of fossil energy sources employed to ensure a constant performance level.
Thanks to the awareness that this development would not be possible anymore, coupled with the understanding of the importance that the development of more sustainable building practices would have, another change in conceiving building envelope occurred. So, it started to be conceived as a set of layers, each of them equipped with a different task, able to perform precise functions and to meet current performance requirements. Building parts previously made of one single material were now engineered and assembled using several different sources and suppliers, privileging materials light in weight and thin in section (Trubiano, 2013). However, the global fascination that led to the construction of skins lighter and thinner than ever before has resulted sometimes in negative consequences for the energy performance of

[1] First attempts to operate an environmental control were tents or cave-shaped shelters that employed timber frame structures with bamboo frames, cladded with leaves or textiles, sometimes equipped with a symbolic meaning and generally with provisional features suitable for nomadic ways of live.

buildings. Indeed, technologically advanced buildings are often the poorest performing, routinely condemned for not addressing the energy required in maintaining their interiors conditions (*ibidem*). Also because to the extreme variation of external boundary conditions, building envelopes with static features have shortly revealed their limits in intelligently control all the parameters responsible for their correspondence to current regulations as well as to the continuously evolving needs of their end-users.

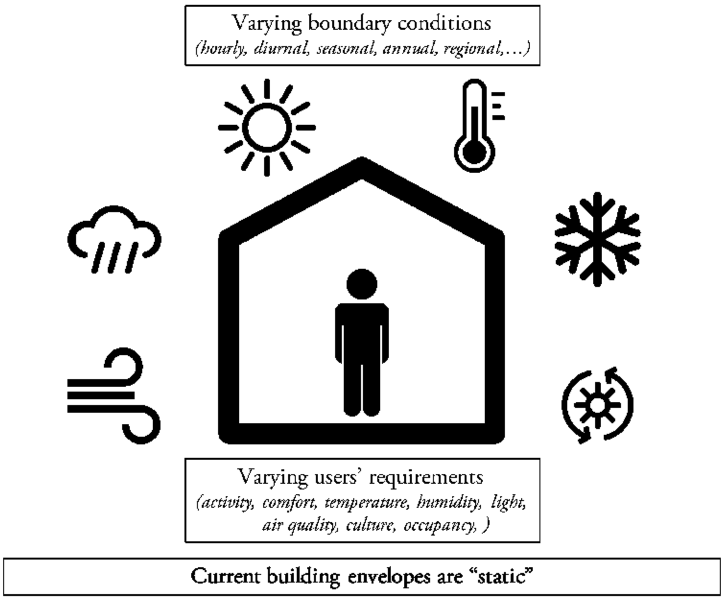

Fig. 02 – Building envelopes' requirements variations according to the evolutions of boundary conditions and users' needs as well; current building envelope are static towards such modifications.

Such a situation led professionals and researchers in the field to seek technical solutions able to overcome this shortcoming, favouring a new concept of building envelope to emerge.
Thus, building systems were no more conceived following the conventional relationship among needs and performance – in linear logic of direct proportionality between climatic conditions and requirements of building materials and component – but rather they started to be imagined as objects able to change their performance responses according to the variability of climatic conditions, characterized by the adaptability and the flexibility of their formal and technological structures regarding the external environment.

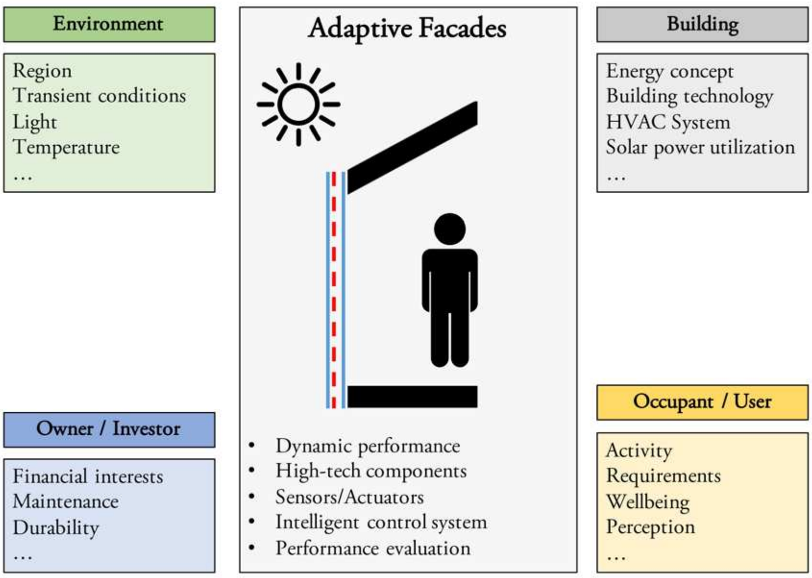

Fig.03 – New building envelope concept: the "adaptive" façade

«This peculiarity, which is the "adaptive" ability, can be either passive or active; the latter case includes the possibility of changing the conformation of the technical elements to activate, therefore, a proper interaction between outdoor and indoor environment» (Lucarelli et al, 2012).
In general terms, indeed, it can be said that there are two levels of mechanism that drive the adaptive behaviour: the micro-level, that implies changes in a smaller scale (general within the material itself), and the macro-level, often associated with motions of various kinds. In macro-level adaptive behaviour, the driving principle is generally an external energy input. Despite this subdivision, combinations are also seen.
Such possibilities, previously unthinkable, led to a further change in how designers think and conceive building envelope, influencing the development of modern architectures whose designs are distinguished by increasingly complex forms. In this innovation process indeed, it is clear the fact that even architectural language suffered significant modifications as well, due to the new opportunities introduced in this field that radically changed how we think and build.

3.2. The CABS: reconciling the multiple-performance in a holistic way

According to what stated so far, the complexity of the current society coupled with the evolution of building envelope performance requirements – continuously implemented by new needs and efforts aimed at bridge the gap between current building practice and future energy-saving targets – has led building envelope to evolve into a system different from the previous reference model, based on static designs that do not possess the flexibility to adapt and react to changing conditions.

In the early past indeed, "conventional" building envelopes typically had static properties (suitable, in their average values, for the nearly surrounding in which they are located), the fixed ratio among transparent and opaque surfaces, fixed insulation values and – sometimes – great amount of glazed surface, often not appropriately shaded; in general, their design was scarcely optimized for energy use, transferring the control of the internal comfort condition to massive use of energy for heating and cooling.

However, even if formerly this approach sounds rather functioning, nowadays it no longer seems possible; for these reasons, "modern" building envelopes started to be conceived as "dynamic" systems, designed in a focused and prompt way to offer variable performance according to the variations of environmental conditions, following a non-linear approach.

In the aim to design architectural built environments that better meet users' needs, adaptive design strategies started to be developed, holding great promises for the next generation of high-performance buildings.

So, to the three typologies of building envelope seen before[2], a fourth model could be added: the **smart building envelope**. Often defined in literature as CABS[3] (firstly by Loonen, R. C. G. M. in 2010, who set, we can say, the first state-of-the-art on the topic) or with other complementary terms[4], these systems are equipped with unconventional features, able to move building performance beyond the level of the best static building envelope design.

The idea to develop adaptive and responsive buildings finds its origins in the early '80 when Mike Davies proposed in his work[5] the concept of a polyvalent wall; further, this conception has been alternatively chased over years, finding inspirations even from nature's adaptability as survival strategies. Such dynamic systems indeed «can be compared to a living organism, in which each part react to external and internal stimuli, adapting to the surrounding context to regulate and optimise the overall energy balance necessary for its functioning» (Romano et. al., 2018).

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[2] See Par. 3.1. "Technological innovations for new architectural languages".

[3] Literally: Climate Adaptive Building Shell

[4] Such as switchable [SWIFT. Ar*chitectural and technical guidelines - Handbook for the use of switchable facades technology*, 2003], adaptive, responsive [Kirkegaard, P.H. and Foged, I. W. (2011) Development and evaluation of a responsive building envelope. In: *Proceedings of adaptive architecture*], dynamic [Lollini, R., Danza, L. and Meroni I. (2010), Energy efficiency of a dynamic glazing system, *Solar Energy*, 84(4):526–37], intelligent [Stacey, M. (2011), Adaptive architecture introduction. In: *Proceedings of adaptive architecture*; Wigginton, M. and Harris, J. (2002), *Intelligent skins,* Oxford: Butterworth-Heinemann; Ochoa, C. E. and Capeluto, I. G. (2009), Advice tool for early design stages of intelligent facades based on energy and visual comfort approach, *Energy and Buildings* 41(5):480–8], reactive, interactive [Fox, M. and Kemp, M. (2009), *Interactive architecture*. New York: Princeton Architectural Press], kinetic [Fox, M.A. and Yeh, B. P. (1999), Intelligent kinetic systems in architecture. In: *Proceedings of managing interactions in smart environments* MANSE], sensitive and many other synonyms used in an interchangeably manner.

[5] Davies, M. (1981), *A wall for all seasons*, RIBA Journal, Volume 88, Issue 2, pp. 55-57. In this work he presented the idea of a generic building envelope, not limited to a particular building type, that would perform different complementary and simultaneously actions such as nano-metric absorber, radiator, reflector, filter, etc.

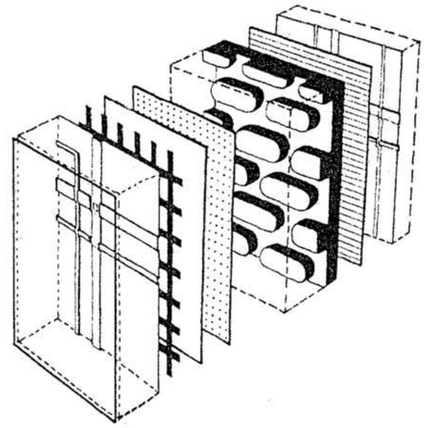


Fig. 04 – Schematization of the concept of Davies' polyvalent wall.

Biological system	Adaptive action performed	Adaptability feature	Similar building component	Corresponding Smart material
Insects	Optimization of lighting	Size, location, colour and efficacy	Technical systems	LEDs, Electroluminescent, Chemoluminescent paints
Spiders and scorpions	Monitoring of structural systems	Stress and deformation, crack and vibration monitoring	Self-healing/repair devices for monitoring facades	Fibre-optics, Piezo-electrics
Lotus leafs	Surface finishes	Self-cleanings, heat and radiation reflection, durability	Coatings	Self-cleaning paints and finishes, conductive and luminesce paints

Tab.01 – Analogy between building needs and biological systems

Although different types of adaptive façade concepts have been developed over years, their implementation is still in the beginning stage; indeed, there is no consistent definition of façade adaptability even if studies related to characterisation issues, design parameters and classification already exist.
According to literature, there are over 30 definitions for an intelligent building, intended as a "technical enhanced building", even if a recurrent statement defines such systems as those able «to change some of their functions, features or behaviour over time, in response to changing performance requirements and variable boundary conditions […] with the final goal of improving overall building performance[6]».
Knaack (2007), again, supports the use of the term "adaptive" as an alternative of "intelligent" or "smart", because, as he stated, «even if buildings able to adapt to changing climatic conditions are called intelligent buildings, […] the term intelligent can be misleading when used in the context of buildings or façades, [so] we will use the term adaptive façade instead».
An intelligent building indeed is an "object" designed to «employ technologies to get the best advantage, in order to make the most of the resources and facilities available»[7], defined by the Intelligent Building Institute (Washington D.C.) as something «which integrates various systems to effectively manage resources […] to maximize: occupant performance, investment and operating cost savings and flexibility» or, in other words, «that incorporates the best available concepts, materials, systems and technologies […] to achieve a building which meets or exceeds performance requirements of buildings' stakeholders» (European Intelligent Building Group).

[6] Loonen, R.C.G.M., Trčka, M., Cóstola, D. and Hensen, J.L.M. (2013), Climate adaptive building shells: State of the art and future challenges, *Renewable and Sustainable Energy Reviews*, 25 (2013), pp. 483–493.

[7] Definition given by McClelland, S. (1988) (ed), *Intelligent Buildings; An IFS Executive Briefing*, Bedford, England: IFS Publication/Springer Verlag, Blenheim Online.

Therefore, the difference between "intelligent" and "smart" is implicitly related to the type of system's control: in the first case, automations are used as controlling elements while in the second case, control is entrusted by materials' properties.
Regarding other terms previously mentioned, each of them could be used and intended with slightly different meanings: "interactive" for instance, could imply the use of technology but still in combination with human inputs (Velikov & Thun, 2013).
So, despite the multiple available definitions, it is interesting to note that Casini (2016) defines "smart buildings" the evolutions of Nearly-Zero-Energy buildings, in which, the possibility of dynamically control building's environmental parameters, accordingly to the variation of external or internal conditions, is added.

Terms	Definition
Kinematics & Kinetics	Kinematics is the study of motion through system geometry without considering mass or external forces that may cause movement (RAO et al., 2003; Meriam and Kraige, 2012). Kinetics is the study of movement laws, induding forces and masses, and emphasizes on the relationship between motion and its causes (Lienhard, 2014).
Dynamics	Defined as the study of movement which occurs due to forces applied to an object (Meriam and Kraige, 2012).
Retractable	Term commonly used in architecture for defining textile membrane roofs, either bunched or folded, a term or expression similar to movable (Barozzi et al., 2016).
Convertible	Mostly associated with building mobility, similar to building envelopes, that suggest change form in the short-term depending on needs and functions (Otto, 1971).
Transformable	The term describes units or systems with the intrinsic property of controlled change, such as the ability to be foldable, retractable or shape-shifting (Hoberman, 2006).
Performative	Referred to systems that can mediate surrounding environment for user comfort, such as building skin systems able to control external factors in relation to predefined architectural performances (Turrin et al., 2012).
Interact	The term refers to either intuitive or automatic responses to meet user requirements. Interactive building architectures use sensors to operate kinetic systems and enable intelligent materials in order to initiate change in appearance and the environment (Sung, 2012).
Smart	Process-related concept that conveys automatic control or operation of building envelopes, including heat loss or gain, daylighting, air ventilation and other systems. Smart systems use information technology to connect several subsystems that typically operate independently (Brooks, 2011).
Responsive	Referred to a system moving and responding from the outside based on specific factors, thus allowing interaction with a passive environment (Hasselaar, 2006).
Adaptive	The ability of a system to adjust by itself in relation to a changing environment. An adaptive system, as in the case of building skins, has the ability to adapt the features, behavior or configuration of the external environment (Dewidar et al., 2013).

Fig. 05 – Summary of common terms employed in contemporary architecture to define its "adaptability" feature.

Terms	Reference
Smart	Fox & Yeh, 1999 Velikov & Thün, 2013 Brugnaro, Caini & Paparella, 2014 Casini, 2016
Switchable	Beevor, 2010
Adaptive	De Marco Wernder, 2013 Frei, 2015 Möller & Nungesser, 2015
Responsive	Negroponte, 1975 Ferguson, Siddiqi, Lewis & De Weck, 2007 Kirkegaard & Foged, 2011 Heiselberg, Inger & Perino, 2012 Kolodziej & Rak, 2013 Velikov & Thün, 2013 Meagher, 2015
Dynamic	Lollini, Danza, & Meroni, 2010
Intelligent	Hayes-Roth, 1995 Kroner, 1997 Compagno, 2002 Wigginton & Harris, 2002 Clements & Croome, 2004 Knaack & Klein, 2008 Ochoa & Capeluto, 2009 Stacey, 2011 Velikov & Thün, 2013 Masri, 2015
Interactive	Fox & Kemp, 2009 Velikov & Thün, 2013
Kinetic	Zuc & Clark, 1970 Fox & Yeh, 1999 Loonen, 2010 Ramzy & Fayer, 2011 Wang Beltran & Kim, 2012 De Marco Werner, 2013 Fortmeyer & Linn, 2014
Active	Ochoa & Capeluto, 2008
Advanced	Ad, Heiselberg & Perino, 2011
Biomimetic	Vermillion, 2002
Bio-inspired	Loonen, 2015
Controllable	Konstantoglou, Kontadakis & Tsangrassoulis, 2013
Movable	Schumacher, Schaeffer & Voght, 2010

Tab. 02 – Synoptic comparison of terms recently employed to alternatively defined the so-called CABS and related references.

Therefore, it is evident the fact that a shared definition, in literature, is still missing, as each author emphasize certain issues over others; Addington and Schodek indeed, already in 2005, stated that «the blurring of boundaries between disciplines has given rise to a near crisis in the definition of their respective roles. […] Even within the discipline of architecture, terms such as "smart", "responsive" or "adaptive" have been used loosely and interchangeably, creating confusion as to their specific meaning and their conceptual relationship to building performance and design».

However, coherently with the purposes of the present dissertation, a general definition is here provided, trying to recap and synthetize what are key aspects in facades' intelligent and adaptability.

[a smart/advanced/adaptive building is] a construction in which different technologies and devices (sensors, readers, computers, etc.) are allowed to interact within the building envelope – among them and with the surrounding – to provide unconventional behaviors, or to collect data or information useful for further implementations.

Such definition takes its origin from the performance that architecture must ensure to appropriately respond to actual standards through its envelope, thus to tailor its behavior to better meet all the requirements, that basically can be resumed as follow:

- heat-insulation control;
- acoustic control;
- sun protection, during hot seasons;
- daylight control and active shading, when needed;
- maximization of SHG, during cold seasons;
- active air and ventilation control;
- energy production, through renewable sources;
- indoor air quality control;
- passive design strategies and exploitation of the site's resources;
- reports and data on real performance, during operation time;
- self-adjustment capabilities based on users' feedbacks or predetermined input sceneries.

Fig. 06 – Cannon Design, The Occidental Chemical Building (1981), already known as the Hooker Building at Niagara Falls, New York; it is one of the first buildings which incorporate intelligent responses in its skin. The protecting louvres indeed, tilt automatically to keep the sun's direct beams from striking the internal glass wall thanks to the action of a solar cell on one louvre on each bank.

Therefore, a smart adaptive building envelope must:

- **adjust** its performance – according to hourly, diurnal or seasonal variations – to reduce the impact of external changes in the environment that can be of different orders of time.
  The building envelope is firstly influenced by short-term fluctuations, which change in the order of seconds, such as wind speed or wind directions; secondly by changing conditions in the order of minutes, such as cloud variations or daylight availability. Additionally, changes in the order of magnitude of hours and/or diurnal changes are present, as a consequence of occupants' behavior and/or meteorological boundary conditions. Finally, the last group of variations are seasonal changes during winter, summer, spring and autumn, due to different boundary conditions such as sun altitude.

- **adapt** itself to the abovementioned variations, at the macro-scale (that means through the envelope in its whole) or at the micro-scale (that means through a single material). According to Loonen et. al. (2013), macro-level adaptability is related to mechanical movement of envelope's parts, resulting from sliding, expanding, creasing, rolling, inflating and so on. This can be obtained with external, supplemental components or building envelope's components or, again, by the movement of the entire façade or the building as a whole; while micro-scale adaptability mainly attains to materials' properties changes (thermos-physical, optical, energetic, …) in response to different variations.
- **control** its modes of operation, in an extrinsic (that means they make use feedback to implement their operation using sensors, processor or actuators with local processor or through a control unit) or intrinsic (that means they self-adjust their behavior according to external stimuli) way.

So, this allows to draw some important conclusions about adaptive façades in general, conceiving them as systems able to provide an adequate response to changes in the internal and external environment, ensuring or improving functional requirements of building envelope in terms of controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading or humidity control; in few words, able to deliver intended functionality.

Fig. 07 – Widely heralded as "the world's first intelligent building" the edifice designed by Skidmore Owings and Merril in Hartford, Connecticut, employs an integrated services system to manage and link together the previously separated functions of air conditioning, mechanical controls of vertical connections and safety systems.

Purpose	**Responsive function**	**Operation**	**Component** *(materials and systems)*	**Response time**	**Spatial scale**	**Visibility**	**Degree of adaptability**
Thermal comfort	Prevent	Intrinsic	Shading	Seconds	Building material	No	On-off
Energy performance	Reject	Extrinsic	Insulation	Minutes	Façade element	Low	Gradual
IAQ	Modulate		Switchable glazing	Hours	Wall	High	
Visual performance	Collect		PCM	Day	Window		
Acoustic performance			Solar tubes	Seasons	Roof		
Control			Integrated solar systems	Years	Whole building		

Fig. 08 – Purposes for adopting adaptive functions in the building envelope.

3.3. Smart Advanced Technologies: innovation and experimentation

Despite the growing interest towards smart building envelopes, a common ground in which stand innovative materials and technologies available is still not existing even if different efforts have been made in that direction.
The current situation is made of dispersed and individual research activities, too often lacking in cooperation with productive and industry field, that mainly deals with specific performance evaluation of dynamic insulation or smart windows, just to mention a few.
Despite these attempts, it remains unclear what type of desired behaviour results from their applications and what are the best technical solutions as well as how available technologies can be profitably integrated within building systems.

Climate	Smart Envelope materials and technologies
HOT	• Low SHGC glazing or dynamic glazing • Dynamic shading systems • BIPV and PV glazing • Cool roofs and reflective technologies • Phase Change Materials (thermal inertia) • Green roofs and walls • Self-cleaning glazing and surfaces • Ventilated roof and walls • Adaptive skin facades
COLD	• Advanced insulation glazing • Glazed double-skin facades • Dynamic shading systems • Antireflective glazing • Light redirection and optical systems • Heating glazing • Bio-adaptive glazing • ETFE envelope • BIPV technologies • Self-cleaning glazing and surfaces • TIM • Phase Change Materials (passive solar gains) • Advanced insulating materials • Adaptive skin facades

Fig. 09 – Smart buildings' advanced technologies and their relation to climatic conditions.

As an attempt to give an overview of smart advanced technologies suitable for the present dissertation, a classification that descends from building envelopes' requirements previously identified has been done.
So, advanced technological solutions identified, among those that show smart characteristics, have been classified according to the following categories:

- **advanced, integrated façades**, able to provide high-performance as a whole, both actively or passively activated;
- **adaptive glazing** or **daylighting systems** in general, able to regulate the amount of incident solar radiation over time to avoid overheating during summer, while maximizing gains in winter;
- **thermal massive** components, employed with **storage** purposes,
- **dynamic insulation systems**, able to face seasonal variations; summer days indeed, need for low insulation level while during winter thermal insulation is important to keep heat inside the environment.

The first category comprises all the systems definable as advanced façade, that means double skin surfaces as well as all composition of materials and components able to respond as a whole to particular needs, both statically or dynamically.

Within this category further subdivision can be done according to façades modes of operation whether they are initiated by external stimuli (such as temperature variations), through automated control or by mechanical (kinetic abilities) of certain components.
Adaptive glazing (or daylight systems in general) attains instead to all the technologies related to selective control of the incoming incident solar radiation, aimed at reducing, control and filter its entering within rooms. They can be systems with excellent static performance – that not need of activation –, selective (active) components, or chromogenic devices, that are systems able to vary their visible appearance thanks to different external inputs. In this category fit even solar control louvers or shading system in general, especially in their advanced or self-regulating form.
Thermal massive components are all the devices that exploit thermal inertia (and eventually variable thermal mass) «to attenuate peak loads and keep temperature fluctuations within the comfortable range» (Hoes et al., 2011).
Finally, dynamic insulation systems were firstly introduced in windows systems to prevent heat losses in winter, by putting insulation materials within shutters. Recently, different control strategies have been adopted to operate an adaptive insulation level, generally based on the control among heating and cooling loads between outside and inside. Within this category, one of the most promising existing technologies are PCMs, used to store thermal energy while exploiting phase change variations. Indeed, thanks to their ability to store and further release heat they can reduce peak loads in buildings, increasing thermal inertia of the component in which they are embedded.
Since the energy storage capacity of PCMs is greater than in common building materials, they are often used in lightweight construction, whose adoption allows for better control of thermal flows. However, it has generally to be said that smart features in buildings are often resulting from physical interactions among different components and their related domain[8].

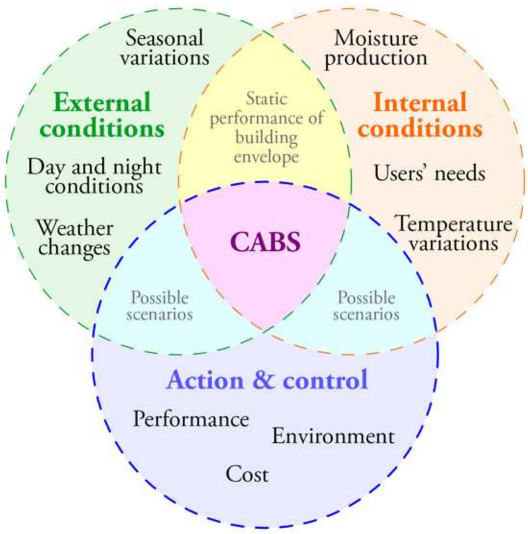


Fig. 10 – CABS' domains: their interaction can origin 15 different possible combinations.

[8] Loonen (2010) recognized four domains for classify building systems according to the physical interactions they influence, that are: 1) thermal, 2) optical, 3) air-flow and 4) electrical. CABS that affect the first domain generally cause changes in the energy balance of the building though processes of heat exchange per conduction, convection or radiation or by heat-storage processes; second domain systems are related to visual perception within confined spaces, that changes due to surface modifications in terms of transparency; third domain systems are related to ventilation effect near the building systems (generated by the façade or by effects of wind direction or speed) while the last domain refers mostly to the conversion of energy.

While most of the abovementioned solutions generally contribute to the energy and comfort optimization, examples for adaptation with completely different intentions are also found. Well-known cases are the media façades that target at aesthetic expressions, art or commercial media performance, most often not incorporating energy use aspects.
Thus, "adaptation" of façade seen from the perspective of architecture is not necessarily linked with performance optimization, even if newer developments of media façades show even more often the employment of renewable energy for its operation or consider their elements as multi-functional components that contribute to the energy concept.

Fig. 11 – Examples for media facades with adaptive functionality: Green Pix Zero Energy Media Wall uses photovoltaics for the needed energy, Bejing, China, by Giostra & Partners

Within the field of smart and advanced technologies, a special mention is deserved by **sensors** and **actuators**, fundamental components of smart systems. Too often indeed we tend to merge the technologies employed with their operational controls even if they are quite commonly separated.
Control is part of a system that includes a sensor, an active device, an interface for inputting the desired response and an algorithmic for controlling the response of the device. So that a system is activated, thus fulfill the expected goal, an input able to generate its reaction is needed. It can be external or internal, defining respectively **extrinsic** or **intrinsic controls**.
Extrinsic controls are those based on sensors, actuators and processors: sensors "connect" the adaptive system with the external environment, transmitting the variations of reference parameters' changes and, after confronting them with the set-points, transferring such information to the processor; actuators are the elements that produce a reaction in the system following a signal received from sensors and then elaborated by a processor; while processors are the controller units in which collected data are elaborated to provide an adequate response, according to design provisions.
On the contrary, **intrinsic control** (even defined such as passive systems) are those which can count on the ability of the systems to self-adjusting in response to external stimuli, generally of environmental nature. The most relevant expressions of such definition are the so-called Smart Materials, which provided a significant evolution in building envelopes domain (see ***Appendix II*** for an insight of smart materials for smart applications in architecture).
As researchers in the field of architecture, by better understanding how smart technologies and material systems work, architecture can be pushed forward to truly reach a new era of innovation, creating better and more adaptive built environments with optimal consequences for their users.

RESEARCH MANAGEMENT TOOLS
Materials and methods

According to what stated so far, under their abilities in implementing buildings' features, **smart technologies** (referred to the specific domain of building envelope) seem equipped with **great potential**, not only from an aesthetic point of view – due to the almost unlimited formal possibilities that they allow – but even from a **performance-oriented perspective**, thanks to the opportunities they offer in controlling building energy consumption, making them suitable for different purposes and needs.
To complete the systematic characterization of the technologies able to provide building envelope with such smart features, as well as to understand how their adoption has innovated building practices as well, by modifying building architectural language, a **sample of theoretical case studies** have been analyzed.
This review has been useful to better understand the current state of such innovative applications as well as to:

- providing a holistic qualitative evaluation framework that helps to gain insight into the degree of fulfilment of every façade requirement;
- developing a map of adopted strategies in such systems as part of high-performance buildings;
- recognizing common patterns and, at the same time, identify unexplored concept to help further development of high-potential innovative smart building technologies;
- identifying what is currently a gap in this broad scenario.

4.1. <u>Case studies' definitions: selection and classification</u>

This section collects and presents **over 50 buildings** and/or prototypes ascribable to the category of 'Smart Buildings', intended in the wide meaning given to this term in the present dissertation. The case studies have been selected among recent architectural expressions that show particular forms of innovations, according to criteria that include environmental sustainability and energy efficiency as well. In particular, a huge sample of buildings has been investigated, analysing their technological characteristics as well as their conditions of use thus seeking after their "smart feature".
To reach for it, have been analysed: ***i***) the opening systems and their potential adoption of particular techniques or technologies designed to resolve critical issues related to thermal or visual comfort; ***ii***) the presence of shading devices equipped with particular advanced, innovative, or anyway, uncommon features, thus, for this reason, considerable as "smart"; ***iii***) the presence of innovative forms of thermal insulation or advanced insulating materials; ***iv***) the existence of energy harvesting or generation systems; ***v***) the typology of building envelope and the possible adoption, within it, of innovative technical solutions or, again, of solution that innovatively reinterpret traditional methods and materials, to allow new functioning models and new performance; and, in general, ***vi***) the presence of advanced technologies as described within the previous chapter.
In this selection, even the geographic position has been taken into consideration to gather data coming from different application contexts.
Such a collection is a result of an extensive literature survey, gathered from different sources such as scientific publications, websites of companies or building components manufacturers

and architecture magazine, online and in their printed version.
This selection does not intend to be comprehensive of the multitude of realizations ascribable under the above-mentioned definition; instead, it would provide a general overview within the state-of-the-art about smart technologies for building envelope, discovering what kind of solutions have been seep through current building practice, understating their strength and weaknesses and trying to comprehend which of them can become new architectural languages by their abilities to solve present and future critical issues.
Also, this collection can be further used for several purposes as, for instance, as a starting point for future research related to smart materials and technologies in architecture, for professionals and consultants active on such topics, or as a catalogue of possible applications of such technologies still not widespread in the broad scenery of architectural design.
Finally, concerning the specific purpose of the present dissertation, the case-studies' analysis has been oriented towards the investigation of the specific role that transparent building components play within smart building envelope systems, understanding their application, technical and performance potential supporting work's future development and promoting their full comprehension.

4.2. Case-studies: assessment criteria and parameters' definition

The sample identified has been examined according to the following criteria.
First, a **general examination** has been done, reporting for each case study its general information, including its intended use (*residential / service-industry / specialized*), its state of development (*concept or prototype / real-scale edifice / under construction*) and the climate condition of its geographic position, defined, in a synthetic way, according to Köppen Climate Classification. Definitions of each category are given at the end of the paragraph.
Secondarily, the study follows according to **two different levels of analysis**; the first level aims at identifying the **type** of component/system equipped with smart function(s) (*insulation / glazing / shading / opening systems / energy harvesting device / energy generation devices / other*) and its **application scale** (*element / material / component / façade system*)[1].
The second level of classification regards case-study behaviour and it is aimed at synthetically describe its operation mode, providing a qualitative analysis of it, by reporting:

- the (main) **purposes** for which the advanced technologies have been adopted (*thermal comfort / visual performance / acoustic comfort / energy management / energy generation / IAQ / interaction and users' control / other*).
- the (main) **smart function** that such technologies perform (*collect and storage / control / prevent / reject / allow interaction*).
- a **categorization of the case study**, based on its behaviour, according to the following categories:
  - *High-performance.* Defined for all the case-studies that shows high-performance or particular features that don't fit with other categories, such as, advance insulation.
  - *Selective.* Defined for all the case-studies that present particular selective filter abilities towards external factors, such as, for instance, blinds or shading systems. It is evident that this category mainly pertains materials and components with selective properties towards light and solar control.
  - *Dynamic façade.* Defined for all the case-studies with one or more façades able to vary their performance features over time. This has been considered as a separate category because previous ones can be prerogative of a single material or component

[1] A component is defined as an assembly of different set of elements; it forms a complete constructional or functional unit as part of a façade, while a façade system is intended as a set of different transparent of opaque components; it fulfils all basic technical façade functions such as insulation, rain and wind tightness.

while in this section are intended only façades in their whole.

- *Adaptive glazing.* This category can be considered a specialization of the previous one even if it has been considered to separate it for its specific role in the context of the present research; within it fit all chromogenic technologies applied to glazed components.
- *Energy generating.* Defined for all the case-studies with particular smart features that allow them to integrate within the envelope energy generation abilities;
- *Control system.* A category that includes in a wide sense all of those case-studies that allow interaction and users' control.

  Due to their complementary nature, more than one category could be suitable for each case-study.

- the **operation mode** of the smart element (*passive*, if activated by means of external stimuli of various nature, or *active*, if activated through electrical control);
- the type of **trigger** of the smart function (*thermal / electromagnetic / optical / air quality / occupants / other)*;
- the **type of response input**, that describes how smart components are controlled (*extrinsic / intrinsic / self-adjusting / users' control*)
- the **degree of adaptability**, that expresses how the component/system with smart functions responds to changing boundary conditions (*on-off /gradual*).

Last information provided regard further evaluation of the case-study identified, aimed at giving a definition of its **technological readiness level**[2], intended, in this dissertation, as the level of diffusion, within the market, of the technologies identified.
Further, a brief description of the case study has been provided, equipped with a picture and/or other schematics that demonstrate the appearance of the case-study and its working mechanism. Specific highlights, if available, have been provided.
Main references to the information collected and employed to describe the case-studies are reported at the end of each form.

*Fig. 01 – (next pages) Category definition employed to perform the case-studies analysis. The following figure resumes and clarifies the criteria employed to conduct the general examination (in green) – concerning case study's general information, intended use, state of development and climatic condition of its application context – and the two-level analysis on each case-study: the first level (in red) aims at identifying the **type** of component/system equipped with smart function(s) and its **application scale**, while the second level (in yellow) regards case-study behaviour and the description of its operation mode. Finally, information regarding the technological readiness level of each case-study (intended, in this dissertation, as the level of diffusion, within the market, of the technologies identified) has been provided (in light blue).*

[2] The Technology Readiness Level (TRL) express the level of technological maturity of a technology, initially developed by the NASA in 1974 and further employed by other authorities such as the European Commission (Technology readiness levels (TRL), HORIZON 2020 – WORK PROGRAMME 2018-2020 General Annexes, Extract from Part 19 - Commission Decision C(2017)7124[3]). It is based on a range from 1 to 9 where 1 is the lower value that express an early technology while 9 is the highest that express a fully developed system.

Category definition			
General information	INTENDED USE	Residential	Basic housing suitable for accommodate one or more family (author's translation from Caniggia, Maffei, 1979, p.106)
		Service/Industry	Building of the tertiary (service-industry) sector, primarily aimed at host offices.
		Specialized	Buildings commonly suitable for a nonresidential use, that means with a high level of specialization. (author's translation from Caniggia, Maffei, 1979, p.106)
First level analysis	BUILDING STATE of DEVELOPMENT	Concept/Prototype	Pilot building at an early stage of development, intended to be used as a model for further reproduction.
		Real scale edifice	Real building
		Under construction	Real building under construction phase.
	CLIMATE CONDITION	Tropical	Tropical region in which the average temperature of the coldest month is higher than 18°C and significant level of precipitations. Generally they lack cold season.
		Dry / Desertic	Region in which the average rainfall level is lower than the dry limit.
		Temperate	Warm region in which the average temperature of the coldest month is between 18°C and -3°C. They lack a regular snowy coverage.
		Continental	Climate with warm summer and cold winter and rich rainfalls over the year.
		Polar	Climate with the average temperature of the hottest month lower than 10°C.
	APPLICATION SCALE	Element / Material	Building material or element manufactured with dimensional, geometric and performance features.
		Component	Technical element given by the assembly of different materials or elements with a specific purpose; the term 'component' describes a functional subsystem which contribute to the definition of the façade system.
		Façade system	Combination of heterogeneous components, elements and materials originating a building envelope system or at least a part of. It indicates the entire set of components of a façade including the control systems that might be used to control adaptive features of the façade.
	TYPE	Insulation	Element mainly aimed at reducing heat flux through the envelope among internal and external environment.
		Glazing	Element mainly glazed thus means aimed at ensuring an adequate level of natural lighting and ventilation within confined spaces.
		Shading	Element mainly aimed at controlling incident solar radiation.
		Opening systems	Element relevant to opening/handling devices, both related to opaque or transparent components.
		Energy harvesting devices	Element aimed at harvest and store energy. Even elements/components/systems aimed at increase thermal inertia and frontal mass of building envelope can be inserted in this category.
		Energy generation devices	Element aimed at produce energy (generally by converting it from one form to another).
		Other	Heterogeneous technologies that do not fit in the abovementioned categories.

Second level analysis			
	PURPOSES	Thermal comfort	If the technology/ies adopted is/are primarily aimed at ensuring the thermal comfort of the indoor environment.
		Visual performance	If the technology/ies adopted is/are primarily aimed at ensuring an adequate visual performance, which means correctly performing a light/solar control.
		Acoustic comfort	If the technology/ies adopted is/are primarily aimed at ensuring the acoustic comfort of the indoor environment.
		Energy management/ generation	If the technology/ies adopted is/are primarily aimed at managing/collecting/converting energy.
		IAQ	If the technology/ies adopted is/are primarily aimed at ensuring an adequate air quality level within confined spaces.
		Interaction and users' control	If the technology/ies adopted is/are primarily aimed at allowing the interaction of end users with the building systems.
		Other	If the technology/ies adopted does/do not fit in the abovementioned categories.
	ADAPTIVE FUNCTION	Collect and storage	If the adopted technologies perform a "collect and storage function" as, for instance, regarding heat or energy (e.g. PCM).
		Control	If the adopted technologies mainly perform a controlling function regarding different kind of factors, such as, for instance, incident solar radiation.
		Prevent / Reject	If the adopted technologies mainly perform a preventing / rejecting function towards different king of factors, such as, for instance towards sound.
		Allow interaction	If the adopted technologies mainly allow interactions among the building system and its end users.
	CLASSIFICATION	High-performance	Defined for all the case-studies that shows high-performance or particular features that doesn't fit with other categories, such as for instance, advance insulation.
		Selective	Defined for all the case-studies that present particular selective filter abilities towards external factors, such as, for instance, blinds or shading systems. It is evident that this category mainly pertains materials and components with selective properties towards light and solar control.
		Dynamic façade	Defined for all the case-studies with one or more façades able to vary their performance features over time. This has been considered as a separate category due to the fact that previous ones can be prerogative of a single material or component while in this section are intended only façades in their whole.
		Adaptive glazing	This category can be considered a specialization of the previous one even if it has been considered to separate it for its specific role in the context of the present research; within it fit all chromogenics technologies applied to glazed components.
		Energy generating	Defined for all the case-studies with particular smart features that allow them to integrate within the envelope energy generation abilities.
		Control system	Category that include in a wide sense all of those case-studies that allow interaction and users' control.
	OPERATION MODE	Passive	If activated by means of external stimulus of various nature
		Active	If activated through electrical or mechanical control

	TRIGGER	Thermal	Thus means due to a temperature gap.
		Electromagnetic	Thus means due to the presence of an electromagnetic input.
		Optical	Thus means due to modification in lighting.
		Air quality	Thus means due to modifications in (generally indoor) air quality such as for instance moisture level or particular values' concentration.
		Occupants	Thus means due to input of anthropic nature.
		Other	Thus means due to other kind of inputs not suitable to other categories identified, as for instance other environmental factors.
	RESPONSE INPUT	Extrinsic	If the adaptive behavior is activated through an external event.
		Intrinsic	If the adaptive behavior is automatically triggered by environmental stimuli.
		Self-adjusting	If the adaptive behavior is self-activating according to variations.
		Users' control	If the adaptive behavior is manually activated by occupants.
	DEGREE OF ADAPTABILITY	On / Off	If the adaptive feature is not adaptable but just switched on or off.
		Gradual	If the adaptive feature is gradual according to different scenario.
Further elaborations	TRL	1	Basic principles observed.
		2	Technology concept formulated.
		3	Experimental proof of concept.
		4	Technology validated in lab.
		5	Technology validated in relevant environment.
		6	Technology demonstrated in relevant environment.
		7	System prototype demonstration in operational environment.
		8	System complete and qualified.
		9	Actual system proven in operational environment.

4.3. Factsheets

CASE-STUDY NAME AND PROGRESSIVE IDENTIFIER

Smart Material House BIQ, Arup&Splitterwerk Architects
Hamburg, Germany, 2013

31

Photo Credits: *IBA Hamburg GmbH / Johannes Arlt from Project whitepaper*

CASE-STUDY BRIEF DESCRIPTION

[Introduction] The building with Bio-Intelligent Quotient (BIQ) is a pilot project with a bio-reactive façade, presented at the International Building Exhibition in Hamburg in 2013 as the first totally passive building in the world powered by algae.
It is a solid cubic structure of stonework and concrete that combines adaptable structural design (different layout typologies of apartments are available in response to contemporary demands) with smart technologies and building materials.

[The Smart Feature] The use of a material largely available in nature as renewable energy source, integrating additional features to the production system, such as dynamic shading – determined by the variable growth of algae as a function of incident solar radiation – and thermal and acoustic insulation, giving life to an organism strongly characterized by the technology employed, also from an aesthetic point of view, and potentially endowed with significant consequences also on the surrounding environment, as a means to reduce CO2 emissions though buildings' façades.

[The technologies] The system, installed on the south-east and south-west building façades (200 square meters approximately), is made up of 129 sun-tracking reactors modules consisting of a double-glazed window (with argon in the air-gap), mounted on a metal frame and

GENERAL INFORMATION

CREDITS

Design team	Arup and Splitterwerk Architects
Location	Hamburg, Germany
Project year	2013

FIRST LEVEL ANALYSIS

	Residential	Service industry	Specialized
Intended use	■		

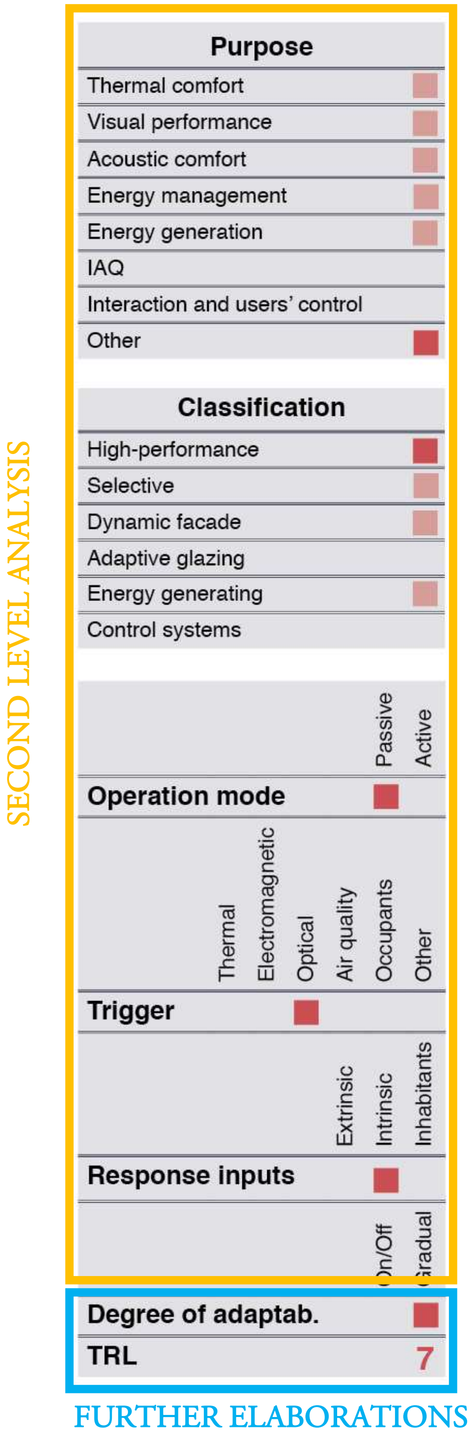
	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	■
Energy generation devices	
Other	

125



separated by a cavity of about 24 lt, filled with water and suitable for the culture medium needed for the proliferation of micro-algae.

The algae's growth, stimulated by the incident solar radiation and by the addition of CO2 as nutrient, allows the production of heat (used for heating the rooms and for the production of domestic hot water or stored for further uses) and biomass (about 30 KWh / m2 year), collected by means of a separator and placed in a container at a controlled temperature to be further used for biogas' production.

The whole system operation is guaranteed by a centralized management device that manage all the processes necessary to operate the bioreactor façade and to fully integrate it with the energy management system of the building.

[The performance] Due to the sunlight and to a constant turbulence that avoid algae aggregation, the production of heat is about the 38% of efficiency, compared to a 60-65% of a conventional solar thermal, while biomass production is at about the 10% of efficiency in comparison of the 12-15% of a conventional PV.

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2) **Lumenhaus** (2002), Viriginia Tech team, Solar Decathlon competition of Madrid (SP).
3) **Jubilee Church, la Chiesa del Dio Padre Misericordioso** (2003), Richard Meier, Rome (IT).
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6) **La Defense Almere** (2004), UNStudio, Almere (NL).
7) **Alterswohnen** (2005), Dietrich Schwarz, Domat-Ems (CH).
8) **Selimex Offices** (2005), Werner Tscholl, Laces, Bozen (IT).
9) **Spots** (2005), Realities:united, Berlin (DE).
10) **SOLAR XXI** (2006), Pedro Cabrito and Isabel Diniz Arquitectos, Lisboa (PT).
11) **Kiefer Technic Showroom** (2007), Ernst Giselbrecht + Partner, Bad Gleichenberg (A).
12) **Forest Hotel** (2008), Enric Ruiz-Geli, Barcelona (SP).
13) **Pola Ginza Building Façade** (2009), Nikken Sekkei + Yasuda Atelier, Ginza district, Tokyo (JP).
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27) **Smart Material Houses Project: Smart is green** (2012), zillerplus Architekten und Stadtplaner, Hamburg (DE).
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Museum of Paper Art, Shigeru Ban Engineer(s)
Shizuoaka, Japan, 2002

01

Photo Credits: *http://filt3rs.net/case/art-paper-museum-moving-facade-shigeru-ban-049*

[Introduction] The Shigeru Ban's Museum of Paper Art exploits contemporary materials to create modern spaces while maintaining the relationship between the inside and the outside typical of traditional Japanese architecture.

[The Smart Feature] The spatial continuity is entrusted by a reinterpretation of the traditional *shitomido*, a

CREDITS

Design team	Shigeru Ban Engineer(s)
Location	Shizuoaka, Japan
Project year	2002

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	■
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

vertical window shutter common in traditional Japanese architecture.
In this buildings indeed, all the external buildings' façades are made of moveable, translucent, glazed fibre-reinforced panels, assembled on a steel frame; in the east/west sides, panels are 10 meters height while in the south side they can be piloted out for the while height to an angle of 90°C.
Panels can be folded, thanks to mechanical guide rails, and that, when opened, act as canopies, directing shadow to the interior spaces and to their adjacent terraces.

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Lumenhaus, Virginia Tech team
Solar Decathlon competition, Madrid, Spain, 2002-2010

02

Photo Credits: *https://vtnews.vt.edu/articles/2012/05/051512-caus-aiasolar.html*

[Introduction] Born as a net-zero home inspired from the Mies Van Der Rohe Farnsworth House and designed from a heterogeneous team built within the campus Virginia tech, to foster collaboration among students of different academic departments.
The aim of such project is to combine the use of alternative technologies, new materials, advances in

CREDITS

Design team	Virginia Tech team in collaboration with the U.S. Department of Energy
Location	Madrid, Spain
Project year	2002

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.	■	
TRL		7

computer science and product design, integrating a range of sustainable strategies (compact volume, minimal air infiltration, high insulation level, natural cross-ventilation, passive heating).
Lumenhaus was exhibited in Washington DC, New York, Chicago and in Madrid, where it won the 2010 Solar Decathlon Europe Competition.

[The Smart Feature] The combination of different technologies which resulted in new possibilities for the practice of architecture in a modular and flexible architecture. The west façade is realized with an electrochromic glass able to automatically tints to regulate the light within confined spaces, the roof is equipped with photovoltaic module, while the other façades (north and south façades) are equipped with intelligent sliding layers made of insulating panels and metal shutters to filters into the house different kind of lights.
Further, Lumenhaus makes use of an innovative computer monitoring and controls system: using sensors and servomotors linked to centralized computer controls, the movable shutters and insulating panels are adjustable on an hourly, daily or seasonal basis to maximize building performance.

[The technologies] This design combine different technologies even if the most relevant is certainly the Eclipsis System, panels able to automatically open and close made of two layer, the first is a stainless steel sheet metal, patterned with a geometry of circular laser-cut openings while the second is a transparent layer made of an innovative wall assembly of two polycarbonate panels filled with Nanogel insulation. LED panels to lighten the spaces are embedded in the system.

References
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2) Lumenhaus website, available at: *https://lumenhaus.com/index2.html*
3) Dunay, Wheeler + Schubert (2013), in Trubiano, F., *Design and Construction of High performance homes. Building Envelopes, Renewable Energies and Integrated Practice*, Routledge.

Jubilee Church, Richard Meier & Partners
Rome, Italy, 2003

03

Photo Credits: *Scott Frances*

[Introduction] Conceived as part of Pope John Paul II's millennium initiative, the Jubilee Church is located outside central Rome.
Its shape, full of symbolical meanings, it's based on a geometrical structure made of squares and circles; the body of the church indeed is generated by the profiles of the three concrete shells that imply the Holy Trinity. Similarly, the reflecting pool located in the front of the complex recalls the role played by water in the sacrament of Baptism, as well as the materials used in the portico, that symbolized the body of Christ's church.

[The Smart Feature] The façades' ashlars are treated with a super brightness photo-catalytic concrete, called Millennium TX and specifically developed for this construction by Italcementi, able to maintain this whiteness over time.
Experimental tests showed indeed that after about 60 hours of sun exposure, samples of such materials – dirty with ash coming from cigarettes – recovered their original colour.

[The technologies] The above mentioned effect is obtained through a photo-catalytic behaviour, based on the use of catalysts able to oxidise harmful substances and pollutants until their complete mineralization.
Applied in architecture, these technologies allow to obtain a passive air purification, by reducing organic and

CREDITS

Design team	Richard Meier & Partners
Location	Rome, Italy
Project year	2003

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	■
Component	
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	■
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

inorganic pollutants, a deodorizing and antimicrobial action and a self-cleaning action, due to the fact that surfaces coated with titanium dioxide are totally water repellent.

References

1) Richard Meier & Partners Architects LLP, "Jubilee Church", project web-page, available at: *http://www.richardmeier.com/?projects=jubilee-church-2*

2) (2009), "Church of 2000 / Richard Meier & Partners", *ArchDaily.com*, available at: *https://www.archdaily.com/20105/church-of-2000-richard-meier*

3) V. Zacchei (2011), "Il cemento autopulente", *Post-it, Material Design*, available at: *http://materialdesign.it/it/post-it/il-cemento-autopulente_13_143.htm*

4) Conforti, C. and Marandola, M. (2009), *Richard Meier,* Minimum. Bilbioteca essenziale di architettura, Motta Editore.

Smart Wrap Pavillion, Kieran Timberlake Associates
Cooper-Hewitt National Design Museum, New York, USA, 2003

04

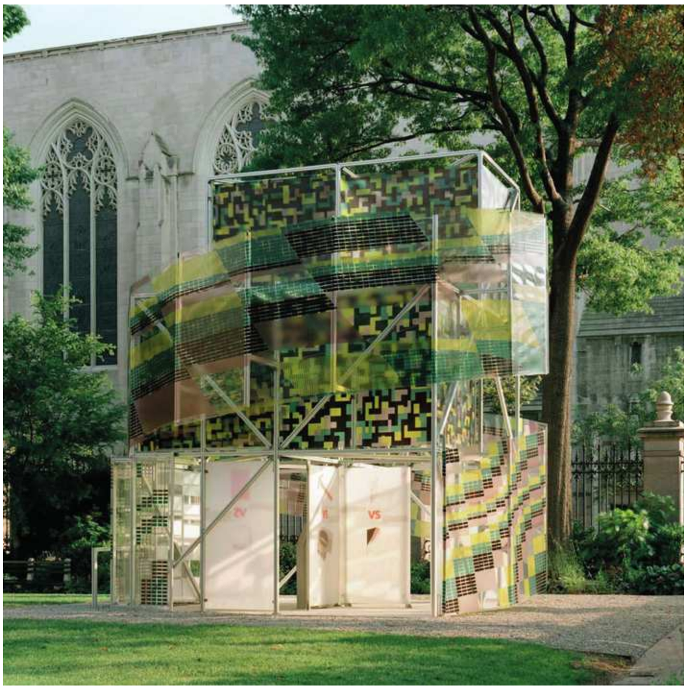

Photo Credits: *Kieran Timberlake*

[Introduction] Designed to re-imagine the traditional building envelope, the Smart Wrap pavilion is a prototype of a mass customizable, energy-generating, lightweight envelope that integrates the common functions of a conventional wall into a multi-layer skin, which can be wrapped all over the structural frame of a building. The concept from which it takes its origin aims at combine several technologies, coming from different industrial sector, to meet buildings requirements.

[The Smart Feature] The special envelope, conceived to substitute a common wall with a new technologies able to overcome its shortcomings, provided within a single solution a lot of benefit and performance that range from climate control, light and power ability.
This ability can be integrated within the envelope before its arrival on site, leading in this way to a significant reduction of costs and construction times thanks to this "mass customizable print façade".

[The technologies] The Smart Wrap deals with active and passive thermal strategies to reach for predetermined goals; it consisted of four functioning layers tensioned on an aluminium structure; each panel, made of a printed and layered polymer composite, included a transparent PET layer, specifically developed by DuPont. The four layers were assembled as follow: an inner layer with thin-film photovoltaic cells to generate electricity, a layer of

CREDITS	
Design team	Kieran Timberlake Associates
Location	New York, USA
Project year	2003

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	■
Visual performance	▪
Acoustic comfort	
Energy management/generation	▪
IAQ	
Interaction and users' control	▪
Other	

Adaptive function	
Collect and storage	■
Control	▪
Prevent/Reject	▪
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	▪
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger	▪		■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	

TRL	7

solar heat and UV blocking film and an interior layer of PET. A vented cavity between the PET layer was added to maximize solar contribution.

The prototype incorporated phase-change materials, to act as thermal regulators, Organic Light-Emitting Diodes (OLED) for lighting and information displays and pockets of aero-gel, to provide the envelope the needed thermal resistance.

During its operation within the exhibition, sensors placed on its west façade collected data on its thermal behaviour to fully understand its insulation and convection capacity.

[The performance] This layered assembly structure achieved the thermal resistance of an insulated 400mm concrete-block cavity wall at approximately 1/100th of the weight.

References

1) K. Timberlake, "How can we use emerging technology to create a building envelope of the future that integrates all the functions of a conventional wall into a thin, transparent plastic film?", Kieran Timberlake website, available at: *http://kierantimberlake.com/pages/view/28*

2) (2003), *"SmartWrap", The Pennsylvania Gazette*, available at: *http://www.upenn.edu/gazette/1103/prendergast4.html*

3) K. Timberlake, "SmartWrap Pavillon", Fabrication: Examining The Digital Practice of Architecture, available at: *http://papers.cumincad.org/data/works/att/acadia04_046.content.pdf*

4) A. Ritter (2006), *Smart Materials in Architecture, Interior Architecture and Design: Types, Products, Architecture*, pp. 191, Birkhäuser GmbH Edition.

5) K. Timberlake, "The Next Generation of SmartWrap", Kieran Timberlake website, available at: *https://kierantimberlake.com/posts/view/105/*

6) J. Prendergast (2003), "A Passion for Putting Things Together", *The Pennsylvania Gazette*, available at: *http://www.upenn.edu/gazette/1103/prendergast4.html*

Articulated cloud, Ned Kahn
Pittsburg Children's Museum, Pittsburgh, USA, 2004

05

Photo Credits: *Ned Khan*

[Introduction] The Articulated Cloud constitutes the external skin of Pittsburgh's Children Museum. It is made of 43.000 white polycarbonate panels attached to a steel frame and able to move individually according to the wind.
The aim of such translucent, plastic moveable squares is to suggest that the building has been enveloped by a digitized cloud; all the windows of the museum indeed

CREDITS

Design team	Ned Kahn and Konig/ Eizenberg
Location	Pittsburgh, USA
Project year	2004

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	■
Component	
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

face the outside through this veil. In addition, the fact that this envelope is hanged at an external frame emphasizes its floating in front of the building.

[The Smart Feature] Thanks to its translucent texture, such plastic envelope changes its optical features according on whether variations, creating at the same time ever-changing atmospheres and patterns within the museum. Moreover, this skin helps in maintain interior comfort conditions thanks to its abilities in shading and diffusing sunlight and reflecting heat.
This project was the first to be awarded with a LEED certification by the US Green Building Council due to the fact that integrate this "artwork" within the energy and environmental design of the building.

References

1) Kahn Ned, "Articulated Cloud", project's website, available at: *http://nedkahn.com/portfolio/articulated-cloud/*

2) "Articulated Cloud | Ned Kahn", *arch2o*, available at: *https://www.arch2o.com/articulated-cloud-ned-kahn/*

Offices "La Defense", UNStudio
Almere, Netherlands, 2004

06

Photo Credits: *Christian Richters*

[Introduction] La Defense office complex rely on its significant aspect to integrate itself within the surroundings; its façades indeed reflect the urban condition of the neighbourhood while the interior façades have been designed to face offices' well-being requirements.

[The Smart Feature] The particular façades' treatment confers to the building the ability to change according

CREDITS	
Design team	UNStudio
Location	Almere, Netherlands
Project year	2004

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

to the variability of the external conditions, providing at the same way the privacy of its occupants. During the day indeed, the façade changes from yellow to blue, to red or from purple to green and back again.

[The technologies] The façades are realized through the use of special glass panels in which a multicoloured foil is integrated; depending on the time of the day as well as the sunlight angle of incidence, the foil reflects different colours.

References

1) (2010), UNStudio, "Offices "La Defense", *DIVISARE.com*, available at: *https://divisare.com/projects/143011-unstudio-christian-richters-offices-la-defense*

2) UNStudio, "La Defense Offices", project webpage, available at: *https://www.unstudio.com/en/page/3289/la-defense-offices*

3) "Offices "La Defense", project, *german-architects.com*, available at: *https://www.german-architects.com/fa/projects/view/offices-la-defense*

4) La Defense Building, *WikiArquitectura*, available at: *https://en.wikiarquitectura.com/building/la-defense-building/*

Alterswohnen, Dietrich Schwarz Architekten
Retirement residence community, Domat/Ems, Switzerland, 2004

07

Photo Credits: *Gaston Wicky*

[Introduction] House for the elderly located in the Swiss Alps in which the south elevation glazed façade heats actively or passively the rooms according to the changing of climatic conditions.

[The Smart Feature] The heat capacity of the glazed wall, almost equivalent to the heat capacity of a concrete wall with a thickness of 15 cm, thanks to the insertion of a PCM.

CREDITS

Design team	Dietrich Schwarz Architekten
Location	Domat/Ems, Switzerland
Project year	2004

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	■
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger	■					

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■

TRL	7

[The technologies] The glazed panels are made of composite glass elements (four plates of 6 mm) that contains in the cavities a noble gas while the inwardly gap is filled with a salt hydrate that acts as PCM, storing latent solar heat. The façade becomes transparent when the material liquefies (when the external temperature increase) while when the temperature drops, the material will return to its solid phase, releasing the absorbed heat In addition, the prismatic glass located outward protect the confined spaces against summer overheating by refracting light.

References

1) (2004), "Alterswohnen", *german-architects.com*, available at: *https://www.german-architects.com/pl/projects/view/alterswohnen*

2) GlassX, project reference, available at: *http://glassx.ch/fileadmin/_migrated/content_uploads/Bilder_09.pdf*

3) "Retirement Residence Community, Domat Ems, CH," Dietrich Schwarz Architekten AG, project webpage, available at: *http://www.schwarz-architekten.com/en/project/retirement_community_domat_ems/*

4) Leydecker, S. (2008), *Nano Materials*, Berlin: Birkhauser Verlag AG.

5) (2013), "What's the deal with PCM", online resource on GLASSX website, available at: *http://www.glassxpcm.com/footer_posts/how-the-pcm-works/*

Selimex Offices, Werner Tscholl
Laces (BZ), Italy, 2005

08

Photo Credits: *Alexa Rainer*

[Introduction] Located right at the entrance of the Latsch-Laces village, the Selimex head-offices represent a significant mark in the surrounding. Also the presence of water emphasises the role of the building ,that seems arising from it.

[The Smart Feature] Completely made of glass, if during the day the proximity of water as well as the reflections of surrounding surfaces let the building to

CREDITS

Design team	Werner Tscholl
Location	Laces (BZ), Italy
Project year	2005

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	■

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

match perfectly with the site, during night the artificial lights give it a continuously changing aspects. To ensure this feature, special spotlights have been created with high power LEDs technology to yield almost endless colours combinations; furthermore, they can be programmed to permit gradually but continuously changing chromatic series.

References

1) (2005), "Werner Tscholl | Uffici Selimex", *Divisare.com*, available at: *https://divisare.com/projects/124973-werner-tscholl-alexa-rainer-uffici-selimex*

2) "Selimex", project web site, *http://www.werner-tscholl.com/new-constructions/selimex-latsch/*

3) "Selimex Headoffices", *archello.com*, available at: *https://archello.com/project/selimex-headoffices*

Spots, Realities:united
Berlin, Germany, 2005

09

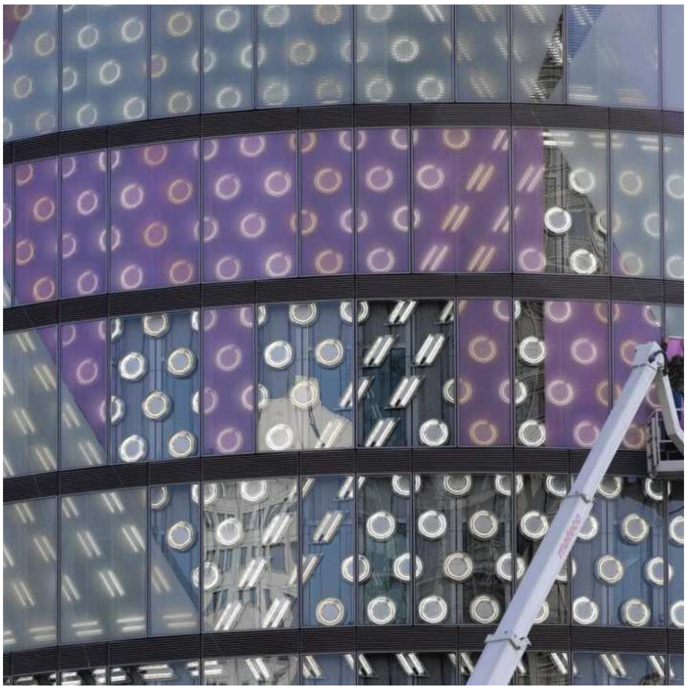

Photo Credits: *Realities:united*

[Introduction] Currently known as one of the world's largest media façade, SPOT it's an installation that comprises a light matrix of about 1800 fluorescent lamp, integrated into the ventilated glass façade of the building located at 10 Postdamer Platz in Berlin.

[The Smart Feature] Thanks to this technology, the external envelope of the building has become a communicative means used to display artistic materials

CREDITS

Design team	Realities:united
Location	Berlin, Germany
Project year	2005

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	■

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	
Allow interaction	■

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.	■	
TRL		8

as moving luminous images, thus equipping it with an ever-changing aspect.

[The technologies] The particular aspect of such installation is possible thanks to common fluorescent lamps, controlled individually by a central computer linked to a bus system, able to adjust their brightness or switching them on and off.

References

1) R. Glynn (2005), "SPOTS - realities:united", Interactive Architecture.org - website of a multidisciplinary research group at the Bartlett School of Architecture, UCL, available at: *http://www.interactivearchitecture.org/spots-realitiesunited.html*

2) "SPOTS", project web site, *http://www.realities-united.de/#PROJECT,81,1*

3) "Realities:united at the Crystal Talk", online resource available at: *https://www.baunetz.de/talk/crystal/pdf/en/talk14.pdf*

Solar XXI, Pedro Cabrito and Isabel Diniz Arquitectos
Lisbon, Portugal, 2006

10

Photo Credits: *Daniel Malhão*

[Introduction] The buildings, located at LNEG Campus is Lisbon, aims at become an example of low energy building, exploiting passive solutions for both heating and cooling. Built as a demonstration project, it consumption is about 1/10 of a standard Portuguese office building.

[The Smart Feature] The smart feature of this building stands in the optimization of its building envelope

CREDITS	
Design team	Pedro Cabrito and Isabel Diniz Arquitectos
Location	Lisbon, Portugal
Project year	2006

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	■
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	■
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	■
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger	■					

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.	■	
TRL		8

functioning; its main façade indeed is covered by windows and photovoltaic modules by equivalent size, thus being able to increasing solar heat gains during winter, in addition the photovoltaic systems contribute to consumption reduction, converting such solar radiation into power.

[The technologies] Based on a combination of passive design techniques with renewable energy technologies (such as photovoltaic and solar collectors).
The main façade has a photovoltaic system with heat recovery to store heat during winter while in summer a ground cooling system made of earth tubes able to pre-cool air before its entering within confined spaces (air temperature injected ranges between 22 and 23°C provoking a decrease of indoor air temperature of about 2-3°C.
The building has no active cooling system because summer overheating is reduced thanks to effective design measure such as Venetian blind, adjustable by users.
In addition, effective ventilation strategies contribute to the minimizing of thermal loads.

[The performance] Monitoring analysis performed in 2011 showed that the buildings has a total amount of energy consumption of 36MWh in face of a production of about 38 MWh of electricity by the three photovoltaic systems.

References
1) Pedro Cabrito and Isabel Diniz Arquitectos (2016), "SOLAR XXI. Office building for the Energy Efficiency Unit, LNEG campus, Lisbon", *Divisare.com*, available at: *https://divisare.com/projects/316535-pedro-cabrito-isabel-diniz-arquitectos-daniel-malhao-solar-xxi*
2) H. Gonçalves, C. Rodrigues and L. Aelenei (2012), "SOLAR XXI: A Portuguese Office Building towards Net Zero-Energy Building", *REHVA Journal*, pp. 34-40, available in pdf at: *http://www.rehva.eu/fileadmin/hvac-dictio/03-2012/case1---solar-xxi.pdf*
3) K. Voss and E. Musall (2013), *Net zero energy buildings: International projects of carbon neutrality in buildings*, pp. 35, Detail Edition.
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Kiefer Technic Showroom, Ernst Giselbrecht + Partner
Bad Gleichenberg, Austria, 2007

11

Photo Credits: *Ernst Giselbrecht + Partner*

[Introduction] This showroom is an office building in Bad Gleichenberg which presents the first example of a user-controlled dynamic facade.

[The Smart Feature] The dynamic façade, able to change according to outdoor conditions and optimizing internal climate while allowing users to personalize indoor spaces.

CREDITS

Design team	Ernst Giselbrecht + Partner
Location	Bad Gleichenberg, Austria
Project year	2007

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

The white panels indeed, are able to expand or contract vertically, regulating the radiance of sunlight.

[The technologies] The opaque buildings' façades are made of solid brick walls, while the transparent one present great striped windows shaded with electronic shutters made of 112 preformed aluminium panels. Each panels is made of perforated, powder-coated light metal cassette, which can be moved in all the three dimensions.

Such dynamic feature is ensured by the presence of electronic controls that can control each of the 54 motors within the façade. Each panel can also be individually controllable.

There are no responsive systems or responds because the only inputs are those given from the building occupants; the façade indeed is functioning as s shading device, which angle is decided by users, that establish the amount of light transmitted into the interior spaces.

<u>References</u>

1) I. Lomholt (2016), "Kiefer Technic Showroom", *e-architect.co.uk*, available at: *https://www.e-architect.co.uk/austria/kiefer-technic-showroom*

2) E.Giselbrecht, "Dynamic Facade (KIEFER TECHNIC SHOWROOM)", *ArchiTonic.com*, available at: *https://www.architonic.com/en/project/ernst-giselbrecht-partner-dynamic-facade-kiefer-technic-showroom/5100449*

3) I. Vinnitskaya (2010), "Kiefer Technic Showroom / Ernst Giselbrecht + Partner", *ArchDaily.com*, available at:, *https://www.archdaily.com/89270/kiefer-technic-showroom-ernst-giselbrecht-partner*

4) L. Alenei et al. (ed. by) (2018), *Case Studies - Adaptive Facades Network,* TU Delft Open for the COST Action 1403 Adaptive Facade Network.

Forest Hotel, Enric Ruiz Geli
Barcelona, Spain, 2008

12

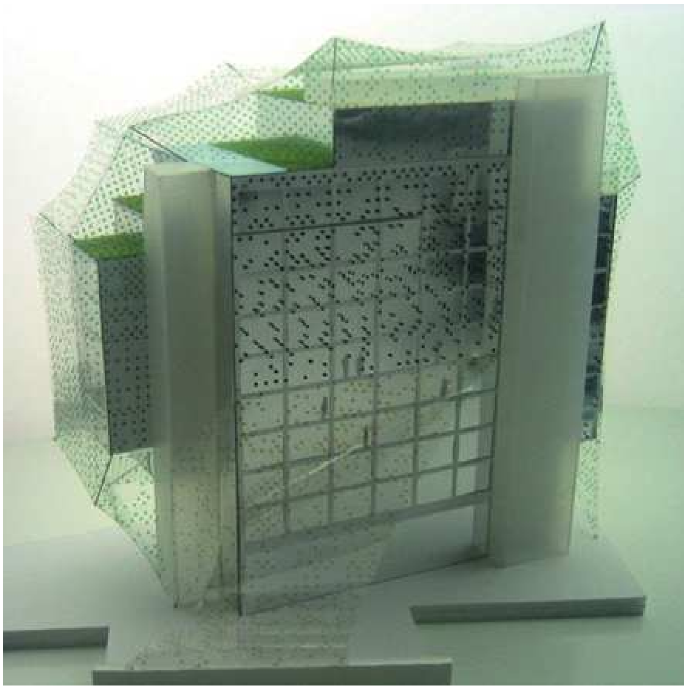


Photo Credits: *https://www.ruiz-geli.com/projects/inprogress/forest-hotel*

[Introduction] With a design inspired by nature, and, in particular, by the natural functions of a forest, this building, proposed in 2006 is currently still not constructed.

[The Smart Feature] The distinctive trait of this concept is clearly its façade, conceived as a mesh equipped with 6500 devices – defined by the designer as "artificial leaves" –, each of them able to change according to

CREDITS

Design team	Enric Ruiz Geli
Location	Barcelona, Spain
Project year	2008

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	■
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	■
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger		■				

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		2

the weather and the seasons thanks to a photocell, a battery and three LEDs. These devices in addition to their lighting functions, are able to store solar energy to further reproduce it within the hotel confined spaces.

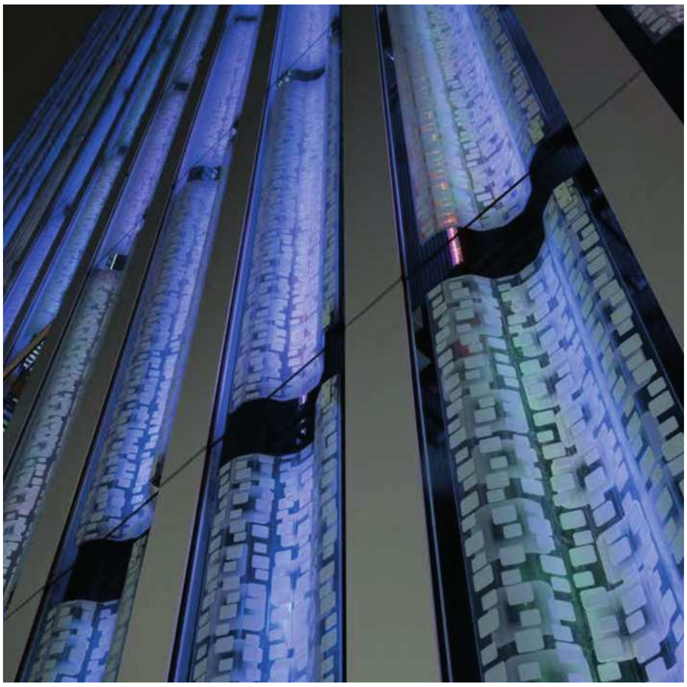
References

1) Enric Ruiz Geli website, available at: *https://www.ruiz-geli.com/projects/inprogress/forest-hotel*

2) E. Ruiz Geli, "Hotel Prestige Forest", *archilovers.com*, available at: *https://www.archilovers.com/projects/5244/hotel-prestige-forest.html*

Pola Ginza Building Façade, Nikken Sekkei + Yasuda
Ginza district, Tokyio, Japan, 2009

13



[Introduction] Mixed-use tower in Tokyo's Ginza with a double-skin glazed facade with kinetic panels, designed in collaboration with the Adaptive Building Initiatives and Hobermann Associates.

[The Smart Feature] The adaptive shading systems, composed of about 185 elements - operable to shield the interiors from direct sunlight - that present the ability to change size and shape.

CREDITS	
Design team	Nikken Sekkei + Yasuda Atelier
Location	Tokyio, Japan
Project year	2009

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

[The technologies] Each shutter, sized approximately 1x3 meters, is composed by a double glazed system which embeds a kinetic polycarbonate layer, that renders it translucent; the acrylic sheet has been formed into a curved surface and presents different patterns that illustrates the cells of life.
The shutters operate in groups of 40 on different mechanism, hasted within the double glazing of the facade.
A building management system coupled with photo sensors, control the translucent shading devices, helping in reducing heat gain during the seasons.

[The performance] The double glazing system reduce annual HVAC energy by 30%.

References

1) A. Seng (2010), "POLA Ginza Building Façade", online resource available at: *https://arthurtseng.wordpress.com/2010/01/13/pola-ginza-building-facade/*

2) J.Gonchar (2010), "Hoberman's "Transformable Design" Gaining Momentum", *Architectural record*, available at: *https://www.architecturalrecord.com/articles/5374-hoberman-s-transformable-design-gaining-momentum?*

North House, Team North
Washington DC, USA, 2009

14

Photo Credits: *Jim Tetro/U.S. Department of Energy Solar Decathlon*

[Introduction] Interdisciplinary research project aimed at develop a full-scale prototype of a net-positive-energy residence, prefabricated, optimized for cold climate applications. The goal of this experimentation is to pair hybrid integrated active and passive envelope systems with interactive controls, delivering a net energy-producing model able to foster new relationships between occupants, building system and environment.

CREDITS

Design team	University of Waterloo, Ryerson University and Simon Fraser University.
Location	Washington DC, USA
Project year	2009

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	
Allow interaction	■

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	■

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		3

[The Smart Feature] Equipped with energy generation capacity, the North House produces annually more energy than what it consumes thanks to BIPVs and BAPVs (Building Applied Photovoltaics). Its distinctive feature are the assemblies developed by the research team, called DReSS (Distributed Responsive System of Skins), CHAS (Central Home Automation Server) and ALIS (Adaptive Living Interface System).
The components of DReSS include: two-stage operable exterior venetian shading, high performance glazing, interior blinds and floor-integrated phase change materials along with building integrated photovoltaic on the exterior cladding. The controls system manages the shading to prioritize passive thermal management based on sensor data; the exterior shade configuration scenarios are based on relative environmental conditions, and related responsive envelope reactions that formed the framework for the development of the home automation system.
Besides, CHAS manages energy production and grid connection with the mechanical demands of the North House HVAC system and responsive envelope; while ALIS is basically a BMS which simplifies occupants' use of complex HVAC, energy production and responsive envelope components. The system combines a control interface with feedback and allows remote operation via smart-phone technology. Thanks to these devices, changes can be made and monitored in real time.
Energy usage is also minimized by the smart interior design, which incorporates elements such as a custom cellular ceiling, made from window-shade material that helps to absorb reflected sound and direct light from the perimeter into the core of the space.

References

1) North House on RVTR website, available at: *http://rvtr.com/projects/project-a/*

2) Thün + Velikov (2013), "North House: Climate-Responsive Envelope and Controls Systems", in Trubiano, F., *Design and Construction of High performance homes. Building Envelopes, Renewable Energies and Integrated Practice*, Routledge.

3) Velikov and Bartram (2009), "North House: Developing Intelligent Building technology and User Interface in Energy Independent domestic Environments", in *Architecture, Energy and the Occupant's Perspective: Proceedings of the PLEA2009 - 26th Conference on Passive and Low Energy Architecture*, Quebec City, Canada, 22-24 June 2009.

100 11th Avenue Building, Jean Nouvel
New York, USA, 2010

15

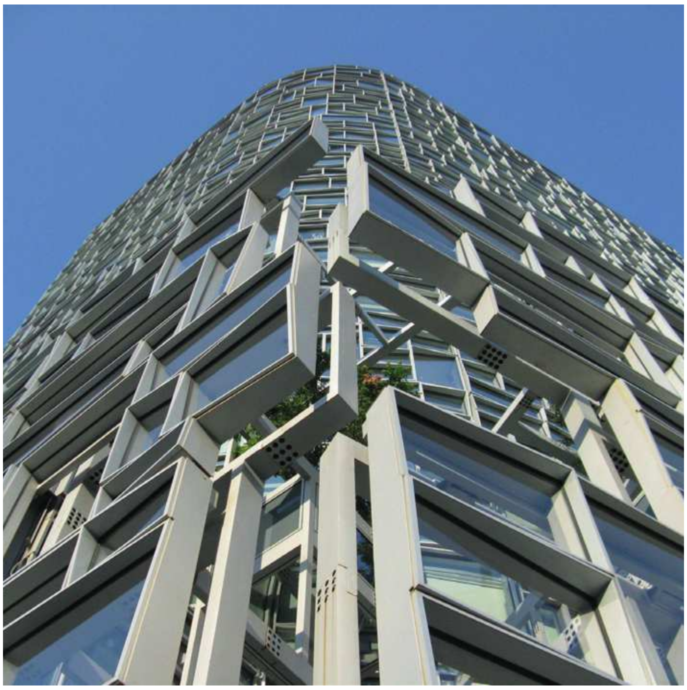


Photo Credits: *Philippe Ruault*

[Introduction] With a number of approximately 1650 different windowpanes, the Nouvel's building can be considered the most highly engineered and complex curtain wall ever constructed in New York City.
His approach indeed, aimed at emphasized windows' mullions to render them scattered frames; furthermore, to simplify construction process the facade has a fragmented surface with various window dimension

CREDITS

Design team	Atelier Jean Nouvel
Location	New York, USA
Project year	2010

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

that allow the curving of the curtain wall, each of them is set in a unique angle and torque.

[The Smart Feature] The ability to overcome common curtain walls with a simplified solution derived from the fragmentation of the façade; in addition, different coatings added to glass allow light to play with the façade, continuously changing its appearance. The ability of changing brightness and darkness of the faced are ensured by sunlight variations; dynamic movements are here indeed, ensured by earth movements.

[The technologies] The project employs over 1650 different E-glass panels, curved with a different tilt angle across its surface; the windows are both fixed and operable, in various sizes and shapes; to give regularly to such a system, the manufactures crated special mega-panels that contain smaller, individual panels.

References

1) K. Cilento (2010), "100 Eleventh Avenue / Jean Nouvel", *ArchDaily.com*, available at: *https://www.archdaily.com/76113/100-eleventh-avenue-jean-nouvel*

2) C. Warmann (2010), "100 11th Avenue by Jean Nouvel", *Deezen.com*, available at: *https://www.dezeen.com/2010/05/28/100-11th-avenue-by-jean-nouvel-3/*

3) "100 11th Avenue by Jean Nouvel", *WikiArchiquitectura,* available at: *https://en.wikiarquitectura.com/building/100-11th-avenue-building/*

4) Atelier Jean Nouvel, "100 11th Avenue", project website, available at: *http://www.jeannouvel.com/projets/100-11th-avenue/*

HelioTrace Façade System, Hoberman & Permasteelisa Group
New York, USA, 2010

16

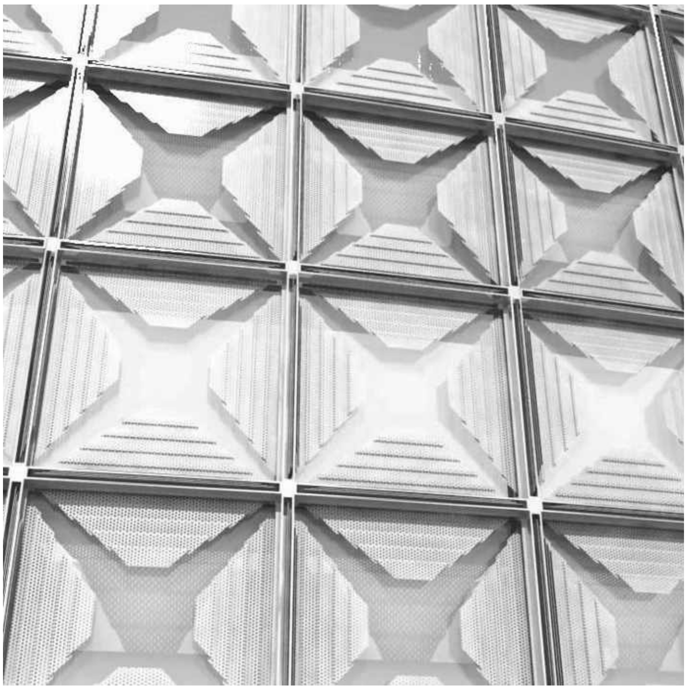


Photo Credits: *Skidmore, Owings & Merrill*

CREDITS

Design team	Hoberman Associates and Permasteelisa Group
Location	New York, USA
Project year	2010

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

[Introduction] Façade system developed in the framework of the Centre for Architecture's competition: "Open Call: Innovative Curtain Wall Design", from Hoberman (through the joint venture Adaptive Building Initiative with Skidmore, Owings and Merril) and the Permasteelisa group.
The kinetic system, integrated into the façade, is obtained by adding to a high-performance curtain wall

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		4

two exterior sunscreen devices, positioned and operated according to empirical data provided by the Sustainable Engineering Studio.

[The Smart Feature] The smart feature of the system is its kinetic shading device, born to be suitable for different climatic context and multiple architectural shapes to respond to external variability.

[The technologies] The shading system is composed by two different devices: the opaque panels, perpendicular to the façade, and the translucent panels, deployed parallel to the building envelope; both can be programmed to respond to solar movements and users' need as well.

[The performance] Thanks to its optimized design it is able to minimize building energy use while maximizing building daylighting and glare performance; its operation indeed allow to obtain an effective shading level of 78% and an annual peak solar gain reduction of 81 %.
Studies conducted have demonstrated that, if compared with last LEED standard (V. 3.0) an office building with a façade system like the HelioTrace is able to reduce of about the 42% its global energy requirement.

References

1) Keegan, E. (2010), "HelioTrace Facade System", *Architectmagazine.com*, available at: *https://www.architectmagazine.com/awards/r-d-awards/citation-heliotrace-facade-system_o*

2) Ahmed M. M. S. et al (2016), "Optimum energy consumption by using kinetic shading system for residential buildings in hot arid areas", *International Journal of Smart Grid and Clean Energy,*, vol. 5, no. 2, available in pdf version at: *http://www.ijsgce.com/uploadfile/2016/0426/20160426063625935.pdf*

3) Sauchelli, M. (2011), "HelioTrace", *Architectipo magazine.it*, available at: *https://www.arketipomagazine.it/heliotrace/*

4) Elkhayat Y. O. (2014), "Interactive movement in kinetic architecture", *Journal of Enginnering Scientces,* Assiut Univeristy, Faculty of Engineering, Vol. 42, No. 3, pp. 816-845, available in pdf version at: *http://www.aun.edu.eg/journal_files/158_J_5991.pdf*

5) Fortmeyer R. and Linn C. (2013), *Kinetic Architecture: Designs for Active Envelopes,* Images Publishing Group Pty Ltd.

SolPix - Energy Positive Media Skin, Simone Giostra & Partners
Cooper Hewitt National Design Museum, New York, USA, 2010

17

Photo Credits: *Simone Giostra & Partners*

[Introduction] Designed for the Triennial of Design at the Cooper Hewitt Museum of New York in 2010 and inspired by the GreenPix media wall for the Xicui Entertainment Complex in Bejing (China), this system is a functional prototype to demonstrate its ability of interaction with the environment, offering at the same time a real contribute to the energy balance of the building.

CREDITS

Design team	Simone Giostra & Partners with Arup, Permasteelisa NA, Rotsztain and Nugent
Location	New York, USA
Project year	2010

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	■
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	■
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	■
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger		■				

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		5

[The Smart Feature] SolPix it is basically a solar powered sun shading media wall system that allows daylight into the building while controlling its exposure to direct sunlight, reducing heat gain and transforming excessive solar radiation into energy for the media wall; the amount of solar energy produced indeed, is enough to power the multimedia skin.

In addition, SolPix has the ability to monitor its own energy performance through a customized integrated software that visualizes the energy balance of the system generating at the same time videos and animations able to transform the installation in an interactive environment.

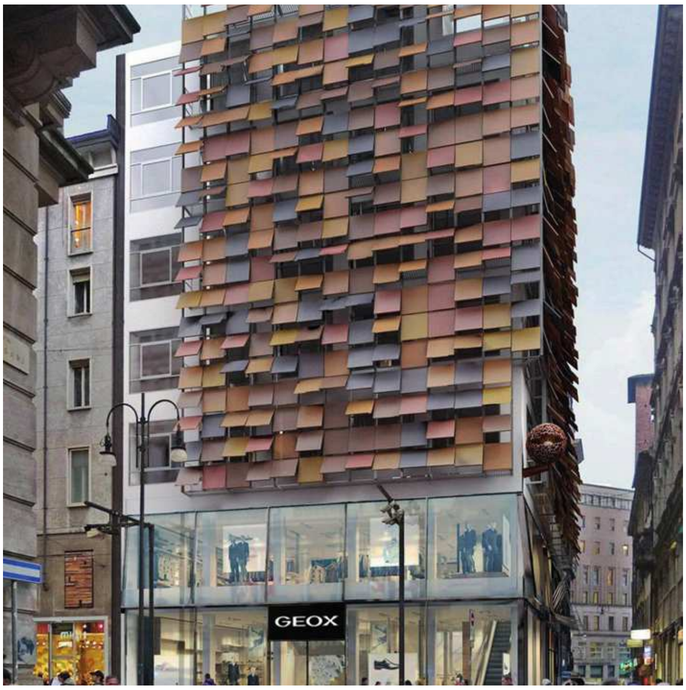
[The technologies] It is equipped with one of the largest colour LED display and the very first photovoltaic systems integrated into a glass curtain wall, achieving in this way a transparent media wall. The photovoltaic panels integrated in the sun-shading system transform the structure into an energy-positive skin, harvesting the energy needed to power the screen while protecting the inside from excessive heat.

When applied to building exteriors, the sun-shading elements provide unobstructed outside views from the building interior, while lending a contemporary texture to the building exterior. The horizontal or vertical panels can be mounted at a preferred angle or can be rotated in order to maximize exposure to direct sunlight.

References
1) L. Alenei et al. (ed. by) (2018), *Case Studies - Adaptive Facades Network*, TU Delft Open for the COST Action 1403 Adaptive Facade Network.
2) SIMONE GIOSTRA & PARTNERS ARCHITECTS on *Luceonline.it*, available at: *http://www.luceonline.it/web/ricerca/simone-giostra-amp-partners-architects/*
3) SIMONE GIOSTRA & PARTNERS ARCHITECTS DESIGN SOLPIX INSTALLATION FOR COOPER HEWITT DESIGN TRIENNIAL, press release, available in pdf at: *http://sgp-a.com/sgp-a/wp-content/uploads/2012/07/sgpa-a35-press-release-en.pdf*

The Breath Building - GEOX megastore, D. Benin
Milan, Italy, 2010

18



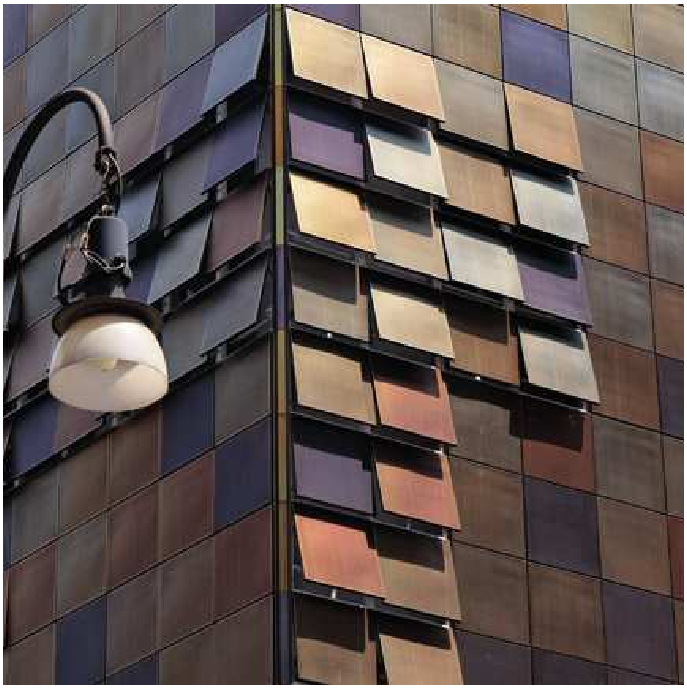


Photo Credits: *http://www.archiportale.com/news/2010/03/architettura/milano-inaugura-il-palazzo-che-respira_17995_3.html*

[Introduction] In this refurbishment only the building envelope has been substituted while the bearing concrete structured has been preserved. The new façade is made of over one hundred of metal sheet, autumn-colored, able to open and to close, offering a dynamic scenery from the street; this effect is increase from a maxi screen that thorough LED technologies reflect different graphics.

CREDITS

Design team	Dante O. Benini & Partners Architects
Location	Milan, Italy
Project year	2010

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

[The Smart Feature] The metal panels do not have only an aesthetic value but rather made up the second skin that protect the internal environment from over heating or cooling, creating an air gap between the external cladding and the internal walls.
In addition, the single-skin walls are coated with a photo-catalytic plaster, with chemical properties that transform air pollutants into dust thus leaving the façade clean more than usually.

[The technologies] The new façade has been built with dry technologies able to support both fenestration and walls as well; the process so industrialized has allowed lower times and cost if compared with traditional solutions.
The micro perforated metal sheets are electrically controlled through a device that allow users to interact with the shadings, choosing its angle depending of sunlight incidence.

References

1) R. Dragone (2010), "Milano inaugura il "Palazzo che respira", *ArchiPortale.com*, available at: *http://www.archiportale.com/news/2010/03/architettura/milano-inaugura-il-palazzo-che-respira_17995_3.html*

ThyssenKrupp Headquarters, JSWD and Chaix & Morel Associès
Essen, Germany, 2010

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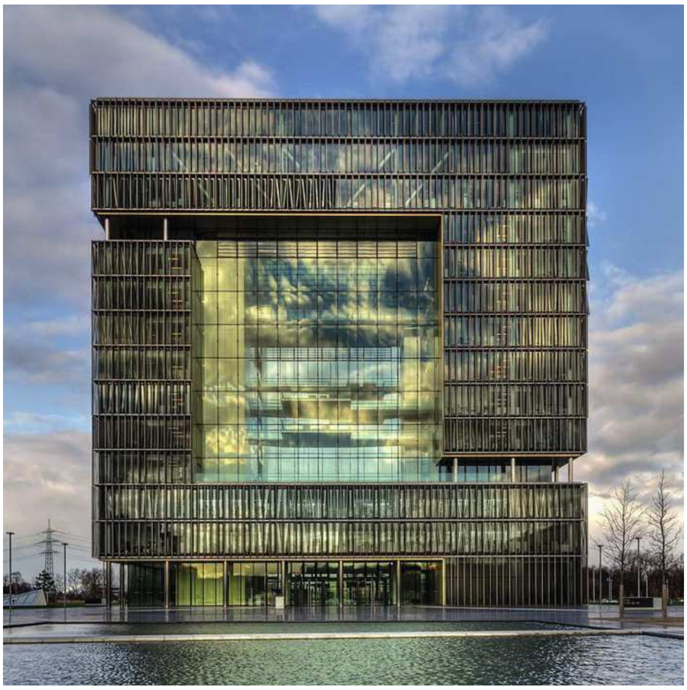

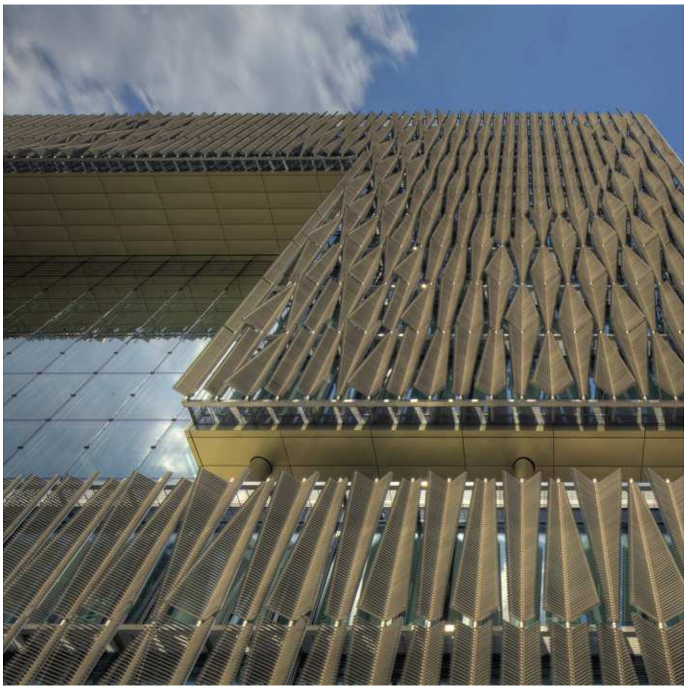

Photo Credits: *thyssenkrupp*

[Introduction] Born to flexibly react to changes within the company, the new ThyssenKrupp Headquarters is composed of different buildings; the Q1, the heart of the campus, is the most representative, thanks to its shape and to its particular sustainable features.

[The Smart Feature] The smart feature of this project is its ability to avoid air conditioning systems thanks to the particular glazed structures, supported by cable

CREDITS

Design team	JSWD Architekten, Chaix & Morel et Associès
Location	Essen, Germany
Project year	2010

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

constructions. The second skin, made of about 400.000 stainless steel devices (louvres and fins with triangular, square and trapezoidal shapes) ensure the solar control of incident radiation thanks to lamellas' orientation as well as their movements, based on the sun's path to maximize views out (thanks to an automatic adjustments of the system), while reducing glare and cutting down on heat gain.

References

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Adaptive Solar Facade (ASF), Prof. Schlüter, ETH Zürich
Zurich, Switzerland, 2011

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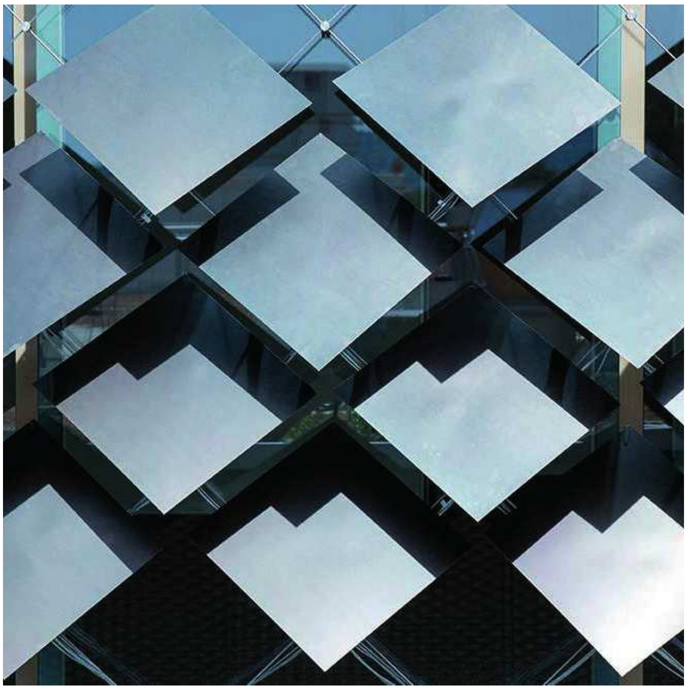

Photo Credits: *Marco Carocari*

[Introduction] Prototype developed by the researchers of the ETH that combines recent developments in architecture, energy technology and robotics to retain a comfortable indoor climate within confined spaces over year.
Actually, it is one of the largest object showcasing soft robotics in architecture. Clearly, its efficiency depends on the relationships among the façade and the other building components.
The Adaptive Solar Façade consists of individual modules mounted on a cable network on the façade; By adjusting the amount of solar radiation through the window, they can control the light and heat of the internal space

[The Smart Feature] The smart feature of this case study stands in the multi-functionality of building envelope coupled with its ability to provide a dynamic appearance thanks to the modules that made it up, continuously reacting to the external environment. Therefore, it's extremely lightness makes this technology suitable even on existing buildings.

[The technologies] Its assembly is made of movable photovoltaic modules, mounted on a lightweight structure; their function is twofold because they do not only produce energy whilst they offer shading and daylight control. The façade is equipped even to

CREDITS

Design team	ETH zurich team, leaded by Prof. Arno Schlüter
Location	Zurich, Switzerland
Project year	2011

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	■
Other	

Purpose	
Thermal comfort	■
Visual performance	■
Acoustic comfort	
Energy management/generation	■
IAQ	■
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		6

store energy and to transform it into pressurised air to be further used to adjust the movable modules when no energy is generated (as for instance, in case of bad whether).
The modules are moveable thanks to a soft robotic actuator (generally used in bio-mimetic robots), made of a flexible material that change its form when the pressure in a special chamber change. With this particular technology, each actuator can be controlled individually and rotated on two axes; this enables the modules to track the sun's movements and to maximize power's generation. In addition, an intelligent and adaptive regulator allows the façade to adapt to changing weather conditions and the habits and wishes of the user.

[The performance] The smart feature of this case study stands in the multi-functionality of building envelope coupled with its ability to provide a dynamic appearance thanks to the modules that made it up, continuously reacting to the external environment. Therefore, it's extremely lightness makes this technology suitable even on existing buildings.

References
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Bioskin, Sony City, N. Sekkei
Osaka, Japan, 2011

21

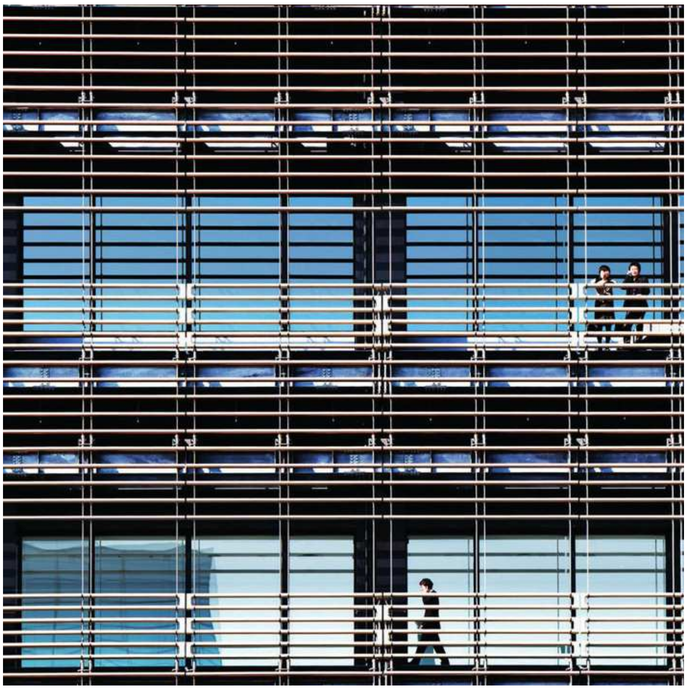

Photo Credits: *Nikken Sekkei Ltd*

[Introduction] Awarded at the WAF of 2012 (World Architecture Festival) of Singapore for the category Production/Energy/recycling, the building employs a particular building envelope system (called Bioskin) that allow the façade to breathe, lowering its surrounding temperature.
In this way the building is able to act even on the local micro-climate, with an action equivalent to two hectares

CREDITS

Design team	Nikken Sekkei
Location	Osaka, Japan
Project year	2011

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger	■					

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

of natural forest, completely mitigating the urban "heat island" effect.

[The Smart Feature] The building functions as an opposite radiator, stealing heat from inside and outside at the same time; therefore, it represents an extraordinary example of static biodynamic façade taking as reference the traditional Japan-ese "*Uchimizu*" technique, which employed bamboo's canes on buildings' exposed sides, in which water was inserted which evaporating was stealing heat to indoor spaced.

[The technologies] The above mentioned principle has been applied to the building, coated with a texture of narrow metallic pipes covered with porous terracotta, within which the rainwater is collected. The water dunks the tubes and slowly evaporates from ceramic surface, cooling the adjacent air. The tube section is able to maximise the heat exchange surface with a dimension of 110x70 mm; the systems is hanged to a metal wired structure and its connected to the water management system.

[The performance] The firm estimates that the Bioskin system can lower the temperature of the surrounding air by about 2°C**.**

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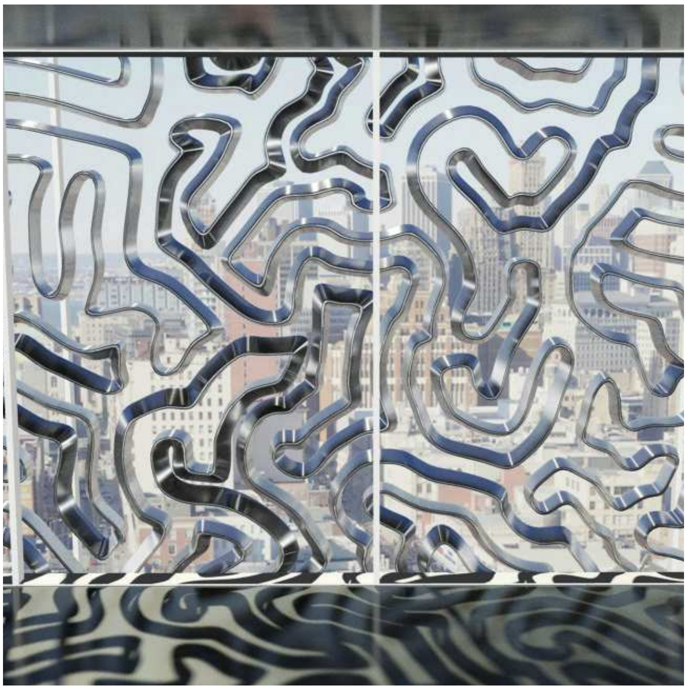

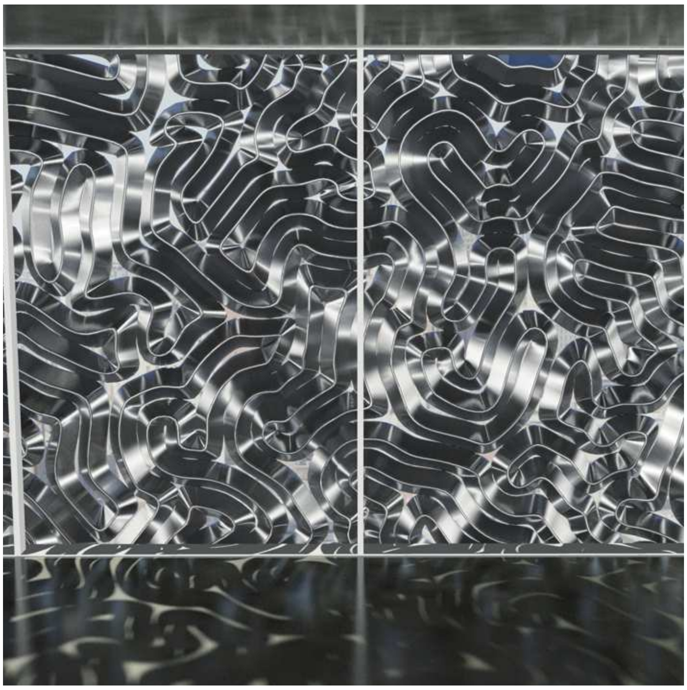

Photo Credits: *Decker Yeadon LLC*

[Introduction] The Homoeostatic façade is a dynamic system able to vary its transparent with heat variations, adjusting to external conditions; its functioning was inspired by a natural self-regulating mechanism based on a homoeostatic reaction.

CREDITS

Design team	Decker and Yeadon Architects
Location	New York, USA
Project year	2011

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger		■				

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

[The Smart Feature] The façade is able to open and close according to light and temperature variations, thanks to the use of smart materials and nano-technologies that auto respond to environmental conditions.

[The technologies] Within the air gap of a double-skin glass façade, a dielectric ribbon made of a polymer that reacts to electric impulses has been installed. Both sides of the dielectric ribbon are coated with silver electrodes, able to reflect the light and to distribute the electrical charge through the material, provoking its deformation: when light hit the façade, ribbon's surfaces are expanding, controlling solar heat gain through it, while when temperature goes down, the tape contracts, allowing light and heat entering within confined spaces.

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Media ICT building, CLOUD 9 - Enric Ruiz-Geli
Barcelona, Spain, 2011

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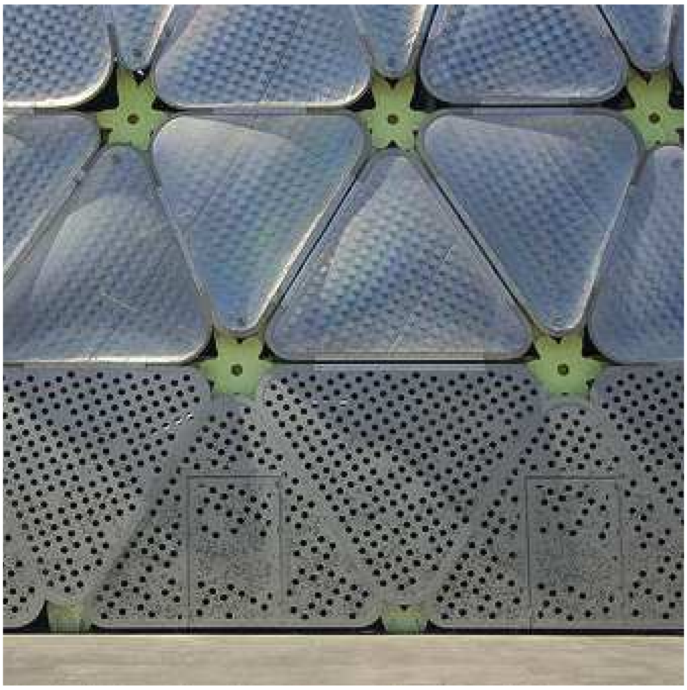

Photo Credits: *Luis Ros*

[Introduction] Commissioned by the Consortium of Zona Franca CZFB and 22@ (an experimental district with a powerful, distributed and accessible, energy load) of Barcelona, the project is entirely based on ICT with the aim to be totally sync with users' preference.
The construction was built from the top with the goal to become transparent at the bottom, thus reducing its impact on the street.

CREDITS

Design team	CLOUD 9 - Enric Ruiz-Geli
Location	Barcelona, Spain
Project year	2011

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	■
Visual performance	□
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	□
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	■

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		7

[The Smart Feature] The Media-ICT is designed to be a generator of energy and to optimize its use. The facade cladding indeed, made of ETFE, performs simultaneously as an external protection and a mobile solar screen to regulate both light and temperature, thus contributing to decrease building energy demand.

[The technologies] The south-east façade is made of inflatable ETFE cushions that act as sunscreen, opening in winter and closing in summer; they are constructed with three layers of materials, with constant pressure and variable circulation of air between the cambers: the first layer is transparent, while the second and the third have reverse pattern design which, when inflated and joined together, become opaque. The systems activates itself automatically according to a temperature sensor network.
Each cushion have it own sensors which are controlled separately.
Another facade, the south-west facing, is based on a lenticular configuration in which, within an ETFE cushion (actually into a number of ETFE longitudinal bags) a nitrogen based fog is introduced, to obtain a greater opacity able to preserve privacy of occupants while reducing solar heat gain through the envelope. This technology in fact has allowed to bring the solar factor down from 0,45 to 0,10.
Even in this side, both the envelope and the internal spaces are equipped with environmental sensors that collect information to adjust interior conditions.

References

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Bloom, DOISU Studio Architecture
Los Angeles, California, USA, 2011-2012

24

Photo Credits: *Brandon Shigeta*

[Introduction] Born as architectural research installation displayed at the Materials and Application Gallery in Los Angeles, Bloom actually perform the role of a prototype of an environmentally responsive form, that gather together material experimentation, structural innovation and computational forms.

[The Smart Feature] The project act as sun tracking instrument, indexing time and temperature thanks to

CREDITS

Design team	DO|SU Studio Architecture
Location	Los Angeles (CA), USA
Project year	2012

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate		■			

Application scale	
Element I Material	■
Component	
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger	■					

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		5

its special material shape able to sense environmental variations; in particular, it changes its form when shaded or ventilated.

[The technologies] The structure is composed of a cellular panel system made with a particular smart thermobimetal, a metallic sheet that curls when heated. The complex shape (made up of about 14.000 laser cut pieces) was obtained with the aid of a complex digital software; the panels – with a hyperbolic paraboloid shape – combine a double-ruled surface of bi-metal with a folded aluminium frame system, specifically designed to appear on the two surfaces.
The metal surface, when changes in temperature and in direct solar radiation occur, reacts: when its temperature is cool, the surface will appear as a solid objects, but once it increases, the panels will adjust to let air flows, increasing shading potential.

References
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Nemours Children's Hospital, Stanley Beaman & Sears
Orlando, Florida, USA, 2012

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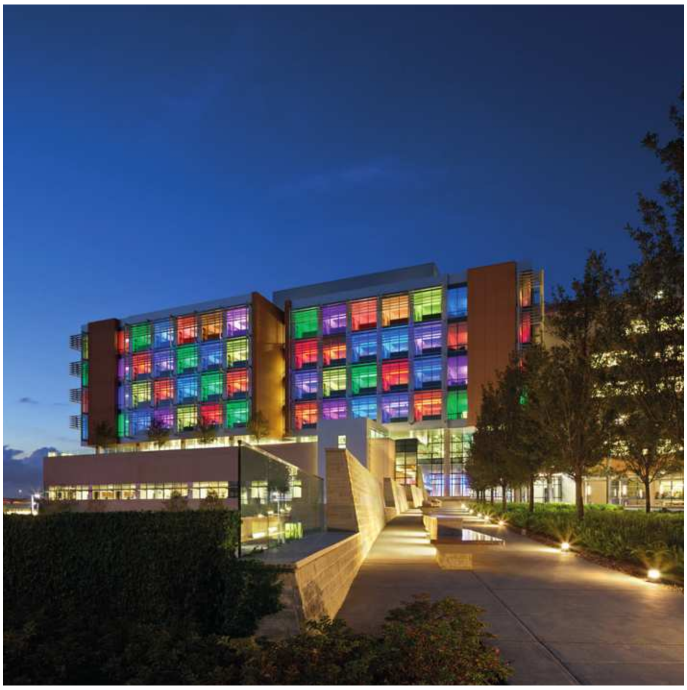

Photo Credits: *Jonathan Hillyer*

[Introduction] Designed to ease and delight children, the project arose out of a collaboration with multiple stakeholders to obtain a place able to both reassure and inspire, with a particular attention toward the surrounding environment.

[The Smart Feature] To increases children's, interest the hospital would like to engage them at most: the colour of patient room accent lighting indeed, can be selected by

CREDITS

Design team	Stanley Beaman & Sears & Perkins + WIll
Location	Orlando (FL), USA
Project year	2012

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate	■				

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	
Allow interaction	■

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

the child, creating and ever-changing dynamic façade.

[The technologies] The "Paint your room with colour" concept lets children customize their own space though the use of simply coloured led, adding a dynamic quality to the architecture. In addition, it is equipped with very high-performance technologies and innovative building materials, such as the acrylic light channels, embedded within terrazzo, that refracting light interact with everyday variations.

References

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RMIT Design Hub, Sean Godsell
Melbourne, Australia, 2012

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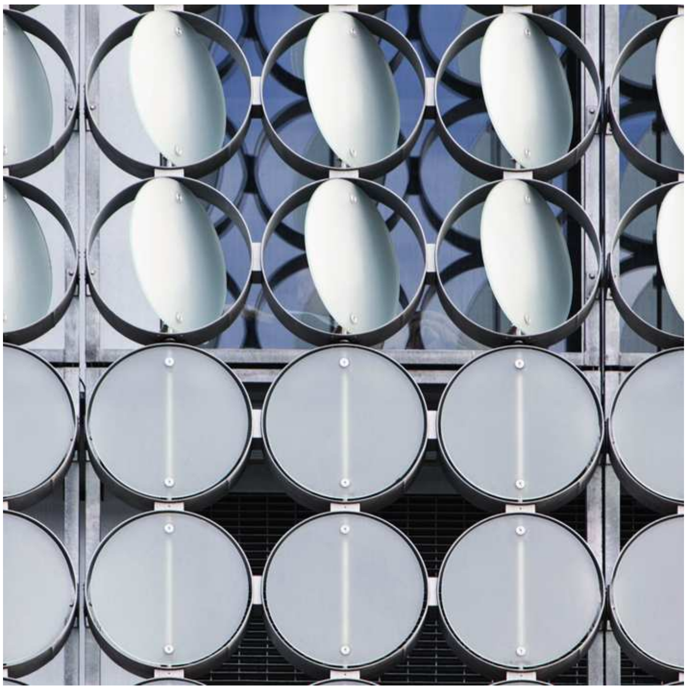

Photo Credits: *Earl Carter*

[Introduction] The Design Hub of RMIT is designed to accommodate the organic nature of research, constantly evolving, adapting, changing and growing. The building incorporates strategies of water, waste and recycling management to provide passive cooling and lower energy consumption coupled with a more desirable thermal comfort alternative to a fully conditioned work environment.

CREDITS

Design team	Sean Godsell, Hayley Franklin
Location	Melbourne, Australia
Project year	2012

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

[The Smart Feature] The external envelope, made of a double glazed inner skin, presents automated operable sun-shading devices that include photovoltaic cells, designed to be easily replaced and specially to contribute to research into the field to be conducted jointly by industry and RMIT. They are able to rotate on a vertical axis to optimize solar radiation, limiting undesired overheating while allowing a good natural light diffusion within confine spaces.
The glass cells track the sun via the building computer automation system to help shade and power the building. In a sections of the facade BIPV will be incorporated, manufactured using the same high-performing interlayer and act as an applied learning and teaching showcase.
The whole building facade has the capacity to be upgraded as solar technology evolves and may one day be able to generate enough electricity to run the entire building.

[The technologies] The second skin shading devices are made of 600 mm diameter sandblasted glass disks, which are fixed to an axles grid, in turn fixed to the outer face of a steel cylinder. 21 glass disks and steel cylinders are fixed together in panels of about 1,8x4,2 m; each panel is composed by 12 operable disks and 9 fixed disks. At the ground level all glass disks are fixed.

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Smart Material Houses Project: Smart is green, Hamburg, Germany, 2012

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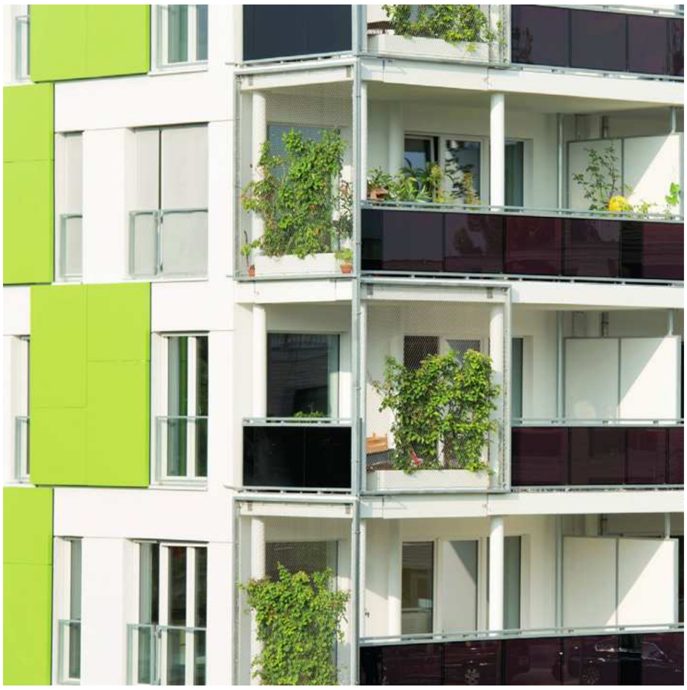


Photo Credits: *http://zillerplus.de/project/smart/?lang=en*

[Introduction] Project in which the whole envelope is an active part of the building concept; using innovative technology indeed it is able to generate power that is fed directly into the house.

[The Smart Feature] The building is able to generate more energy than its use, thanks to the use of smart techniques. In addition, even apartments configuration is smart due to its ability to be modified in a versatile

CREDITS

Design team	zillerplus Architekten & Stadtplaner
Location	Hamburg, Germany
Project year	2012

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	■
Other	

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.	■	
TRL		7

way allowing the, to be separated or extended in order to meet the needs and changing living arrangements of their inhabitants.

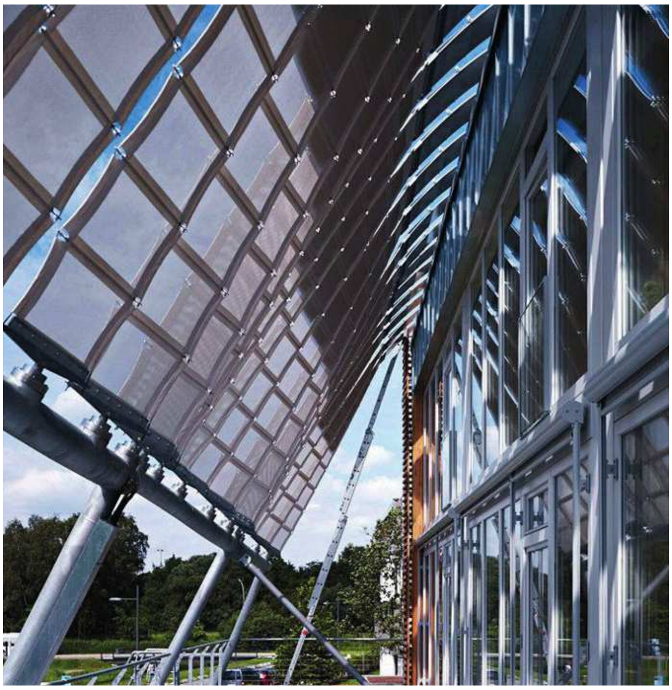
[The technologies] The external envelope is made up of three different layers: a vertical garden façade, that act as a heat shield during summer, an insulating glazing layer and a PCM curtain wall, used also a central storage unit for heat, divided into two tanks. In addition, the outer skin is equipped with photovoltaic panels while solar thermal arrays on the roof convert sunlight into thermal energy.

References

1) IBA Hamburg GmbH (2012), "Smart is green", IBA Hamburg website, available at: *https://www.iba-hamburg.de/en/themes-projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/smart-is-green/projekt/smart-is-green.html*

Smart Material Houses Project: Soft House, Hamburg, Germany, 2012

28



[Introduction] The Soft House its part of the competition for the International Bau Austellung (IBA) of 2012. It represents, as its competitors, a novel model for low carbon construction that can be customised to meet end-users' needs.
It is based on a flexible living concept that integrate architecture, smart technologies and clean energy infrastructures.

[The Smart Feature] The façade, covered with a

CREDITS

Design team	Kennedy & Violich Architecture
Location	Hamburg, Germany
Project year	2012

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	■
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	■
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	■
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		7

dynamic textile membrane, is moveable according to sunlight variations; photovoltaic cells are incorporated within it to exploit sun for producing energy.
In addition, moveable transparent curtains – equipped with LED lighting systems – are adopted inside the apartments to change their layout on demand, replacing traditionally steady interior elements; their operation is guaranteed by the electricity generated by the membrane façade.

[The technologies] The building's structure consists of wood panels and flexible solar nano-materials embedded in a light, smart textile that bends to reach for the best angle to harvest solar energy.

References

1) IBA Hamburg GmbH (2012), "Soft House", IBA Hamburg website, available at: *https://www.iba-hamburg.de/en/themes-projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/soft-house/projekt/soft-house.html*

2) N.K. Parthenopoulou and M. Malindretos (2016), Materials Today: Proceedings 3 (2016), pp. 898 – 912.

3) Lin, J. (2013), "Otto", designer pages, available at: *http://media.designerpages.com/otto/2013/03/the-soft-house-opens-in-hamburg/*

SAHMRI, Woods Bagot
Adelaide, Australia, 2012

29

Photo Credits: *Woods Bagot*

[Introduction] The South Australian Health and Medical Research Institute (SAHMRI) is designed to become a world class centre of research excellence in medicine, creating synergies among researchers and clinicians and integrating research into practice.
Therefore, even the architecture has been conceived to allow visual connections between inside and outside and floors as well.

CREDITS

Design team	Woods Bagot in collaborration with Aurecon
Location	Adelaide, Australia
Project year	2012

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

[The Smart Feature] The particular facade of the building, inspired by the skin of a pine cone, is able to adapt and respond to the external environment thanks to the triangulated movable structure which acts as an articulated sun-shading device. Its specific design has been developed following intensive environmental analysis and a parametric modelling tools to integrate environmental and formal requirements into such system.

[The technologies] The sun shading system is made of a free-hanging metallic grid placed on each glass panels of the curtain wall, with every shade designed site-specifically to modulate the amount of light needed inside the building, as determined by computer modelling.

References

1) Woods Bagot website, "South Australian Health and Medical Research Institute", available at: *https://www.woodsbagot.com/projects/south-australian-health-and-medical-research-institute*

2) Jordana S. (2013), "In Progress: SAHMRI / Woods Bagot / Woods Bagot", *Archdaily.com*, available at: *https://www.archdaily.com/454746/in-progress-sahmri-woods-bagot-woods-bagot*

3) (2018), "Woods Bagot unveils concept for SAHMRI sequel", *ArchitectureAU.com*, available at: *https://architectureau.com/articles/woods-bagot-unveils-concept-for-sahmri-2/*

4) Risen C. (2014), "South Australian Health and Medical Research Institute, Designed by Woods Bagot", *Architectmagazine.com*, available at: *https://www.architectmagazine.com/design/buildings/south-australian-health-and-medical-research-institute-designed-by-woods-bagot_o*

Windswept, Charles Sowers
The Randall Museum, San Francisco (CA), USA, 2012

30

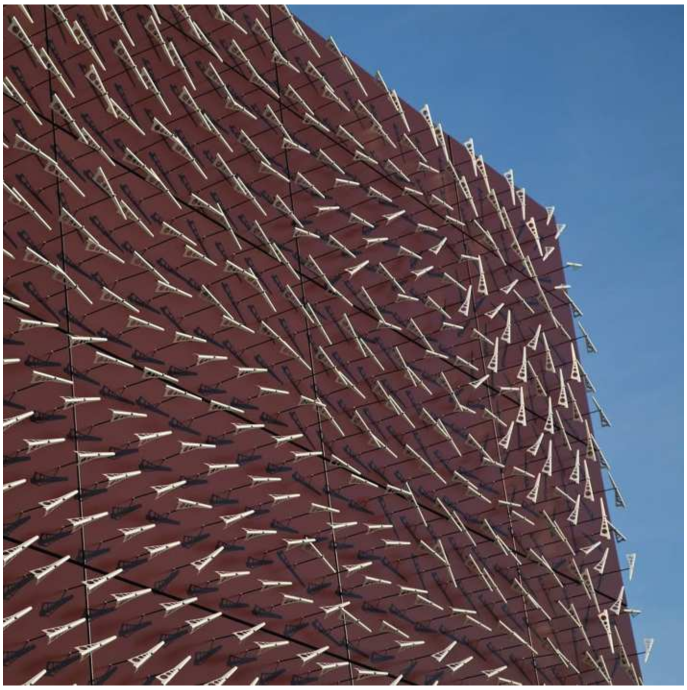


Photo Credits: *Charles Sowers website*

[Introduction] Windswept is an installation on the Randall Museum façade developed by Charles Sowers with the aim to show the interactions between the wind and the environment.

[The Smart Feature] This wind-driven kinetic façade would inspire to think about the wind as a potential energy source, sensitizing people about energy consumption and conferring to the building an ever-

CREDITS	
Design team	Charles Sowers
Location	San Francisco (CA), USA
Project year	2012

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	■
Component	
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	
Allow interaction	■

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

changing aspect due to the multiple interactions it has with wind.

[The technologies] Made of 612 anodized aluminium arrows, mounted parallel to the façade following a grid, the installation shows the air movements through the façade of the museum. It consists of over 500 freely rotating directional arrows that uses the power of wind to move.

References

1) Charles Sowers, website, available at: *http://charlessowers.com/windswept*

2) B. Brownell and M. Swackhamer (2015), *Hypernatural. Architecture's New Relationship with Nature*, Princeton Architectural Press.

3) E. Chalcraft (2012), *"Windswept by Charles Sowers"*, *Deezen.com*, available at: *https://www.dezeen.com/2012/11/06/windswept-installation-by-charles-sowers/*

4) A. Furuto (2012), "Windswept Installation / Charles Sowers Studios", *ArchDaily.com*, available at: *https://www.archdaily.com/214862/windswept-installation-charles-sowers-studios/*

5) B. Meinhold (2012), "Windswept is a Fascinating Kinetic Façade That Reveals the Direction of the Wind", *InHabitat.com*, available at: *https://inhabitat.com/windswept-is-a-fascinating-kinetic-facade-that-reveals-the-direction-of-the-wind/*

Al Bahar Towers, Aedas UK
Abu Dhabi, UAE, 2013

31

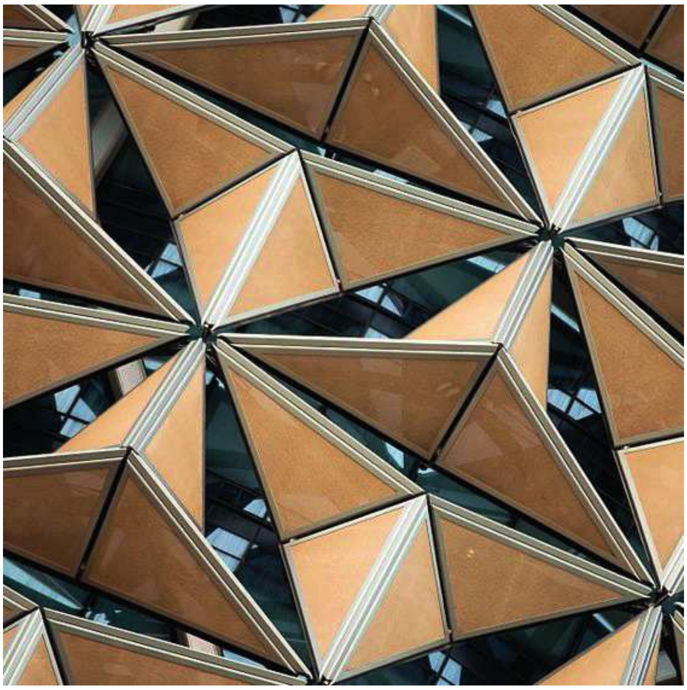


Photo Credits: *AHR sectors - http://www.ahr-global.com/Al-Bahr-Towers*

[Introduction] Honoured with the Tall Building Innovation Award, the towers, headquarters of the Abu Dhabi Investment Council, make of their special building envelope system their distinguishing feature. Totally glazed, their ability to adapt in an extreme climatic context such as the Emirates' desert is guaranteed by the peculiar shading systems, fully automated and able to be activated when the external conditions change,

CREDITS

Design team	Aedas Architects UK & ARUP
Location	Abu Dhabi , UAE
Project year	2013

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate		■			

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

controlling in a selective way the solar radiation without compromising the outside view.

[The Smart Feature] The responsive façade, inspired from the traditional Islamic shading device, that react in direct response to the sun's movements. Thanks to these smart devices indeed it was possible to create a fully glazed building without recurring to heavy tinted glazing that could have affected natural lighting within confined spaces.

[The technologies] This system, made by over 1000 hexagonal PTFE elements inspired by the typical shape of the Arab *mashrabiya* (each tower counts 1049 shading devices, each weighing about 1,5 tonnes), reacts according to the external temperature, contracting itself when it goes down.
Its dimensioning, and in particular, the definition of the geometry of the single inserts, was realized thanks to a parametric descriptor that simulated its behaviour during a daily solar cycle. The screen operates as a curtain wall separated from the buildings bearing structure; each triangle is programmed to respond to the movement of the sun; in the evening all the screen will close, completely changing the appearance of the building.
The shape of the building in plan and elevation led to 22 different variations in its geometry.

[The performance] In this building, the presence of a well-established construction elements such as a shading systems, reinterpreted according to local traditions, has allowed to achieve a reduction in energy consumption of about 50% and in solar gain of about the 80%.

References
1) K. Cilento (2012), "Al Bahar Towers Responsive Facade / Aedas", *ArchDaily.com*, available at: *https://www.archdaily.com/270592/al-bahar-towers-responsive-facade-aedas*
2) AHR Global, website, available at: *http://www.ahr-global.com/Al-Bahr-Towers*
3) A. Welch (2013), "Al Bahar Towers. Aedas designs world's largest dynamic building facade", *e-architect.co.uk*, available at: *https://www.e-architect.co.uk/dubai/al-bahar-towers-abu-dhabi*

Conjoined Media Towers Location, REX Architects
Doha, Qatar, 2013

32

Photo Credits: *luxigon*

[Introduction] Conjoined headquarters of two middle eastern media companies, the two towers developed by REX recall the traditional architecture of the emirates, satisfying at the same time functional and programmatic needs.

[The Smart Feature] The buildings' western façades transform according to sun path thanks to a large

CREDITS

Design team	REX Architects
Location	Doha, Qatar
Project year	2013

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state			■

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate		■			

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

retractable sunshades.

[The technologies] The geometry of the shielding devices is inspired by the traditional Arab *mashrabiya*. During the evening, when the sun is low, the shades are closed while when the sun rises, the entire facade transforms reacting in 60 seconds.
In addition, LEDs integrated in this system contribute in the creation of a huge media wall, broadcasting the companies' content in real-time.

References

1) Stevens P. (2014), "REX clads media headquarters with retractable sunshades", *Designboom.com*, available at: *https://www.designboom.com/architecture/rex-media-headquarters-buildings-04-17-2014/*

2) Rosenfield K. (2014), "REX Designs Conjoined Media Towers with Retractable Facade for Middle East", *Archdaily.com*, available at: *https://www.archdaily.com/497572/rex-designs-conjoined-reactive-media-towers-in-middle-east*

3) Lenetsky A., "Conjoined Media Towers | REX", *arch2o.com*, available at: *https://www.arch2o.com/conjoined-media-towers-rex/*

Europaallee 21, David Chipperfield Architects
Zurich, Switzerland, 2013

33

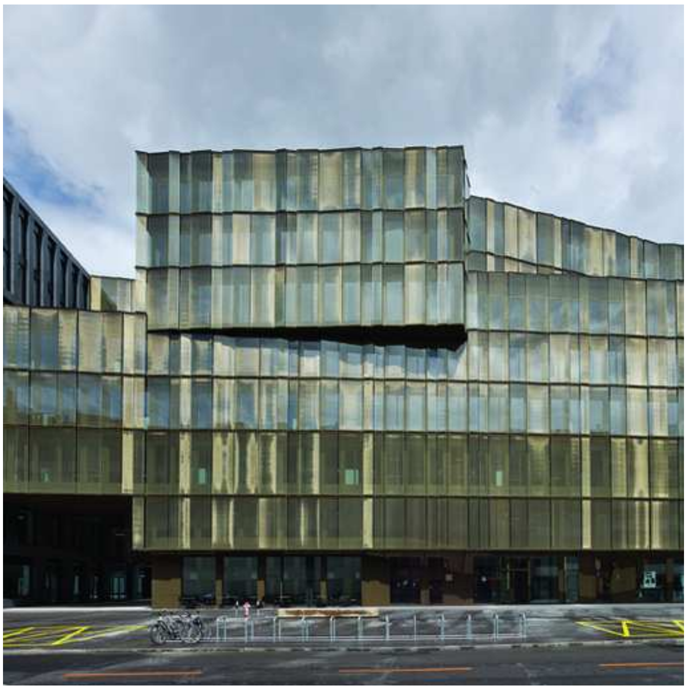


Photo Credits: *Stefan Muller*

[Introduction] Part of a complex that comprises four buildings, grouped around a public courtyard, all the individual buildings are connected each other by bridges.

[The Smart Feature] The responsive façade that change building's appearance according on prevailing light and viewing angle.

CREDITS	
Design team	David Chipperfield Architects
Location	Zurich, Switzerland
Project year	2013

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		8

[The technologies] Obtained through a printed synthetic mesh with different levels of perforation in the external glass panels.

References

1) (2013), "David Chipperfield Architects, EUROPAALLEE 21. Freischutzhasse House", *DIVISARE.com*, available at: *https://divisare.com/projects/235325-david-chipperfield-architects-stefan-muller-europaallee-21-freischutzgasse-house*

2) E. Margaretha (2013), "Kohärentes System: Europaallee 21 in Zürich", *Detail-online,* available at: *https://www.detail.de/artikel/kohaerentes-system-europaallee-21-in-zuerich-10731/*

Hanwha Headquarters, UNStudio
Seoul, South Korea, 2013

34

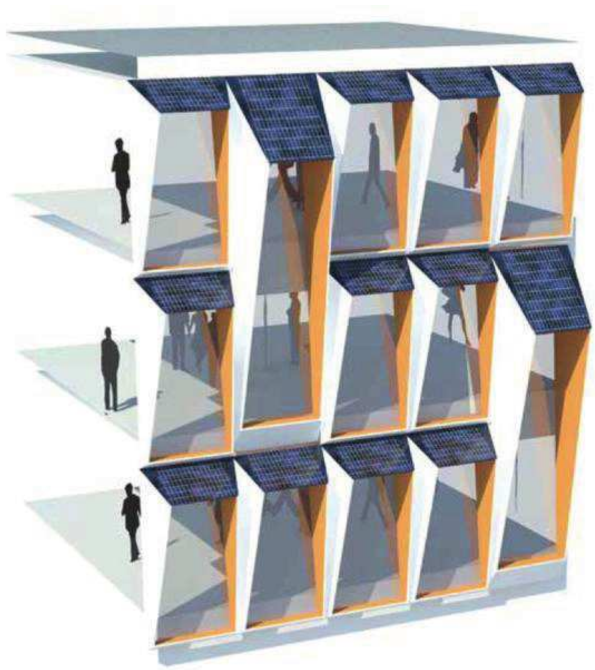


Photo Credits: *MOKA Studio for UNStudio*

[Introduction] The façade is part of a refurbishment project of the building aimed at renovate the aspect of the Hanwha Headquarters; located in Cheonggyecheon in Seoul it aimed at reflect the role of the company as leading environmental technology providers in the world.

[The Smart Feature] The responsive surface that controls the indoor climate during the day and that

CREDITS

Design team	UNStudio
Location	Seoul, South Korea
Project year	2013

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state			■

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	(■, lighter)

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		7

transform the building's façade into a dynamic light show during the night.

[The technologies] The novel façade is made of clear insulated glass with aluminium framing whose position and geometry were sized and calculated in relation to the movement of the sun to ensure users' comfort and reducing energy consumption.
During night, the façade lightning is ensured by hundreds of LED pixels, activated in response to the movements of pedestrian and vehicles on the facing street.

References
1) A. Frearson (2014), "UNStudio's dynamic facade will control indoor climate for Seoul tower", *Deezen.com*, available at: *https://www.dezeen.com/2014/04/30/hanwha-hq-seoul-unstudio-dynamic-facade/*
2) F. Cambiaso (2015), "UNSTUDIO: interactive and dynamic facades in Seoul", *Alchimag.net*, available at: *https://alchimag.net/en/architecture/unstudio-interactive-and-dynamic-facades-in-seoul/*
3) Hanwha Headquarters Remodelling, project web page, available at: *https://www.unstudio.com/en/page/3405/hanwha-headquarters-remodelling*
4) K. Rosenfield (2014), "UNStudio's Responsive Facade to Transform Seoul Office Tower", *ArchDaily.com*, available at: *https://www.archdaily.com/500006/unstudio-s-responsive-facade-concept-selected-to-transform-seoul-office-tower*

Smart Material House BIQ, Arup&Splitterwerk Architects
Hamburg, Germany, 2013

35

Photo Credits: *IBA Hamburg GmbH / Johannes Arlt from Project whitepaper*

[Introduction] The building with Bio-Intelligent Quotient (BIQ) is a pilot project with a bio-reactive façade, presented at the International Building Exhibition in Hamburg in 2013 as the first totally passive building in the world powered by algae.
It is a solid cubic structure of stonework and concrete that combines adaptable structural design (different layout typologies of apartments are available in response to contemporary demands) with smart technologies and building materials.

[The Smart Feature] The use of a material largely available in nature as renewable energy source, integrating additional features to the production system, such as dynamic shading – determined by the variable growth of algae as a function of incident solar radiation – and thermal and acoustic insulation, giving life to an organism strongly characterized by the technology employed, also from an aesthetic point of view, and potentially endowed with significant consequences also on the surrounding environment, as a means to reduce CO2 emissions though buildings' façades.

[The technologies] The system, installed on the south-east and south-west building façades (200 square meters approximately), is made up of 129 sun-tracking reactors modules consisting of a double-glazed window (with argon in the air-gap), mounted on a metal frame and

CREDITS

Design team	Arup and Splitterwerk Architects
Location	Hamburg, Germany
Project year	2013

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	■
Other	

Purpose	
Thermal comfort	□
Visual performance	□
Acoustic comfort	□
Energy management/generation	□
IAQ	
Interaction and users' control	
Other	■

Adaptive function	
Collect and storage	■
Control	
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	□
Dynamic facade	□
Adaptive glazing	
Energy generating	□
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger		■				

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		7

separated by a cavity of about 24 lt, filled with water and suitable for the culture medium needed for the proliferation of micro-algae.
The algae's growth, stimulated by the incident solar radiation and by the addition of CO_2 as nutrient, allows the production of heat (used for heating the rooms and for the production of domestic hot water or stored for further uses) and biomass (about 30 KWh / m2 year), collected by means of a separator and placed in a container at a controlled temperature to be further used for biogas' production.
The whole system operation is guaranteed by a centralized management device that manage all the processes necessary to operate the bioreactor façade and to fully integrate it with the energy management system of the building.

[**The performance**] Due to the sunlight and to a constant turbulence that avoid algae aggregation, the production of heat is about the 38% of efficiency, compared to a 60-65% of a conventional solar thermal, while biomass production is at about the 10% of efficiency in comparison of the 12-15% of a conventional PV.

References

1) M. Casini (2016), *Smart Buildings. Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance,* Woodhead Publishing Series in Civil and Structural Engineering: Number 69, Elsevier.
2) The BIQ House: first algae-powered building in the world (2015), The European Portal For Energy Efficiency in Buildings, available at: *http://www.buildup.eu/en/node/43910*
3) SolarLeaf prototype, website, available at: *https://www.arup.com/en/projects/s/SolarLeaf*
4) Project BIQ leaflet, available in pdf at: *http://www.iba-hamburg.de/fileadmin/Mediathek/M10_wilhelmsburgmitte/M11_bainderba/M112Smartmaterial/Projectflyer_BIQ_en_121018.pdf*
5) Project BIQ whitepaper, available in pdf at: *http://www.iba-hamburg.de/fileadmin/Mediathek/Whitepaper/130716_White_Paper_BIQ_en.pdf*
6) Project BIQ, website, available at: *http://www.biq-wilhelmsburg.de/energiekreislauf/energiekonzept.html*
7) Solarleaf bioreactor façade, website, available at: *http://www.colt-info.de/solarleaf.html*
8) The BIQ House, video explanation, available at: *https://www.youtube.com/watch?v=5r3p3NJVq_k*

Torre de Especialidades, elegant embellishments
Mexico City, Mexico, 2013

36

Photo Credits: *elegant embellishments*

[Introduction] The Torre de Especialidades is an addition to the Hospital Manuel Gea Gonzales, located in the southern Tlalpan neighbourhood of Mexico City. Built as part of a government project to improve the city's health infrastructure (called ProAire initiative), it is designed to transform air pollutants into harmless chemicals, improving surrounding air quality (an aspect of particular importance in an area full of hospital

CREDITS

Design team	elegant embellishments. D. Schwaag and A. Dring
Location	Mexico City, Mexico
Project year	2013

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	■
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		8

patients).

[The Smart Feature] The building façade (approximately of about 2,500 square metres) is made up of a new type of tile which can neutralize the surrounding air pollutants thanks to the special paint within which the façade's modules are treated, made from a titanium dioxide-based pigment. When daylight reaches the tiles' surface, the titanium dioxide triggers a chemical reaction between the treated surface and the smog in the air, reducing air pollution by breaking down smog into safer chemicals.

[The technologies] Inspired by fractals in nature, the undulating shapes of the façade's modules are designed to better distribute pollutants across the active surface, slowing wind speed and creating turbulence. Moreover, the particular geometry of the tiles, obtained through lightweight thermoformed plastic panels, allow shadowing the inside of the building, helping to maintain proper internal comfort conditions, lowering at the same time the electric energy needed for conditioning.

[The performance] Based on third-party testing of the material employed for the realization of this façade, it has been estimated that it allows to neutralise roughly the same amount of smog produced each day by about 1000 vehicles in Mexico City. Further, performing its depolluting action, the pigment which covers the tiles remains unchanged, which means that such a system can keep purifying the air for as long as a decade.

References

1) elegantembellishments, website, available at: *http://www.elegantembellishments.net/home-1/*

2) eDepolluting facade "Prosolve 370e", website, available at: *http://www.prosolve370e.com*

3) (2013), "Fighting foulness: de-polluting façade by Elegant Embellishments", *Detail-online*, available at: *https://www.detail-online.com/blog-article/fighting-foulness-de-polluting-facade-by-elegant-embellishments-24764/*

Allianz Headquarters, Wiel Arets Architects
Wallisellen, Switzerland, 2014

37

Photo Credits: *Jan Bitter*

[Introduction] Composed of two edifices linked by a series of glazed bridges, the headquarters is located on the edge of Zurich's city centre in the framework of the new district's master-plan.
Planning guidelines established that all building façades be made of stone, so it was chosen to frit buildings' glazed façades with a marble pattern (taken from the marble surfaces of the Barcelona Pavilion) that helps in

CREDITS

Design team	Wiel Arets Architects
Location	Wallisellen, Switzerland
Project year	2014

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

integrate building within the surroundings.

[The Smart Feature] The pattern, obtained from two version of the same image, were fritted on the back side of two different layers of glass; in this way, the reflections of it appears ever-changing, according with sun variations.

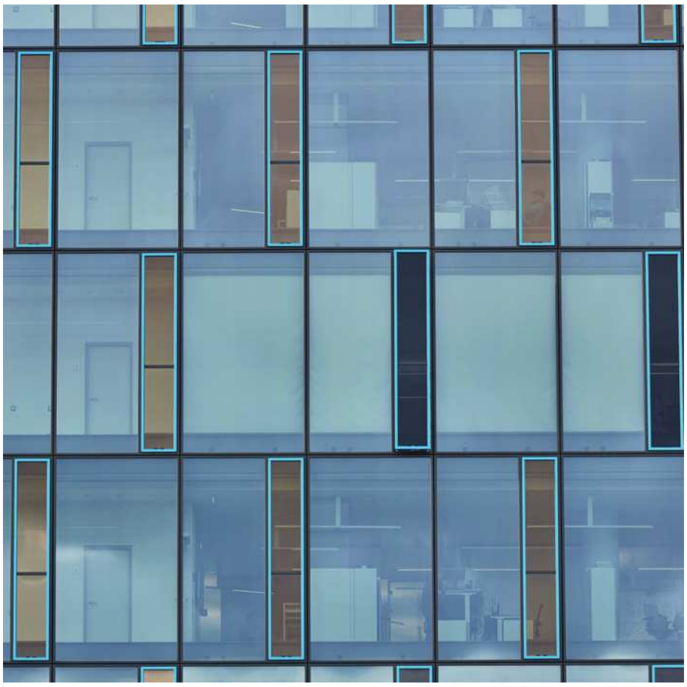
[The technologies] Each façades' element contains a cavity system mechanically ventilated, to avoid condensation problem. In this cavity an aluminium coated silver curtain stands; its operation is function of external environmental factors and it's controlled by a computer algorithm.

[The performance] Thanks to the highly-insulated multiple glazing, the building meet the Swiss Minergie standard and 2000W label.

References
1) Wiel Arets Architects (2014), "Allianz Headquarters / Wiel Arets Architects", *Archdaily.com*, available at: *https://www.archdaily.com/489836/allianz-headquarters-wiel-arets-architects*
2) Frearson, A. (2014), "Allianz Headquarters by Wiel Arets features glass fritted to reference Mies' Barcelona Pavilion", *Deezen.com*, available at: *https://www.dezeen.com/2014/03/26/allianz-headquarters-wiel-arets-architects/*
3) Stevens, P. (2014), "wiel arets clads zurich's allianz HQ in onyx marble pattern", *designboom.com*, available at: *https://www.designboom.com/architecture/wiel-arets-architects-allianz-headquarters-zurich-03-25-3014/*
4) L. Alenei et al. (ed. by) (2018), *Case Studies - Adaptive Facades Network,* TU Delft Open for the COST Action 1403 Adaptive Facade Network.

Festo's Automation Centre, Ulrich & Jens Jaschek Architects
Stuttgart, Germany, 2014

38



[Introduction] Located in the south of Germany, Festo's AutomationCentre presents a smart automated glass façade that fulfil Germany's strict energy standards.

[The Smart Feature] The completely glazed dynamic façade.

[The technologies] The façade was designed to reduce the excessive sunlight from internal spaces using an inside glare-protection screen with room-temperature

CREDITS

Design team	Ulrich & Jens Jaschek Architects
Location	Stuttgart, Germany
Project year	2014

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	■
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger		■				

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

inner surface. The system, designed as a common double-glazed facade, with a ventilation channel between the screen and the exterior envelope, has actually a dynamically adaptable solar energy transmittance thanks to electro-chromic glass panels.

[The performance] The system is extremely efficient: even at an outside temperature of over 35°C the indoor temperature remains constant and never exceeding 26°C.

References

1) Festo Automation Centre, reference of EControl-Glas website, available at: *https://www.econtrol-glas.de/en/references/festo/*

2) L. Grozdanic (2014), "Atkins' H2 low carbon building is an "ecological sandwich" in China", *inhabitat.com*, available at: *https://inhabitat.com/atkins-h2-low-carbon-building-is-an-ecological-sandwich-in-china/*

May-September, Rob-Ley, Urbana Studio
Eskenazi Hospital facade, Indianapolis, USA, 2014

39

Photo Credits: *Serge Hoeltschi, Rob-Ley.com*

[Introduction] Commonly identified with the façade of the Indianapolis hospital, this dynamic envelope is actually the cladding of the multi-story car park that faces it; originated to transform a generally unappreciated infrastructure – as a parking – into an interactive terrain.

[The Smart Feature] The chromatic variations of the façade, coupled with the different angle of the panels

CREDITS

Design team	Rob-Ley, Urbana Studio
Location	Indianapolis, USA
Project year	2014

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	■
Component	
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

that made it up, the offer a dynamic visual experience, implementing performance features such as shielding and ventilation functions.

[The technologies] Made using about 7000 panels in aluminium and steel, the façade has been designed according to the direction of the prevailing winds on the site as well as to users' points of view, thanks to a computer-aided system that simulated the mutual arrangement of the individual panels, thus optimizing the final image obtained.
Therefore, its main feature is the three-dimensionality, obtained through the mobility of the elements that compose it in users' perception and emphasized by the different colours on their two sides rather than by means of actual kinetic components.

References

1) Eskenazi Hospital, Indianapolis, IN (2014), project webpage, available at: *http://rob-ley.com/May-September*
2) T. Grisi (2017), "Facciata dell'Ospedale Eskenazi a Indianapolis – Rob Ley", *ArketipoMagazine.it,* available at: *https://www.arketipomagazine.it/facciata-dellospedale-eskenazi-a-indianapolis-rob-ley/*

SDU Campus Kolding, Henning Larsen Architects
Kolding, Denmark, 2014

40

Photo Credits: *HUFTON + CROW*

[Introduction] The new campus of the Design School of the Syddansk Universitet has a triangular shape and created a new significant landmark in Kolding.

[The Smart Feature] The climate-responsive kinetic façade, obtained through a dynamic solar shading which adjusts to outdoor climate conditions and users' patterns as well, providing optimal daylighting during the whole day.

CREDITS

Design team	Henning Larsen Architects
Location	Kolding, Denmark
Project year	2014

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger		■				

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

[The technologies] The shading system consists of approximately 1600 triangular elements of perforated steel, mounted on the façade in a way that allow them to move according to the changing of daylight levels.
Their rotation defines shapes and transparencies always different; even the perforation is articulated following a circular pattern and it was studied to optimize the ration among users' view towards the outside and façade's shading function.
This system is equipped with sensor that continuously measure light and heat levels and that regulate the shutters accordingly by means of a motor.

References
1) Henning Larsen Architects (2015), "SDU Campus Kolding / Henning Larsen Architects", *ArchDaily.com*, available at: *https://www.archdaily.com/590576/sdu-campus-kolding-henning-larsen-architects*
2) SDU – Campus Kolding, project website, available at: *https://henninglarsen.com/en/projects/featured/0942-sdu-campus-kolding*
3) A. G. Brake (2015), "Henning Larsen's university building has a facade that moves in response to changing heat and light", *Deezen.com*, available at: *https://www.dezeen.com/2015/07/14/henning-larsen-syddansk-universitet-sdu-kolding-campus-building-denmark-green-standards-university/*
4) Henning Larsen Architects (2015), "Kolding campus of the University of Southern Denmark", *Divisare.com*, available at: *https://divisare.com/projects/301561-henning-larsen-architects-hufton-crow-kolding-campus-of-the-university-of-southern-denmark*

The W.I.N.D. House, UNStudio
North-Holland, The Netherlands, 2014

41

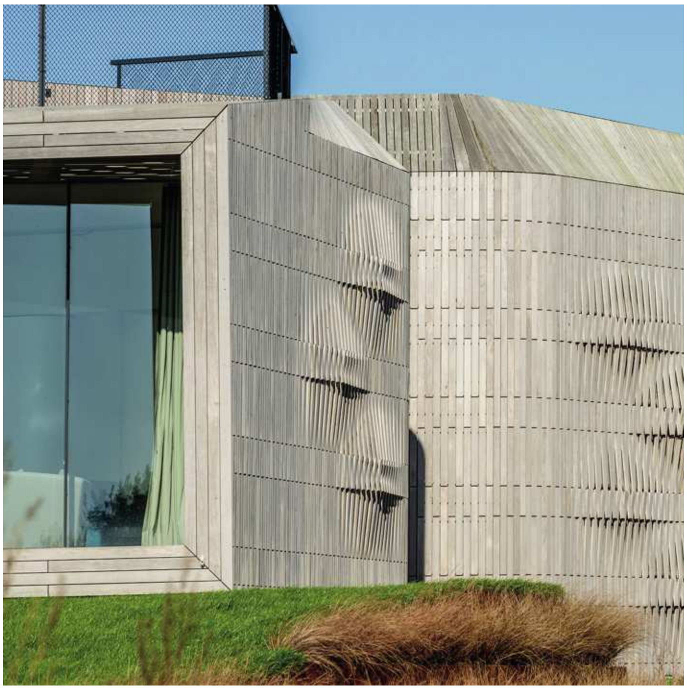


Photo Credits: *Fedde de Weert*

[Introduction] Described as the “home of the future” due to the interaction that occurs through its systems and appliances – thanks to ICTs – thus resulting in energy consumption reduction, safety and security, the W.I.N.D: House incorporates both integrated sustainable solutions and home automations regulating and maximizing the effects of its surrounding landscape.

CREDITS

Design team	UNStudio Architects
Location	North-Holland, Netherlands
Project year	2014

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	
Allow interaction	■

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	■

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

In addition, flexible layouts are available in order to respond to family's changing needs.

[The Smart Feature] The organization of the house, defined by its external conditions, as well as the complete control of all the home's appliances, including electrical systems, solar panels and mechanical installations.

[The technologies] The complete control of this Smart Home is possible by a central touch-screen interface located in the living area; furthermore, remote control is possible by independent devices via LAN-connection.

References

1) UNStudio (2015), *"The W.I.N.D. House / UNStudio", ArchDaily.com*, available at: *https://www.archdaily.com/595850/the-w-i-n-d-house-unstudio*

2) UNStudio, The W.I.N.D. House, project webpage, available at: *https://www.unstudio.com/en/page/3419/the-w-i-n-d-house*

3) A. Frearson (2015), "UNStudio completes a digitally controlled home with a flower-shaped plan", *Deezen.com*, available at: *https://www.dezeen.com/2015/02/03/unstudio-digitally-controlled-home-wind-house-flower-shaped-plan-netherlands/*

4) UNStudio, "The W.I.N.D. House", *world-architects.com*, available at: *https://www.world-architects.com/ca/architecture-news/works/the-wind-house*

Umbrella Facade at Madrid pavillon, 3GATTI
UBPA, Shangai Expo Area, China, 2014

42

Photo Credits: *3Gatti*

[Introduction] Novel concept of façade developed for the Madrid Pavilion after its conversion into a retail and office complex once the Expo was concluded.

[The Smart Feature] The shading system, inspired from Chinese culture, adjustable on-demand by occupants to control light levels within the building.

CREDITS	
Design team	3GATTI Architecture Studio
Location	UBPA, Shangai, China
Project year	2014

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

[The technologies] Starting from the Chinese tradition to repair oneself with umbrellas in sunny days, the architects transferred this concept to the sun shading devices designed for covering the glazed building's façades. Each "module" is made of perforated Corten steel and it is able to be controlled by a pulley.

References

1) A. Frearson (2013), "Umbrella Facade for the Madrid Pavilion by 3Gatti Architecture Studio", *Deezen.com*, available at: *https://www.dezeen.com/2013/04/23/umbrella-facade-madrid-pavilion-by-3gatti/*

2) (2013), "Umbrella facade designed for Madrid Pavilion in Shanghai", *designMENA.com*, available at: *http://www.designmena.com/thoughts/umbrella-faade-created-madrid-pavilion*

Homed, FramLab
New York City, USA, 2015

43

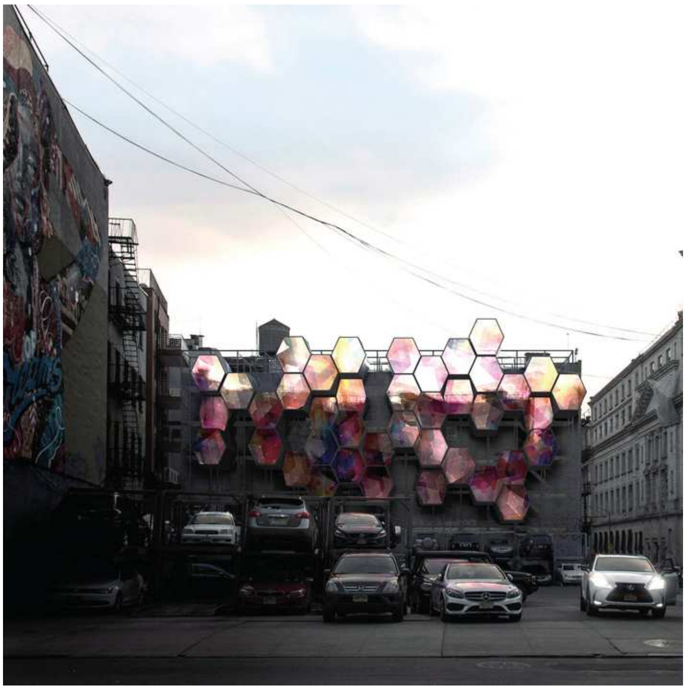


Photo Credits: *FramLab*

[Introduction] Temporary shelters system designed to house the homeless population by covering existing empty walls with this honeycomb-like clusters.
The hexagon shaped systems is conceived to be hanged to windowless façades, using these "vertical lots" instead of new land. The access to the units would be provided by staircases integrated within scaffolding frames.

CREDITS

Design team	FramLab studio
Location	New York, USA
Project year	2015

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	■
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	■

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	■
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger					■	

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■
TRL		3

[The Smart Feature] The ability of this structure to be easily and quickly erected or disassembled, making the system suitable for different needs.

[The technologies] The units are designed with an outer aluminium shell and a inner 3D-printed wall structure made from recycled polycarbonate; smart-glass windows are considered for the front of the units to offer views for residents from one side and used, from the other, to display artwork or advertisements to enhance the empty walls.

References

1) Creating a shelter with dignity, project web site, available at: *https://www.welcomehomed.com*

2) NYU Furman Center, "Rent Stabilization in New York City", final fact sheet, available in pdf at: *http://furmancenter.org/files/publications/HVS_Rent_Stabilization_fact_sheet_FINAL_4.pdf*

3) E. Gibson (2017), "Framlab proposes parasitic hexagonal pods to sleep New York's homeless", *Deezen.com*, available at: *https://www.dezeen.com/2017/11/21/homed-famlab-parasitic-hexagonal-pods-new-york-homeless-shelters/*

4) Shelter with dignity, project web page, available at: *https://www.framlab.com/homed*

InDeWaG, Prof. Dr. Dieter Brüggemann
Bayreuth, DE, 2015

44

Photo Credits: *Ümit Esiyok*

[Introduction] The research project InDeWaG (Industrial Development of Fluid Flow Glazing Systems), funded by the European Community within the framework of the HORIZON2020 program, is focused of an insulating glazing unit filled up with a water-glycol fluid circulating within one the IGU cavities.

CREDITS

Design team	Prof. Dr. Dieter Brüggemann
Location	Bayreuth, DE
Project year	2015-2019

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	■
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	■
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		3

[The Smart Feature] This technology is conceived to serve for both heating and cooling with the aim to combine these units with other technologies in HVAC systems, to minimize buildings' total energy consumption without restrictions in daylight autonomy.

[The technology] InDeWaG facade is designed to have passive control so it does not need of sophisticated electrical integration; this objective has been made possible thanks to a "triple glazing element" in which a fluid water-glycol mixture is circulating, with a minimum of forced pumping. The two laminated glass panes consist each of 2,0x8,0 mm with a 1,52 mm interlayer.
In order to ensure the optimal integration of the Fluid Flow Glazing (FFG) modules in the overall building climate concept, so to understand their exact spectral, thermal, mechanical and fluid dynamic properties, mathematical models for the relevant physical processes (heat exchange, fluid flow dynamics, optical and structural behaviour as well as environmental influences) within a software model of the glazing are mapped, using highly complex flow simulations Computational Fluid Dynamics (CFD).

References
1) L. Alenei et al. (ed. by) (2018), *Case Studies - Adaptive Facades Network,* TU Delft Open for the COST Action 1403 Adaptive Facade Network.
2) Project website, available at: *http://www.indewag.eu/*
3) Luis, J. et al., (2016), "A New and Inexpensive Open Source Data Acquisition and Controller for Solar Research: Application to a Water-Flow Glazing", *Renewable Energy*, v. 92, pp. 450-461

Smart Facade, Fraunhofer Institute IWU
Chemnitz, Germany, 2015

45

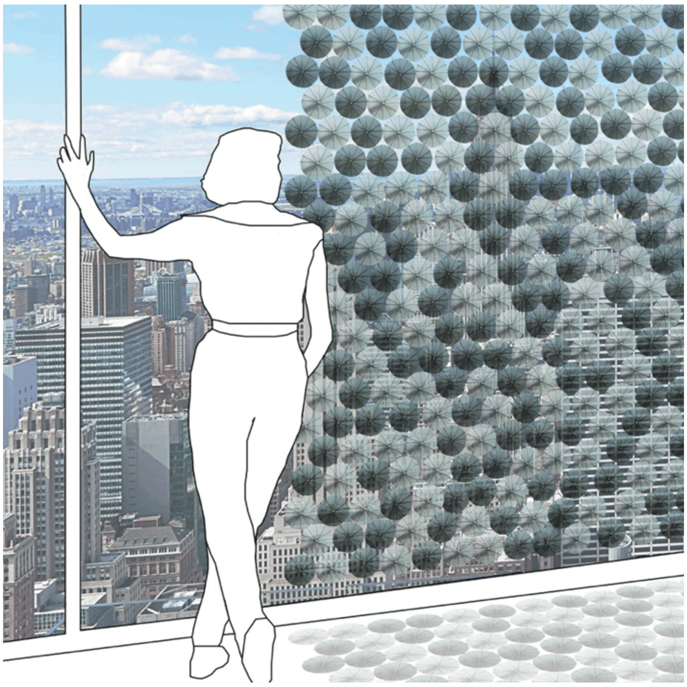


Photo Credits: *Wilm Ihlenfeld/Fotolia, Fraunhofer IWU*

[Introduction] Developed by researchers from the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Dresden, in collaboration with the Department of Textile and Surface Design at Weissensee School of Art in Berlin, as a response to buildings' glass façades consumption.
Future development plans include climate functions for the façade element, such as, for instance variable heat

CREDITS

Design team	Fraunhofer Institute IWU
Location	Chemnitz, Germany
Project year	2015

	Residential	Service industry	Specialized
Intended use	■		

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	■ (light)
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger	■					

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.		■

TRL	3

insulation or the deposition of malleable, organic solar cells on components, to generate electricity that can be used within the building.

[The Smart Feature] The façade element, designed for reducing energy consumption by harnessing solar thermal energy, thanks to the use of integrated shape-memory alloys able to autonomously respond to sunlight.

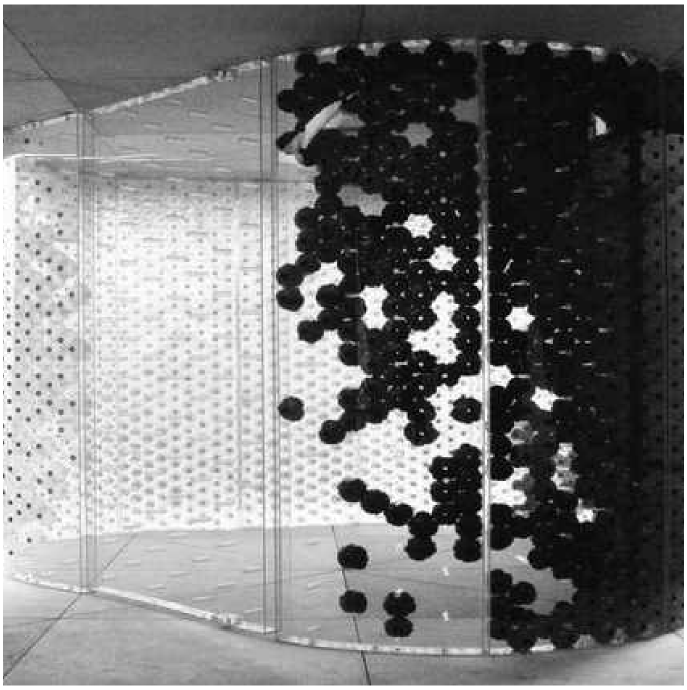
[The technologies] The demonstrator consisted of a matrix of 72 individual fabric components, flowers-shaped; each of them has shape-memory actuators integrated within it that remember their original shape when exposed to heat. When the façade heats up the actuators are activated and contract to open the textile components thus covering the exposed surface. When the sun goes down or disappears, the components close again making the façade transparent once more.
Those sun shielding devices can be applied either on the outer layer of glass on in the air gap in case of multi-layer façades.
Such technology can be shaped in different design and it fits even on curved area of glass; its control is possible through an application specially designed for this purpose.

References

1) H. Schneider (2015), "Saving energy with smart façades", press release of Fraunhofer-Gesellschaft, available at: *https://www.fraunhofer.de/en/press/research-news/2015/april/saving-energy-with-smart-facades.html*

The Breathing Skins Showroom, Studio Tobias Becker
Mandelbachtal, Germany, 2015

46



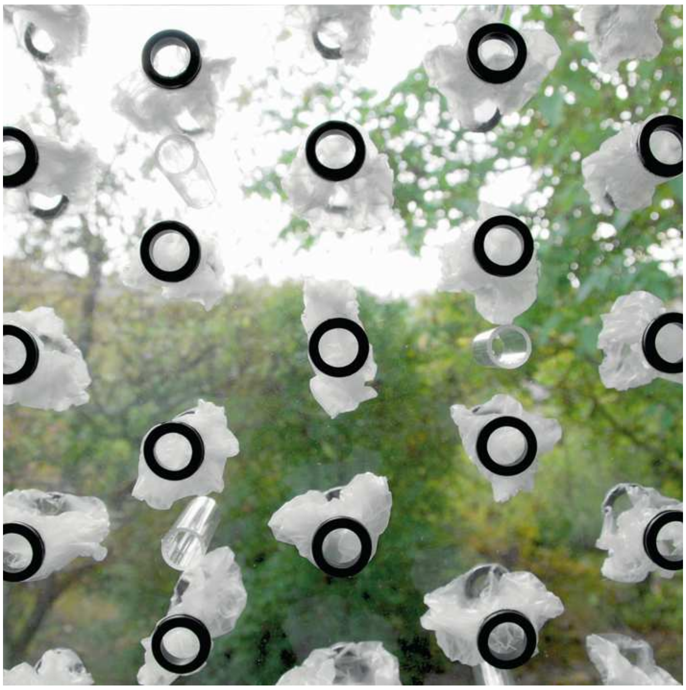


Photo Credits: *The Breathing Skins Project*

[Introduction] Breathing skins tried to conceived the envelope as an adaptive media of exchange, able to act as a real filter among inside and outside, reducing the barriers among the two environments.

[The Smart Feature] The novel concept of responsive architecture that conceive the indoor as a part of the natural environment.

CREDITS	
Design team	Ing. Tobiaas Becker, B.A. Simon Huffer
Location	Mandelbachtal, Germany
Project year	2015

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	■
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.	■	
TRL		7

[The technologies] Made of polycarbonate sheets – equipped with great mechanical property and workability in bending – the Breathing Skins technology takes inspiration from human skin. It is indeed constituted by a set of channels (about 140 on every square meters for a total amount around 2800 air channels) that can be pneumatically closed after the application of an air pressure within the façade. This deformation process, operated by a pneumatic actuator, require minimal energetic input.
The more the pneumatic muscles open, the more the appearance of the façade changes.
The façade elements, separated into 14 curved panels, are built as sandwich construction with weight lower than 11kg/m2.

References

1) the Breathing skins, website, available at: *https://www.breathingskins.com*
2) Breathing Skins Showroom (2016), EPSE, European Polycarbonate Sheet Extruders website, available at: *http://www.epse.org/breathing-skins-showroom*
3) Breathing Skins Showroom's video, available at: *https://vimeo.com/158980746*

Chromazone, Hal Ingberg
Montreal, Canada, 2016

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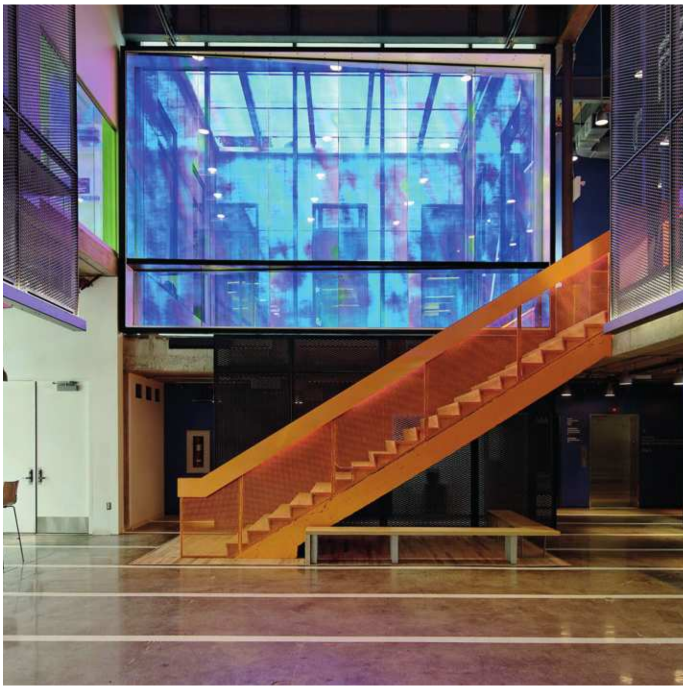

Photo Credits: *Hal Ingberg*

[Introduction] Born to create a perceptual experience, Chromazone is a glass wall whose aim is to explore optical complexity, ambiguity and mutability.
It stands within the Centre culturel de Notre-Dame-de-Grace, in Montreal and it offers a high-angle view of the lobby on the ground floor while allowing for a perceptual experience related to the transparency and reflective power of glass.

CREDITS	
Design team	Hal Ingberg
Location	Montreal, Canada
Project year	2016

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state	■		

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		8

[The Smart Feature] It employs dichroic glass whose optical features' perception varies according to light conditions and users' movements thanks to the multiple layers of coloured metal oxide film it contains. During the day indeed, light is transmitted through the glass that is perceived as coloured and transparent, while in the evening a minimum of light is transmitted: the coloured reflections of the glass cause it to work as a mirror, mixing its colours with the ones of the hall.

<u>References</u>

1) (2016), "Hal Ingberg | Chromazone", *Divisare.com*, available at: *https://divisare.com/projects/320980-hal-ingberg-chromazone*

2) Chromazone, project web site, available at: *https://www.halingberg.com/chromazone*

3) Hal INGBERG CHROMAZONE 2016, Art Publique Ville de Montreal web site, available at: *https://artpublic.ville.montreal.qc.ca/en/oeuvre/chromazone/*

CJ Blossom Park, Yazdani Studio - CannonDesign
Seoul, South Korea, 2016

48

[The Smart Feature] The centre is composed by three towers wrapped in an organic curved curtain wall shielded with a responsive façade, able to significantly control solar heat gain.

[The technologies] The technology employed a custom-designed retractable mechanism inspired by umbrellas, made of perforated steel strips installed on scissor actuations that can be opened or closed automatically.

CREDITS

Design team	Yazdani Studio, CannonDesign
Location	Seoul, South Korea
Project year	2016

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	■
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs	■			

	On/Off	Gradual
Degree of adaptab.		■
TRL		6

Each unit groups has three ribbons, allowing the windowpane to be completely covered or not.

References

1) CannonDesign (2016), "CJ Blossom Park / CannonDesign", *ArchDaily.com,* available at: *https://www.archdaily.com/875800/cj-blossom-park-cannondesign*

2) A. Michler (2012), "CJ Research Center's Kinetic Folding Facade / Yazdani Studio", *eVolo.us*, available at: *http://www.evolo.us/architecture/cj-research-centers-kinetic-folding-facade-yazdani-studio/*

3) "CJ CORPORATION, CJ BLOSSOM PARK CANNONDESIGN", *The Plan.it*, available at: *https://www.theplan.it/eng/project_shortlist/1909*

Forti Holding Spa, ATIPROJECT
Montacchiello (PI), Italy, 2016

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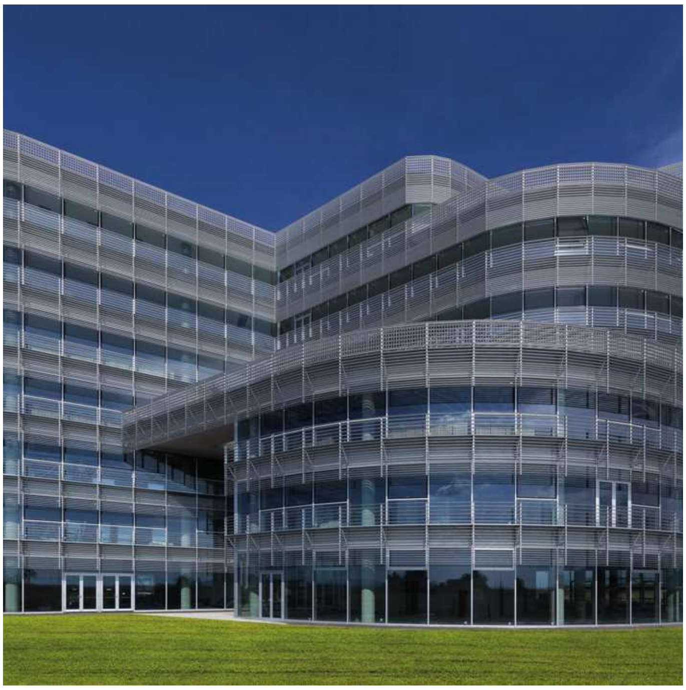

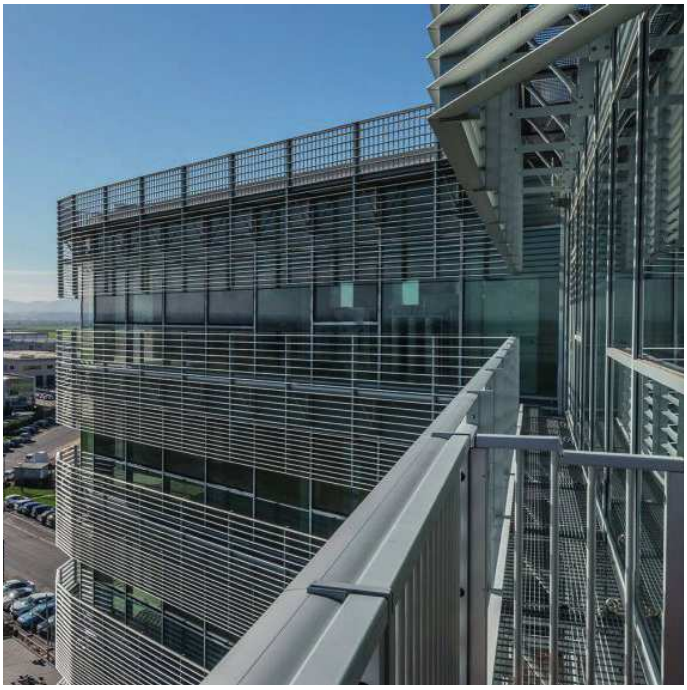

Photo Credits: *Daniele Domenicali*

[Introduction] The building is considered as an example of green architecture, resulted in extremely high-energetic performance.
In its design, opaque and transparent surfaces have been taken carefully in account according to their specific size and orientation.

CREDITS

Design team	ATIPROJECT
Location	Montacchiello (PI), Italy
Project year	2016

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

[The Smart Feature] The smart building envelope system, intended as a mix of technological solutions able to meet current requirements.

[The technologies] The building envelope is made up of a ventilated façade and of a totally glazed façade, with a sunscreen system to filter light entering within confined spaces. The south façade is covered with solar panels and it has been dimensioned to fully meet building's energetic needs. Thanks to the special technological solutions adopted the envelope becomes the first system of the building able to significantly limit its consumption.

References

1) "ATIPROJECT Forti Holding S.P.A. // Headquarters and office building", *Divisare.com*, available at: *https://divisare.com/projects/307528-atiproject-forti-holding-s-p-a-headquarters-and-office-building*

2) Centro Direzionale "Umberto Forti", project web page, available at: *http://atiproject.com/architecture/#1338*

3) C. Scalco (2017), "Headquarter Forti Holding a Montacchiello (Pi) – ATIproject", *Arketipo Magazine*, online version available at: *https://www.arketipomagazine.it/headquarter-forti-holding-a-montacchiello-pi-atiproject/*

4) "Centro direzionale 'Umberto Forti' ATIPROJECT", *The Plan.it*, online version available at: *https://www.theplan.it/project_shortlist/1007*

Siemens Headquarters, Henning Larsen Architects
Munich, Germany, 2016

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Photo Credits: *Hufton + Crow*

[Introduction] Designed to merge tradition with the future, the Siemens' new global headquarters combines a brave architectural design with high-efficiency technologies, becoming one of the most European sustainable buildings.

[The Smart Feature] The smart building technologies applied to the edifice.

CREDITS

Design team	Henning Larsen Architects
Location	Munich, Germany
Project year	2016

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	
Facade system	■

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	■

Purpose	
Thermal comfort	
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	■
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	
Allow interaction	■

Classification	
High-performance	
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	■

	Passive	Active
Operation mode		■

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs				■

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

[The technologies] All the façades are covered by triple glazed, slightly tilted to increase the amount of natural light that entering the interior spaces.

The building is completely controlled by Siemens smart building technologies which collect data to control heating, ventilation and air conditioning systems; occupants can adjust their own patterns to meet individual needs.

References

1) Henning Larsen Architects, "Siemens Headquarters / Henning Larsen Architects", *ArchDaily.com,* available at: *https://www.archdaily.com/791741/siemens-headquarters-henning-larsen-architects*

2) (2016), New corporate Headquarters, Munich, Siemens website, available at: *https://www.siemens.com/press/en/feature/2014/corporate/2014-07-siemens-palais.php*

3) Siemens' Global Headquarters, Henning Larsen Architects, project webpage, available at: *https://henninglarsen.com/en/projects/featured/1133-siemens-global-headquarters/*

4)T. Laylin (2011), "Henning Larsen Wins Bid To Re-Structure Siemens Munich Headquarters", *inhabitat.com*, available at: *https://inhabitat.com/henning-larsen-wins-bid-to-re-structure-siemens-munich-headquarters/*

Bloomberg Center, Morphosis Architects
Cornell Tech Campus, Roosvelt Island, New York, USA, 2017

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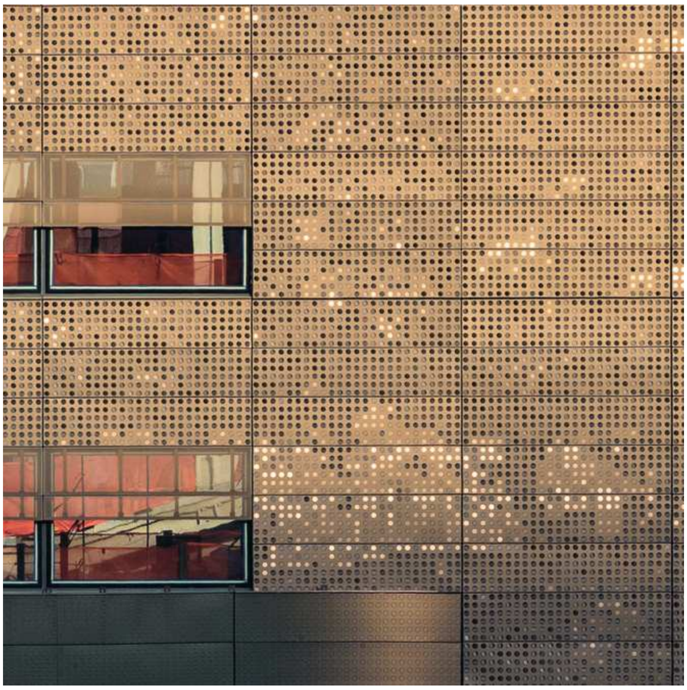

Photo Credits: *Mattew Carbone*

[Introduction] Four-story building under a photovoltaic roof; its most distinctive feature is its facade, optimized to balance transparency and opacity to maximize at the same time daylighting and exterior views with insulation and thermal bridges reduction.

[The Smart Feature] The external layer of the facade is made of aluminium panels coated with an iridescent PPG polymer coating.

CREDITS	
Design team	Morphosis Architects | Thom Mayne
Location	Roosvelt Island (NY), USA
Project year	2017

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate				■	

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

Thanks to a particular technological systems the facade are able to create image patterning.

[The technologies] Each pixel of the image is translated into the "*specific turn-and-tilt of a two-inch circular tab punched into the aluminium panelling; the depth and rotation of each tab determines the amount of light reflected. This pixel map was fed into a re-purposed welding robot, which processed the digital information into the mechanical turning-and-tilting of the façade's 337,500 tabs. The algorithm controlling the robot was developed in collaboration with Cornell and MIT students*".

References

1) J. Stoughton (2017), "Morphosis-designed Bloomberg Center at Cornell Tech celebrates opening", *The Architect's Newspaper*, online version available at: *https://archpaper.com/2017/10/morphosis-designed-bloomberg-center-cornell-tech-celebrates-formal-opening/#gallery-0-slide-0*

2) Morphosis Architects, Bloomberg Center at Cornell Tech. A new model for performance and learning, project web page, available at: *https://www.morphosis.com/architecture/209/*

3) Morphosis Architects (2017), "Bloomberg Center / Morphosis Architects", *ArchDaily.com*, available at: *https://www.archdaily.com/880792/bloomberg-center-morphosis-architects*

4) Morphosis Architects | Thom Mayne (2017), "Bloomberg Center at Cornell Tech Campus on Roosevelt Island", *Divisare.com*, available at: *https://divisare.com/projects/368942-morphosis-architects-thom-mayne-matthew-carbone-bloomberg-center-at-cornell-tech-campus-on-roosevelt-island.*

King Abdullah Research Centre, Zaha Hadid Architects
Riyadh, Saudi Arabia, 2017

52

Photo Credits: *Hufton + Crow*

[Introduction] KAPSARC it's a non-profit institution for independent research about policies that contribute to the most effective use of energy. The campus incorporates five buildings, conceived as an unified whole and designed in response to the environmental conditions of the surrounding to minimize energy and resource consumption.

CREDITS

Design team	Zaha Hadid Architects
Location	Riyadh, Saudi Arabia
Project year	2017

	Residential	Service industry	Specialized
Intended use			X

	Concept I Prototype	Real-scale edifice	Under construction
Building state		X	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate		X			

Application scale	
Element I Material	
Component	
Facade system	X

Type	
Insulation	
Glazing	
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	X

Purpose	
Thermal comfort	■
Visual performance	
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	■
Selective	
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger						■

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		9

[The Smart Feature] Its design optimization coupled with system selection that allow to obtain a 45% reduction in energy performance if compared to the ASHRAE baseline standards.

References

1) Zaha Hadid Architects (2017), "King Abdullah Petroleum Studies and Research Centre / Zaha Hadid Architects", *ArchDaily.com*, available at: *https://www.archdaily.com/882341/king-abdullah-petroleum-studies-and-research-centre-zaha-hadid-architects*

2) J. Mairs (2017), "Zaha Hadid Architects reveals honeycomb-like oil research centre in Riyadh", *Deezen.com*, available at: *https://www.dezeen.com/2017/10/26/zaha-hadid-architects-king-abdullah-petroleum-studies-research-centre-riyadh-saudi-arabia/*

3) King Abdullah Petroleum Studies and Research Centre, Zaha Hadid Architects, project webpage, available at: *http://www.zaha-hadid.com/architecture/king-abdullah-petroleum-studies-and-research-centre/*

Louvre Abu Dhabi, Ateliers Jean Nouvel
Abu Dhabi, UAE, 2017

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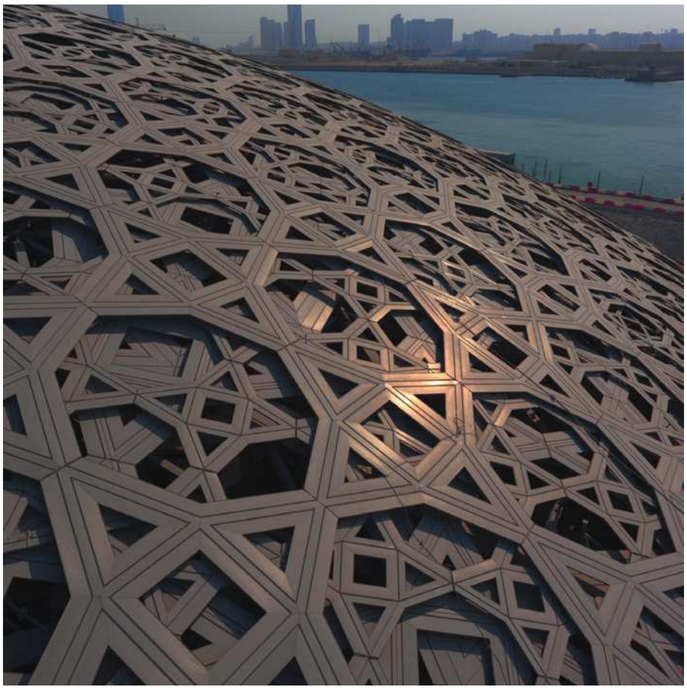

Photo Credits: *Roland Halber*

[Introduction] Designed with the will to combine light and shadow, the Louvre Abu Dhabi recall one of the major symbol of Arab architecture, the dome, proposal under a modern point of view. It counts in total 55 buildings that made up the museum city.

[The Smart Feature] The particular composition of the dome, both in performance as in design terms. It's complete pattern indeed, repeated at various sizes

CREDITS

Design team	Ateliers Jean Nouvel
Location	Abu Dhabi, UAE
Project year	2017

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate	■				

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

and angles along the surface, involve the 8 layers that compose the dome: each ray of light penetrates the whole layers before appearing to further disappears, thus resulting in a cinematic effect as the sun's path progresses during the day.
This effect, at night, forms a constellation of about 7800 stars, visible from both sides

[The technologies] The dome is made of eight different layers; the four outers layers are cladded in stainless steel while the four inner ones, are cladded in aluminium, separated by a steel frame five metres high.
Such a frame is made of 10.000 structural pre-assembled components – 85 super-sized elements – each of them weights up to 50 tons.
The buildings' façades are made up of panel of ultra-high performance fibre concrete (UHPC).

References

1) (2017), "Louvre Abu Dhabi / Ateliers Jean Nouvel", *ArchDaily.com*, available at: *https://www.archdaily.com/883157/louvre-abu-dhabi-atelier-jean-nouvel*

2) Atelier Jean Nouvel, project website available at: *http://www.jeannouvel.com/en/projects/louvre-abou-dhabi-3/*

3) J. Mairs (2017), "Jean Nouvel's completed Louvre Abu Dhabi is spanned by a huge geometric-patterned dome", *Deezen.com*, available at: *https://www.dezeen.com/2017/11/07/jean-nouvel-louvre-abu-dhabi-art-museum-united-arab-emirates/*

Metropole Rouen Normandy, Jacques Ferrier Architecturel
Rouen, France, 2017

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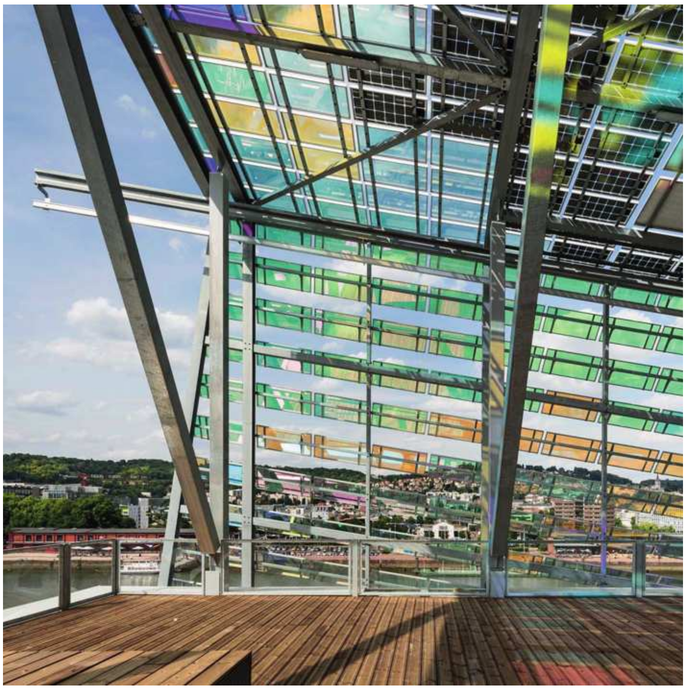

Photo Credits: *Luc Boegly*

[Introduction] Designed to fits in the surroundings, this particular building exploit the technological component to reach for a synthesis between the formal aspect and the performance aspect, able to foster its integration thanks to its dynamic envelope, able to offer even advantages in terms of performance.

CREDITS

Design team	Jacques Ferrier Architecture
Location	Rouen, France
Project year	2017

	Residential	Service industry	Specialized
Intended use			■

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	■
Prevent/Reject	
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		8

[The Smart Feature] The dynamic building envelope, inspired by Monet's paintings of the Cathedral of Rouen, able to confer building a changing appearance throughout the day.

[The technologies] The building is equipped with a double layered façades whose external skin is made of individual glass elements, covered with a layer of metal oxides that give them a changing chromatism, enlightened by the presence of water all around.
On the roof, the glass scales make way for solar panels that provide a considerable contribution to the building's energy self-sufficiency

References

1) (2017), "Jacques Ferrier Architecture, Metropole Rouen Normandy", *Divisare.com*, available at: *https://divisare.com/projects/370209-jacques-ferrier-architecture-luc-boegly-metropole-rouen-normandy*

2) Jacques Ferrier Architecture (2017), "Headquarters of Métropole Rouen Normandie / Jacques Ferrier Architecture", *ArchDaily.com*, available at: *https://www.archdaily.com/882635/headquarters-of-metropole-rouen-normandie-jacques-ferrier-architecture*

3) M. Rinaldi (2017), "Headquarters of Métropole Rouen Normandie by Jacques Ferrier Architecture". *com/2017/10/headquarters-metropole-rouen-normandie-jacques-ferrier-architecture.html*

4) Jacques Ferrier Architecture, Métropole Rouen Normandie, project web site, available at: *http://www.jacques-ferrier.com/projets/metropole-rouen-normandie/#1*

Offices Quai Ouest, Brenac & Gonzalez & Associes
Boulogne-Billancourt, France, 2017

55

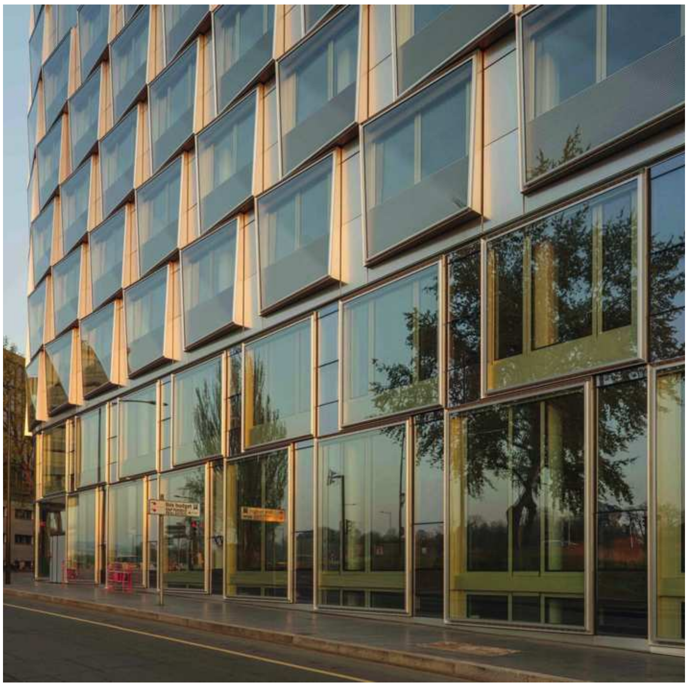

Photo Credits: *Sergio Grazia*

[Introduction] The intervention under examinations it's actually the restructuring of the early buildings, built at the beginning of '90 and no more adapt to new environmental regulations.
So, even to provide it a new identity, the architects decided to provide the old structure with a novel double ventilated glass skin.

CREDITS

Design team	Brenac & Gonzalez & Associes
Location	Boulogne-Billancourt, France
Project year	2017

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	■
Shading	
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.		■
TRL		9

[The Smart Feature] The prismatic envelope, endorsed by the proximity of the river that encourage the sparkle effect.

[The technologies] The sparkling, translucent effect was achieved through glass panels, folded diagonally to create two triangles separated by a sharp crest; in this way the upper triangle reflects the sky while the lower reflects the movements of the surrounding.

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2) Brenac & Gonzalez & Associes (2017), "Quai Ouest / Brenac & Gonzalez & Associés", *ArchDaily.com*, available at: *https://www.archdaily.com/876545/quai-ouest-brenac-and-gonzalez-and-associes*

3) Brenac & Gonzalez & Associes, Quai Ouest, project web site, available at: *http://brenac-gonzalez.fr/en/projet/quai-ouest/*

US Embassy, Kieran Timberlake
London, UK, 2017

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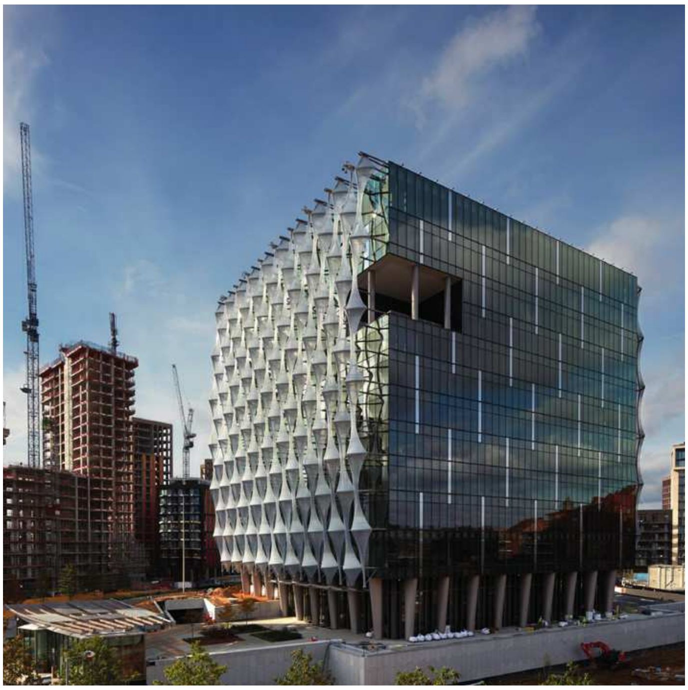

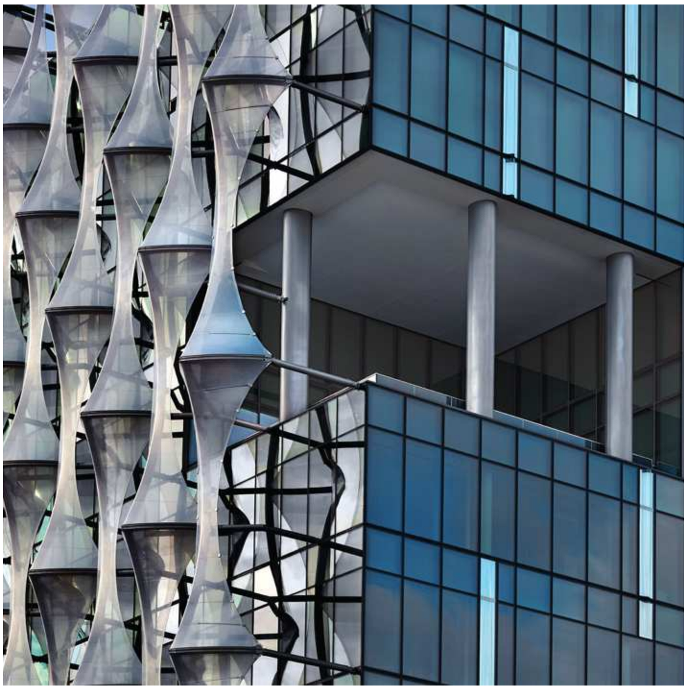

Photo Credits: *Richard Bryant*

[Introduction] The United States embassy in Britain aims at combine high safety standards with an appearance of openness and transparency, making use of responsibly and sustainable materials to demonstrate the attention towards the environment.

[The Smart Feature] The laminated glazing façade, enveloped with a transparent film of ETFE, that give it a changeable translucent appearance.

CREDITS

Design team	Kieran Timberlake Associates
Location	London, UK
Project year	2017

	Residential	Service industry	Specialized
Intended use		■	

	Concept I Prototype	Real-scale edifice	Under construction
Building state		■	

	Tropical	Dry/Desertic	Temperate	Continental	Polar
Climate			■		

Application scale	
Element I Material	
Component	■
Facade system	

Type	
Insulation	
Glazing	
Shading	■
Opening systems	
Energy harvesting devices	
Energy generation devices	
Other	

Purpose	
Thermal comfort	
Visual performance	■
Acoustic comfort	
Energy management/generation	
IAQ	
Interaction and users' control	
Other	

Adaptive function	
Collect and storage	
Control	
Prevent/Reject	■
Allow interaction	

Classification	
High-performance	
Selective	■
Dynamic facade	
Adaptive glazing	
Energy generating	
Control systems	

	Passive	Active
Operation mode	■	

	Thermal	Electromagnetic	Optical	Air quality	Occupants	Other
Trigger			■			

	Extrinsic	Intrinsic	Self-adjusting	Users' control
Response inputs		■		

	On/Off	Gradual
Degree of adaptab.	■	
TRL		8

[The technologies] The glazed envelope is wrapped on the most exposed sides with sails in ETFE that reflect the radiation, modifying their chromatism according to weather and sun position; even the particular form of the façade is designed to minimize solar gain and glare, allowing natural light to entering.
The building integrates also renewable energy sources, such as solar panels embedded in its envelope.

References

1) I. Block (2017), "Kieran Timberlake completes £750 million "crystalline cube" for US Embassy in London", *Deezen.com*, available at: *https://www.dezeen.com/2017/12/18/kieran-timberlake-us-embassy-london-nine-elms-american-architecture-uk/*

2) D. Basulto (2010), "US Embassy in London / KieranTimberlake Architects", *ArchDaily.com*, available at: *https://www.archdaily.com/50922/us-embassy-in-london-kieran-timberlake*

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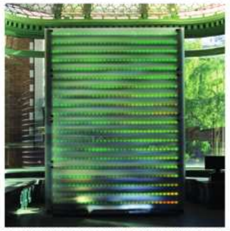
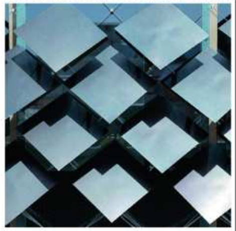
5) J. Sayer (2017), "New U.S. Embassy in London fails to face its neighbours", *The Architects Newspaper*, available at: *https://archpaper.com/2017/12/us-embassy-london-kierantimberlake/#gallery-0-slide-0*

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
1		2002	Specialized	Real-scale edifice	Temperate	Façade system	Opening systems	Interaction and users' control	Prevent / Reject	Dynamic facade	Active	Other	Users' control	On/Off	9
2		2002	Residential	Concept or protoype	Temperate	Component	Shading	Visual performance	Prevent / Reject	Dynamic facade	Active	Occupants	Extrinsic	On/Off	7
3		2003	Specialized	Real-scale edifice	Temperate	Element | Material	Other	IAQ	Control	High-performance	Passive	Optical	Intrinsic	On/Off	9
4		2003	Specialized	Concept or protoype	Continental	Façade system	Other	Thermal comfort	Collect and storage	High-performance	Passive	Optical	Intrinsic	On/Off	7

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
5		2004	Specialized	Real-scale edifice	Continental	Element | Material	Shading	Visual performance	Prevent / Reject	Dynamic facade	Passive	Other	Intrinsic	Gradual	8
6		2004	Service Industry	Real-scale edifice	Temperate	Component	Glazing	Visual performance	Prevent / Reject	Selective	Passive	Optical	Intrinsic	On/Off	9
7		2004	Specialized	Real-scale edifice	Temperate	Component	Glazing	Thermal comfort	Collect and storage	Adaptive glazing	Passive	Thermal	Intrinsic (interior)	Gradual	7
8		2005	Service Industry	Real-scale edifice	Continental	Façade system	Other	Other	Control	High-performance	Active	Other	Users' control	On/Off	9

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
9		2005	Service Industry	Real-scale edifice	Continental	Façade system	Other	Other	Allow interaction	Dynamic facade	Active	Other	Users' control	On/Off	8
10		2006	Service Industry	Real-scale edifice	Temperate	Component	Energy generation devices	Energy manag./gen.	Collect and storage	Energy generating	Passive	Thermal	Extrinsic	On/Off	8
11		2007	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Control	Selective	Active	Optical	Users' control	Gradual	9
12		2008	Specialized	Concept or protoype	Temperate	Façade system	Energy harvesting device	Energy manag./gen.	Collect and storage	Dynamic facade	Active	Electromagnetic	Intrinsic	Gradual	2

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
13		2009	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Control	Selective	Active	Other	Users' control	Gradual	8
14		2009	Residential	Concept or protoype	Continental	Component	Other	Interaction and users' control	Allow interaction	Control systems	Active	Occupants	Users' control	Gradual	3
15		2010	Service Industry	Real-scale edifice	Continental	Component	Glazing	Thermal comfort	Control	High-performance	Passive	Optical	Intrinsic	Gradual	9
16		2010	Specialized	Concept or protoype	Continental	Façade system	Shading	Visual performance	Control	Dynamic facade	Passive	Optical	Extrinsic	Gradual	4

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
17		2010	Specialized	Concept or protoype	Continental	Component	Energy harvesting device	Energy manag./gen.	Collect and storage	Energy generating	Passive	Electromagnetic	Intrinsic	On/Off	5
18		2010	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Control	Selective	Active	Occupants	Extrinsic	Gradual	9
19		2010	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Control	Selective	Passive	Optical	Intrinsic	Gradual	9
20		2011	Specialized	Concept or protoype	Temperate	Component	Energy generation devices	Thermal comfort	Collect and storage	High-performance	Passive	Other	Extrinsic	Gradual	6

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
21		2011	Service Industry	Real-scale edifice	Temperate	Component	Other	Thermal comfort	Control	High-performance	Passive	Thermal	Extrinsic	Gradual	8
22		2011	Service Industry	Real-scale edifice	Continental	Façade system	Shading	Visual performance	Control	Dynamic facade	Passive	Electromagnetic	Intrinsic	Gradual	8
23		2011	Service Industry	Concept or protoype	Temperate	Façade system	Other	Thermal comfort	Collect and storage	Control systems	Passive	Optical	Users' control	Gradual	7
24		2011	Specialized	Concept or protoype	Dry/Desertic	Element | Material	Other	Visual performance	Control	Dynamic facade	Passive	Thermal	Intrinsic	Gradual	5

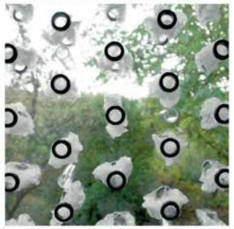
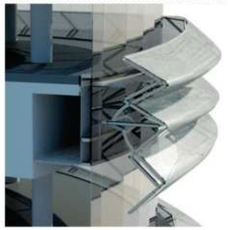
			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
25		2012	Specialized	Real-scale edifice	Tropical	Component	Glazing	Interaction and users' control	Allow interaction	Dynamic facade	Active	Occupants	Users' control	On/Off	9
26		2012	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Control	Selective	Active	Optical	Extrinsic	Gradual	8
27		2012	Residential	Concept or protoype	Temperate	Component	Energy generation devices	Thermal comfort	Collect and storage	High-performance	Passive	Optical	Extrinsic	On/Off	7
28		2012	Residential	Concept or protoype	Temperate	Façade system	Energy harvesting device	Energy manag./gen.	Collect and storage	Energy generating	Passive	Optical	Intrinsic	On/Off	7

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
29		2012	Specialized	Real-scale edifice	Temperate	Component	Shading	Visual performance	Prevent / Reject	Selective	Active	Optical	Intrinsic	Gradual	9
30		2011	Specialized	Real-scale edifice	Temperate	Element | Material	Other	Interaction and users' control	Allow interaction	Dynamic facade	Passive	Other	Intrinsic	Gradual	9
31		2012	Service Industry	Real-scale edifice	Dry/Desertic	Component	Shading	Visual performance	Control	Dynamic facade	Passive	Optical	Intrinsic	Gradual	8
32		2012	Service Industry	Under construction	Dry/Desertic	Component	Shading	Visual performance	Prevent / Reject	Dynamic facade	Passive	Optical	Intrinsic	Gradual	8

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
33		2013	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Prevent / Reject	Selective	Passive	Optical	Intrinsic	On/Off	8
34		2013	Service Industry	Under construction	Continental	Façade system	Shading	Visual performance	Control	Dynamic facade	Passive	Optical	Extrinsic	Gradual	7
35		2013	Residential	Concept or protoype	Temperate	Component	Energy generation devices	Other	Collect and storage	High-performance	Passive	Electromagnetic	Intrinsic	Gradual	7
36		2013	Specialized	Real-scale edifice	Temperate	Component	Shading	IAQ	Prevent / Reject	High-performance	Passive	Optical	Intrinsic	On/Off	8

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
37		2014	Service Industry	Real-scale edifice	Temperate	Façade system	Glazing	Visual performance	Control	Selective	Passive	Optical	Extrinsic	Gradual	9
38		2014	Service Industry	Real-scale edifice	Continental	Component	Glazing	Visual performance	Control	Adaptive glazing	Active	Electromagnetic	Extrinsic	Gradual	9
39		2014	Specialized	Real-scale edifice	Continental	Element | Material	Shading	Visual performance	Control	Dynamic facade	Passive	Other	Intrinsic	Gradual	9
40		2014	Specialized	Real-scale edifice	Temperate	Component	Shading	Visual performance	Control	Selective	Active	Electromagnetic	Extrinsic	Gradual	9

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
41		2014	Residential	Real-scale edifice	Temperate	Component	Other	Interaction and users' control	Allow interaction	Control systems	Active	Occupants	Users' control	Gradual	8
42		2014	Specialized	Concept or protoype	Continental	Component	Shading	Visual performance	Control	Selective	Active	Occupants	Users' control	Gradual	8
43		2015	Residential	Concept or protoype	Continental	Façade system	Other	Other	Control	Adaptive glazing	Active	Occupants	Users' control	Gradual	3
44		2015	Service | Industry	Concept or protoype	Temperate	Component	Glazing	Thermal comfort	Control	Adaptive glazing	Active	Other	Intrinsic	On/Off	3

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
45		2015	Residential	Concept or protoype	Temperate	Façade system	Glazing	Thermal comfort	Prevent / Reject	Selective	Active	Thermal	Users' control	Gradual	3
46		2015	Specialized	Concept or protoype	Temperate	Façade system	Insulation	Thermal comfort	Prevent / Reject	High-performance	Active	Other	Extrinsic	On/Off	7
47		2016	Specialized	Concept or protoype	Temperate	Component	Glazing	Visual performance	Prevent / Reject	Selective	Passive	Optical	Intrinsic	Gradual	8
48		2016	Service Industry	Real-scale edifice	Continental	Façade system	Shading	Visual performance	Control	Dynamic facade	Active	Other	Extrinsic	Gradual	6

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
49		2016	Service Industry	Real-scale edifice	Temperate	Component	Other	Thermal comfort	Prevent / Reject	High-performance	Passive	Other	Intrinsic	On/Off	9
50		2016	Service Industry	Real-scale edifice	Temperate	Façade system	Other	Interaction and users' control	Allow interaction	Control systems	Active	Other	Users' control	On/Off	9
51		2017	Specialized	Real-scale edifice	Continental	Component	Shading	Visual performance	Control	Selective	Passive	Optical	Intrinsic	On/Off	9
52		2017	Specialized	Real-scale edifice	Dry/Desertic	Façade system	Other	Thermal comfort	Control	High-performance	Passive	Other	Intrinsic	On/Off	9

			GENERAL INFORMATION			FIRST LEVEL ANALISYS		SECOND LEVEL ANALISYS							F.E.
ID	IMG	Year	Intended use	Bld. state of development	Climate condition	Application scale	Type	Purposes	Adaptive function	Classification	Operation mode	Trigger	Response imputs	Degree of adaptability	TRL
53		2017	Specialized	Real-scale edifice	Dry/Desertic	Component	Shading	Visual performance	Control	Selective	Passive	Optical	Intrinsic	Gradual	9
54		2017	Specialized	Real-scale edifice	Temperate	Component	Glazing	Visual performance	Control	Selective	Passive	Optical	Intrinsic	On/Off	8
55		2017	Service Industry	Real-scale edifice	Temperate	Component	Glazing	Visual performance	Prevent / Reject	Selective	Passive	Optical	Intrinsic	Gradual	9
56		2017	Service Industry	Real-scale edifice	Temperate	Component	Shading	Visual performance	Prevent / Reject	Selective	Passive	Optical	Intrinsic	On/Off	8

4.4. Lessons learned

Analysis and critical consideration on the case-studies' sample investigated

The case-studies' analysis has allowed producing the development of a **supporting database** (in the form of **comprehensive synthetic tables**, which summarizes the findings from this phase and finds the distribution of the specific parameters identified) of the different technological solutions and applications within the domain of smart technologies for building envelope, as defined in the present dissertation.

Such a catalogue could be considered as a **first achievement** of the present work since it provides a systematic characterization of smart building technologies for future trends in design, mapping strategies adopted in such systems, recognizing common patterns and identifying unexplored concepts to help further development of high-potential, innovative smart building components. Additionally, this recognition of smart building technologies was necessary to acquire knowledge about different features and application possibilities related to each of them; moreover, this allowed to choose which technologies to consider in the further work, depending on their features and their behavior to study cutting edge components based on different operating principles.

Finally, this review has been useful for understanding and identifying what is currently a gap in this broad scenario; according to the case-studies analysis indeed, it is even more evident the **significant role that fenestration plays in building energy efficiency** and internal environmental comfort as well.

So, such analysis revealed that:

- the great majority of the case-studies investigated have been conceived in the last 8 years (**Fig. 01**), with a peak in correspondence of the years 2011 and 2012;
- the 45% of the buildings investigated are non-residential buildings nor specialized buildings but rather their intended use is **service industry** (**Fig. 02**);
- most of them (the 64%) are **real-scale edifices**, already built (only a few of the case-studies identifies have already been under construction – the 4%), even if some concepts or prototypes buildings are existing (32%) (**Fig. 03**);
- a greater part of the case-studies sample is located in **temperate climates** (61%), a 28% of them is located in continental climates, a 9% is sited in dry/desertic climate while only a 2% is located in tropical climates and none of the case-studies investigated is located in polar climates (**Fig. 04**);
- the majority of the case studies investigated pertain to the **application of such advanced technologies to building components** (61%); a 30% concerns whole façades systems while only the 9% is related to single element or materials (**Fig. 05**);
- **the almost totality of technological innovations and solutions adopted in case-studies addresses transparent components**, being mostly related to glazing (20%) or shading (39%) systems; other percentage pointed out are those related to energy generation devices (7%) and energy harvesting devices (5%) as well as significant are systems related to other technologies (25%) (**Fig. 06**). Marginal is the percentage of case-studies oriented towards opening systems (intended as those merely aimed at the movement of such components) and insulation, both at the 2%.
- It follows that **the main purpose addressed is the one related to visual performance**, with a percentage of case-studies that fit within this category of 50%. Other relevant are: thermal comfort (21%), interaction and users' control (11%), energy management/generation (7%)

and IAQ (4%) (**Fig. 07**);

- thus, the main adaptive function (**Fig. 08**) is the one related to the **control** (46%), followed by the prevent/reject function (25%), the collect and storage function (18%) and the ability to allow users' interaction with the building system (11%).

From these considerations, descends the classification given for the case-studies investigated, according to the (main) purposes for which the advanced technologies have been adopted. Such classification shows that:

- most of the case-studies have been classified into the **"selective" category** (32%); the following are the category of "dynamic façades" (27%) and the "high-performance" category (22%) while secondary is the "adaptive glazing" category and the "control system" category (both with the 7%) at the end followed by the "energy-generating" category with the 5% (**Fig. 09**).
- Within the sample investigated, the greater majority of case-studies presents a **passive operation mode** (61%) (**Fig. 10**) and a gradual degree of adaptability (61%) (**Fig. 13**);
- while the **trigger** of their adaptive features is **most of optical nature** (43%) even if occupants' presence (12%), electromagnetic (11%) and thermal (9%) trigger, as well as other kinds (25%) of triggers, are relevant (**Fig. 11**).
- Final considerations about the type of response inputs have been made (**Fig. 12**), showing that the most of the technologies investigated through case-studies' analysis present an **intrinsic** (52%) **response**; only a 25% is activated through extrinsic inputs while the 23% operate after input of human nature.
- At the end, regarding the TRL associated with technologies investigated, it emerges that the "smart" features of case-studies investigated is greatly concerned with "*actual systems proven in the operational environment*", thus means at **TRL 9** (with a percentage of 37%) (**Fig. 14**), proving in this way the research hypothesis for which the "smartness", in the building environment, could be associated even with traditional materials and technologies, already seeped through current building practices, although innovated in their application and mutual behavior.

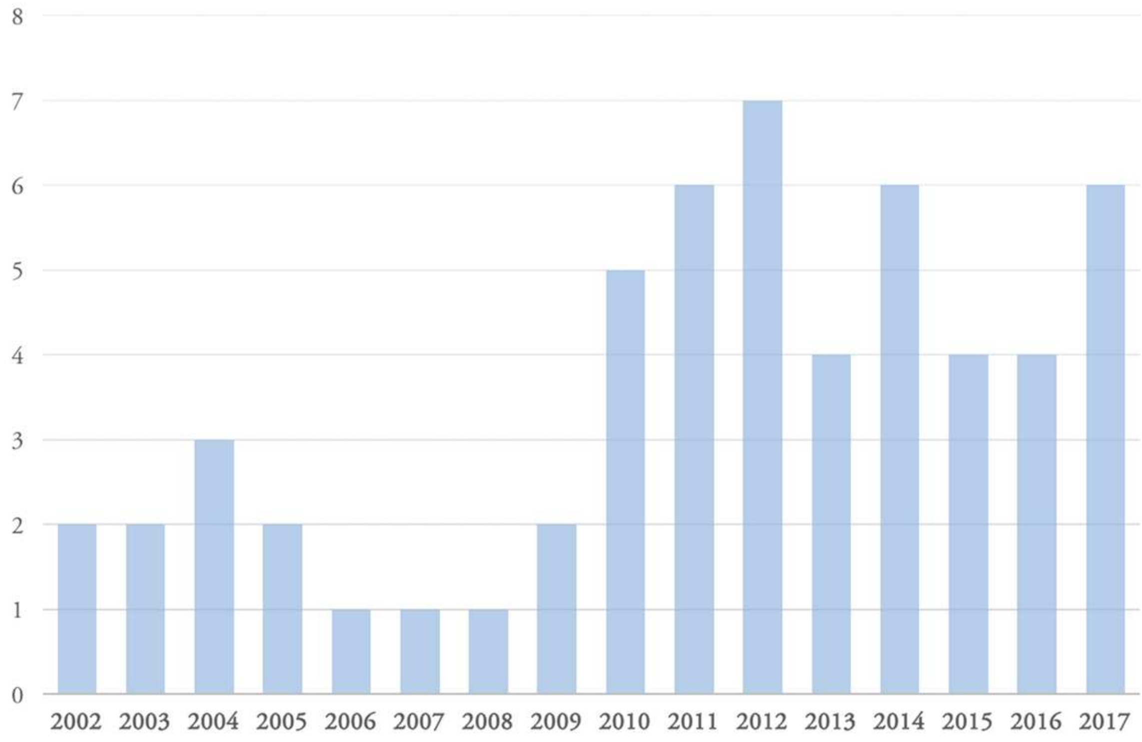


Fig. 01 – Case-studies' distribution over the years. The great majority of them have been concentrated in the last 8 years with a peak in correspondence of the years 2011 and 2012.

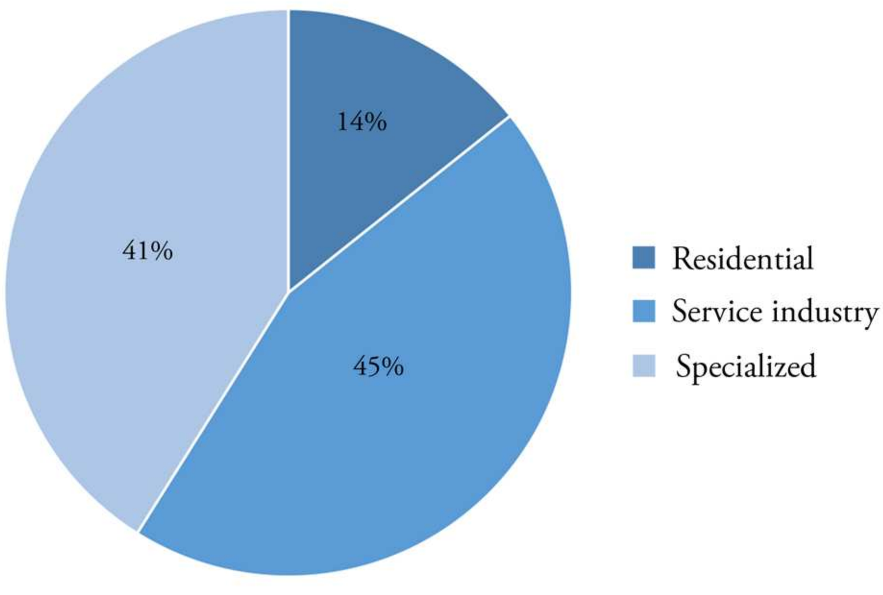


Fig. 02 – Buildings' intended uses. The 45% of the case studies investigated are non-residential buildings nor specialized but rather addressed to service industry uses.

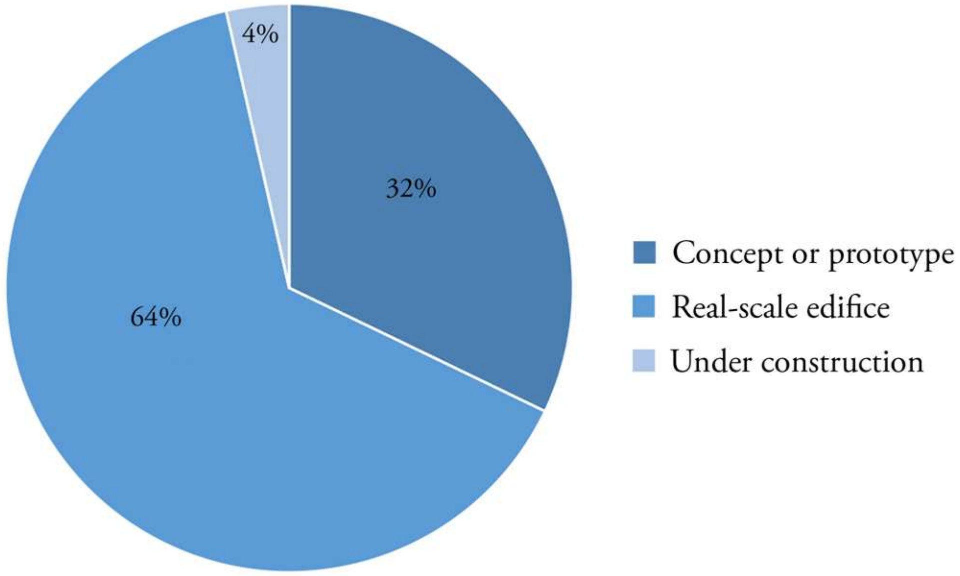


Fig. 03 – Buildings' state of development; most of them are real-scale edifices even if some prototypes are existing. Only a few are already under construction.

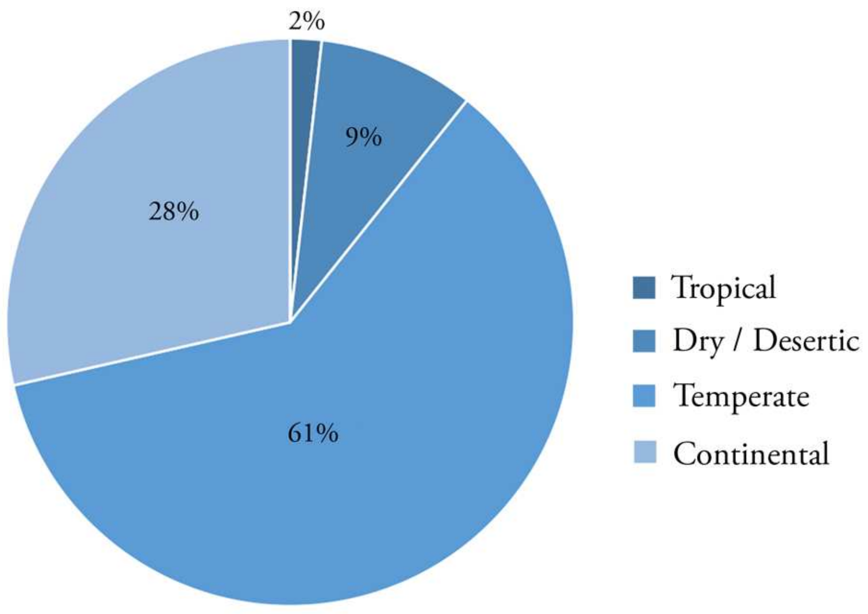


Fig. 04 – Application context of the case-studies sample investigated: a greater part of them is located in temperate climates, other significant percentages are sited in continental climates or dry/desertic climates while only a 2% is located in tropical climates and none of the case-studies investigated is located in polar climates.

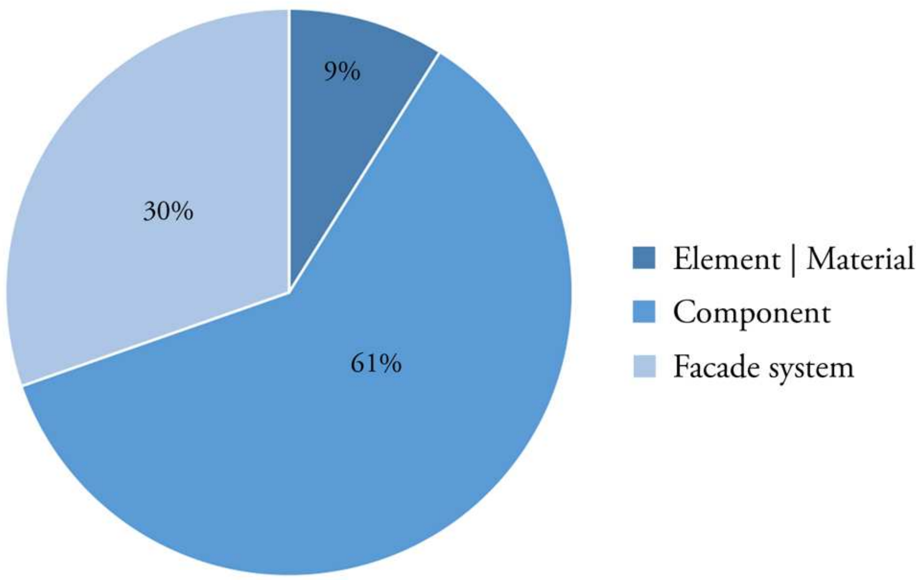


Fig. 05 – Application scale of the advanced technologies: most of them are related to building components, a significant amount concerns whole façades systems while only 9% is related to single element or materials.

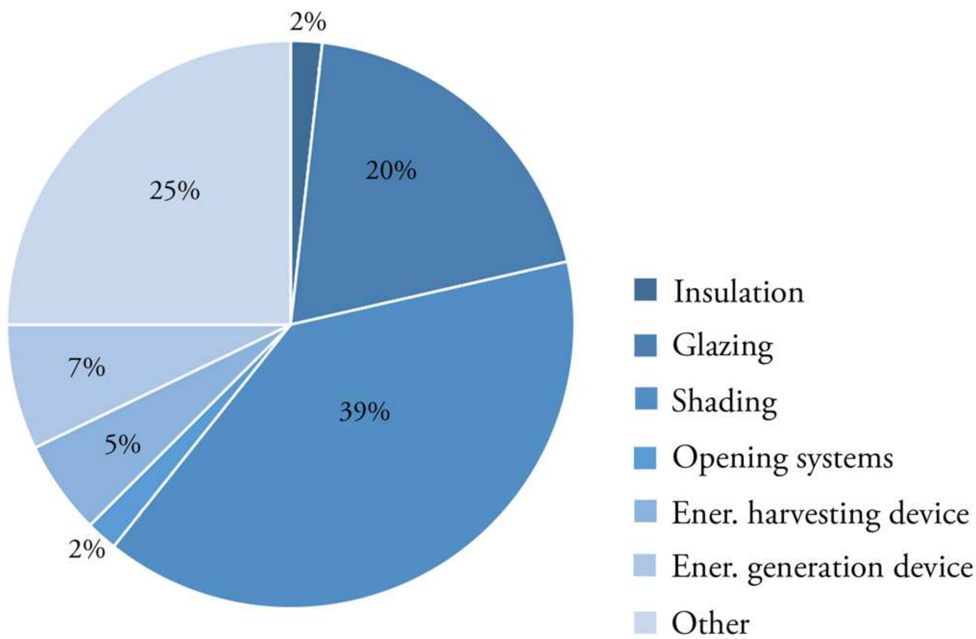


Fig. 06 – The almost totality of technical solutions adopted in case-studies addresses transparent components, being mostly related to glazing or shading systems; other significant percentages are those related to energy generation and energy harvesting devices, as well as significant, are systems related to other technologies. Marginal is the percentage of case studies oriented towards opening systems (intended as those merely aimed at the movement of such components).

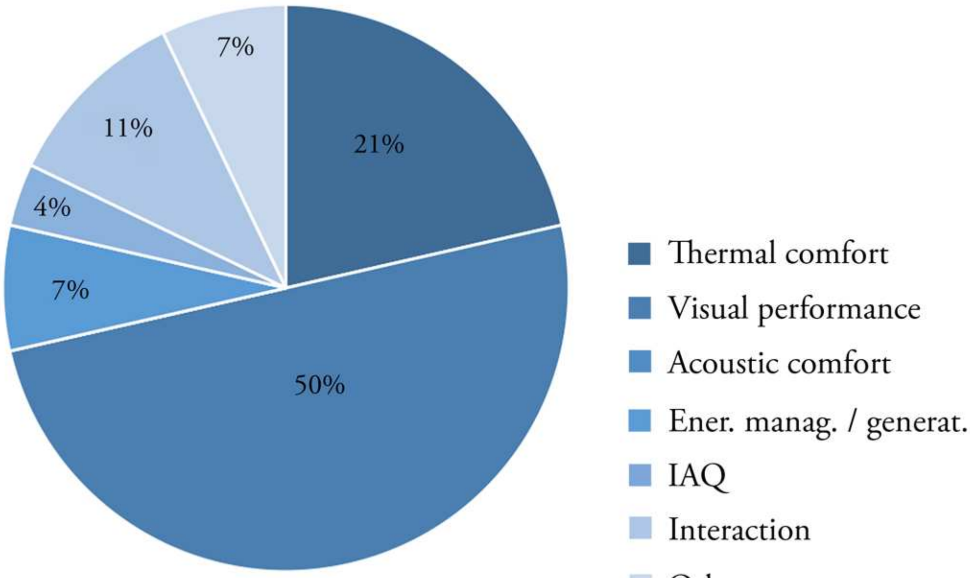


Fig. 07 – Purposes addressed by the advanced technologies applied in the case studies; the main is the one related to visual performance. Other relevant are: thermal comfort, interaction and users' control, energy management/generation and IAQ.

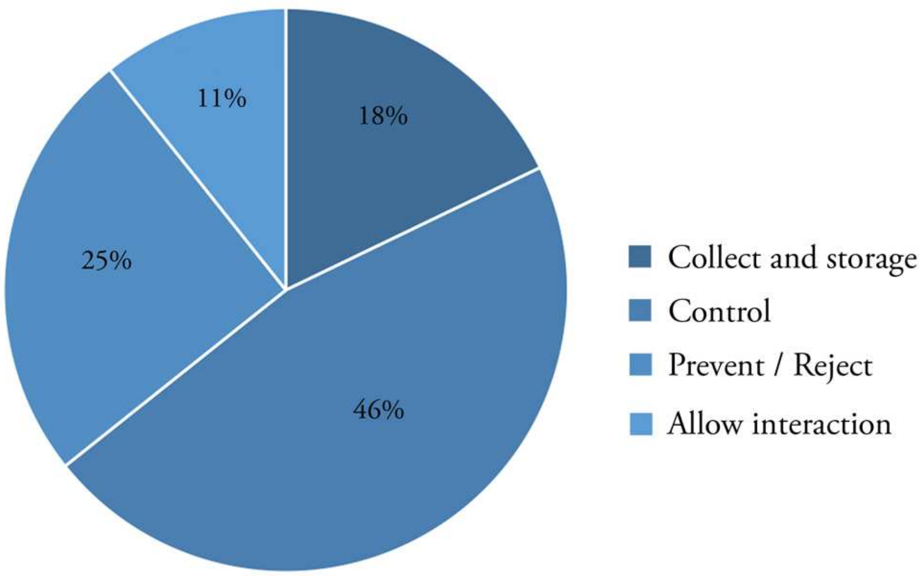


Fig. 08 – Adaptive function of advanced technologies applied to the case studies: the mains are related to the control function, followed by the prevent/reject function, the collect and storage function and the ability to allow users' interaction with the building system.

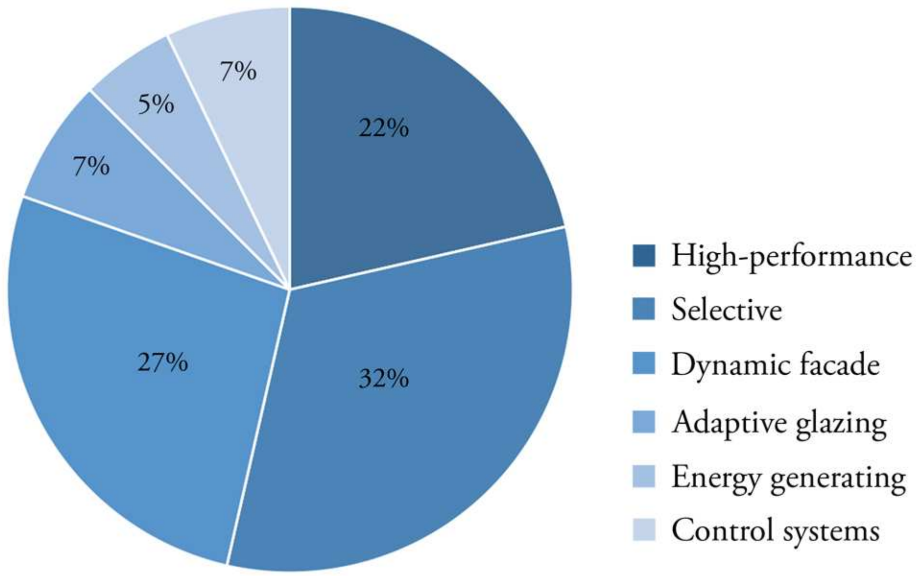


Fig. 09 – Case-studies' classification according to the main purposes for which the advanced technologies have been adopted. Most of them have been classified into the "selective" category while the following – in a descendant order – are: "dynamic façades", "high-performance", "adaptive glazing", "control system" and "energy-generating".

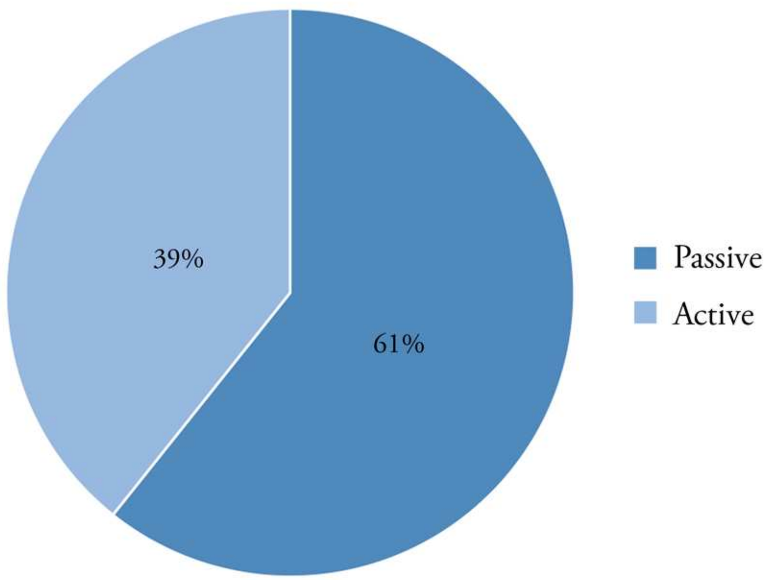


Fig. 10 – Operation mode of the "smart" technologies adopted within the case-studies' sample investigated.

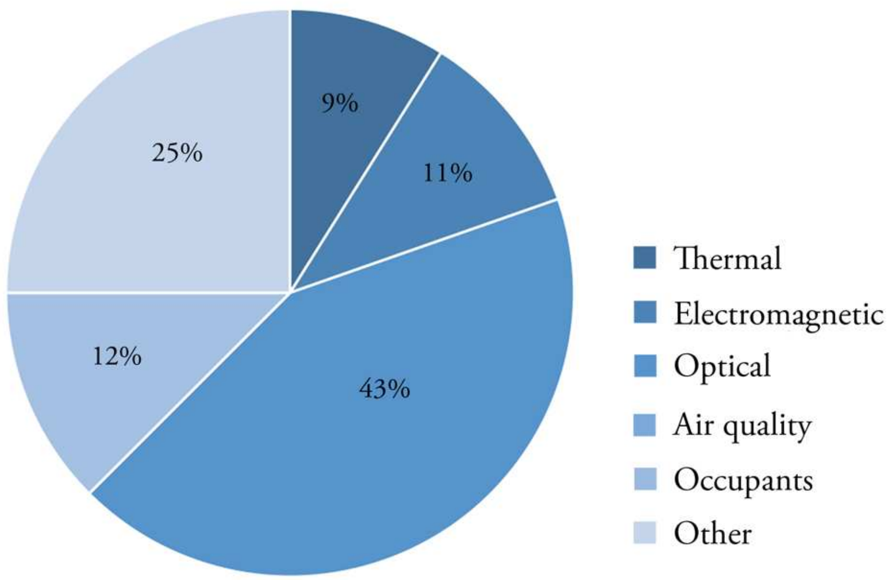


Fig. 11 – Type of trigger of the adaptive feature of each case study. The most frequent is optical, followed by occupant presence, electromagnetic and thermal trigger even if other kinds of triggers are relevant.

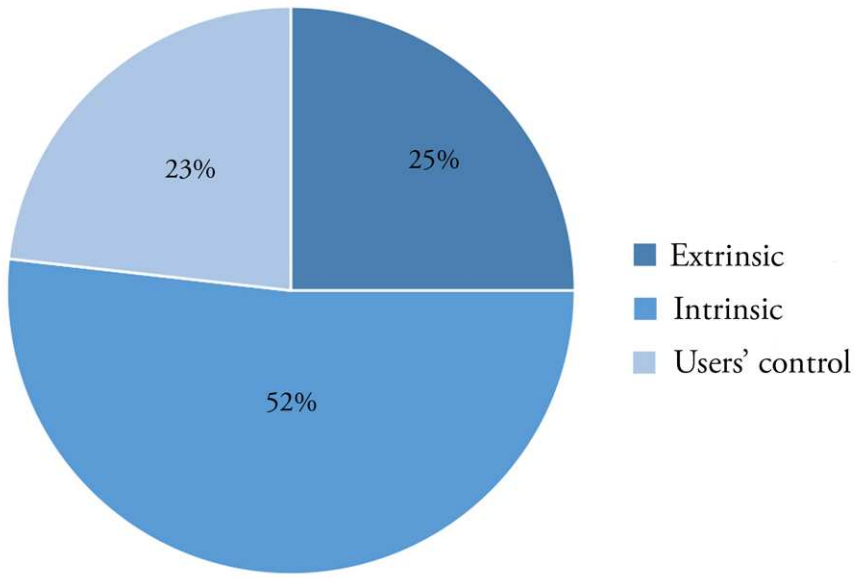


Fig. 12 – Response input. Most of the technologies investigated through case-studies' analysis present an intrinsic response; only 25% is activated through extrinsic inputs while the 23% operate after input of human nature.

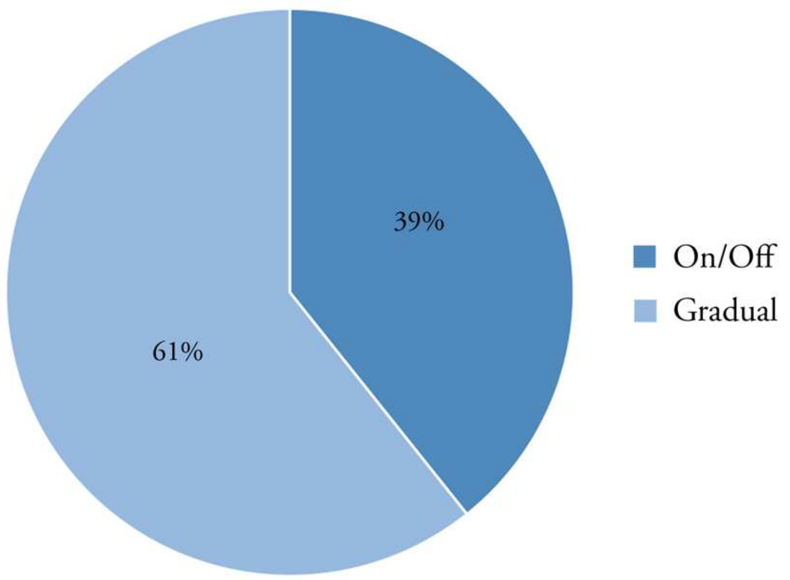


Fig. 13 – Degree of adaptability of the "smart" technologies adopted within the case-studies' sample investigated.

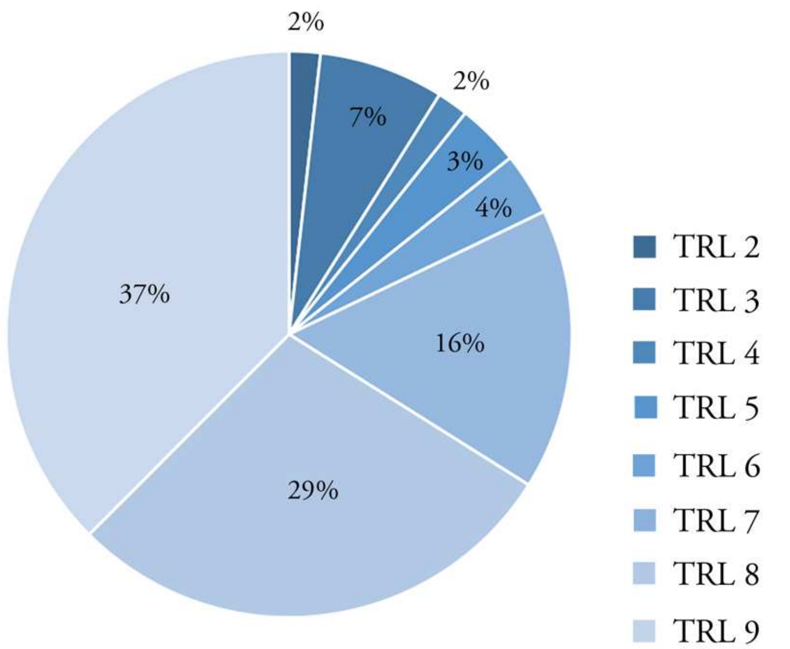


Fig. 14 – TRL associated with technologies investigated; the "smart" features of case-studies investigated is greatly concerned with "actual systems proven in the operational environment", thus means at TRL 9 (with a percentage of 37%).

According to the case-studies' analysis, reasons for adopting smart elements in the building envelope are mostly related with the control of solar radiation and outdoor temperature, as figured out by the fact that most of the technical solutions showed in the previous chapter addresses transparent building components.
Assessing external factors associated with smart building technologies' adoption, on the representative sample, it was found that solar radiation coupled with the need of maintaining internal thermal comfort (through the control of the external temperature) under reference levels are the most frequent determinants due to their direct influence on thermal and visual comfort as well as on the whole energy performance of buildings.
Transparent components indeed, due to the fact that have the abilities to almost completely let the solar radiation to passing through them, allow the trigger of physical phenomena induced by incident solar radiation and, as a discontinuity element of building envelope, must fulfil very strictly requirement, primarily by virtue of the material that composes them, generally the glass, which needs for its own nature of a very implementation in terms of performances.
So, despite the growth of glass' applications over years, due to its specific functional role coupled with its aesthetic quality – really appreciated by architects and designers – technical, performance and maintenance criticalities connected with installation in building sector still remain.

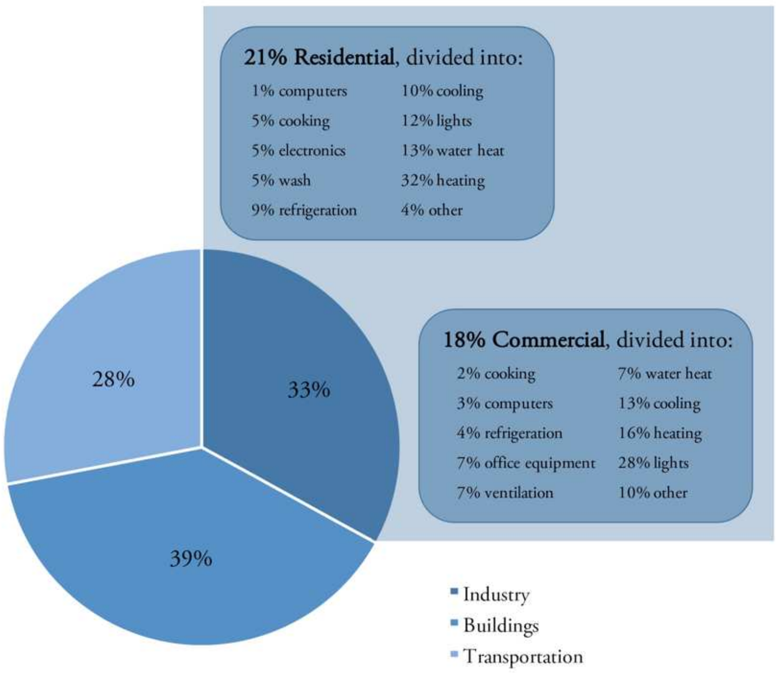


Fig. 01 – Fenestration impacts on Building Energy Consumption.

Fig. 02 (pag. 226) – Office building in Zagreb.

5.1. The role of glazed components

Whilst a key desirable feature in architecture, windows are recognized as a key weak spot within buildings energy efficiency.
Although the increasing development of the industrial sector and the use of advanced technologies, the building sector is still absorbing a huge amount of final consumption of the entire country (approximately the 40% of the entire energy consumption percentage), generating one-third of the global greenhouse gas emissions (being responsible for about the 32% of GHG emissions in Europe).
Despite the fact that Europe is well on track to meet its targets (as confirmed from latest Eurostat data)[1], doing well also with renewables, heat and gain losses through windows still play a significant role in buildings energy efficiency, as responsible for about the 60% of the total energy consumption of a building (Jelle et al., 2012, op. cit.). If compared to insulated walls with the same extension indeed, heat-gain phenomena on fenestrations can have hundred times higher effects (K. M. Al-Obaidi et al., 2013). Experimental tests and measurement campaigns carried out during last years[2] shown that almost half of this phenomena could be attributed to air leakages and heat-transfer-mechanism determined by incident solar radiation.

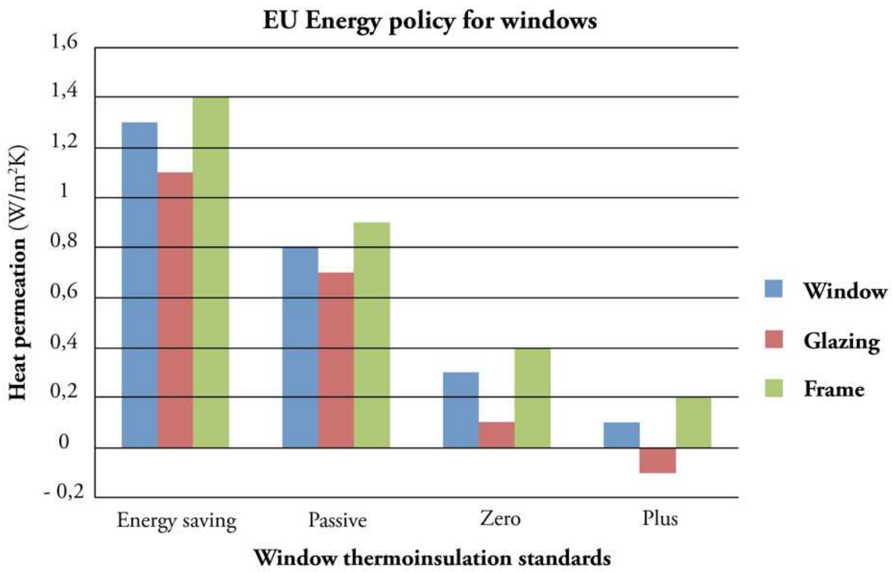


Fig. 03 – Incidence of windows' components on the whole building envelope performance.

Fenestrations are, by their own nature, discontinuity points of the building envelope, as openings in opaque building components surrounded by a wooden, metallic or plastic frame which retains a glazed pane. Glass, moreover, if compared to a heavyweight structure like masonry, is a very light material that suffers daily temperature fluctuations; so, its high-transmission properties and, particularly, its solar radiation transmission feature, have a great influence on lighting, heating and cooling requirements of buildings, significantly affecting the amount of energy transmitted through their envelope.
As a matter of fact, even buildings with a small amount of glazed surface, if not adequately protected, would experience overheating in summer and significant heat-losses in winter, whose resolution is entirely entrusted to artificial systems.

[1] C. Canevari (2017), "Clean Energy for All Europeans - Unlocking Europe's growth potential", in *RAEE, Rapporto Annuale Efficienza Enegetica*, Analisi e Risultati delle policy di efficienza energetica del nostro paese, Agenzia Nazionale Efficienza Energetica, Enea, Roma

[2] E. Cuce (2017), Role of airtightness in energy loss from windows: Experimental results from in-situ tests, *Energy and Buildings*, 139, 449-455, http://dx.doi.org/10.1016/j.enbuild.2017.01.027

In other words, windows are crucial elements to control the energy performance of buildings, especially in order to meet the energy agenda.

Windows' critical issues basically result in:

- **winter heat losses**, due to fenestration lower insulating properties, since they are made of different and heterogeneous materials;
- **overheating during summer**, due to the amount of entering of solar radiation through glass' surface that can considerably increase the indoor temperature.

In addition to these two main challenges, glazing has the task to limit air infiltrations while permitting natural ventilation, allowing daylight entrance to save energy costs for artificial lightning and permitting occupants to interact with the outside worlds.
However, despite the growing users' consciousness about these issues, there is still a lack of an overall strategy able to properly manage the design complexities inherent transparent building components within building systems, especially if equipped with adaptive features, in addition to a not-so-spread awareness about the fact that they differ from other buildings components as they can make a positive energy contribution to the whole performance by letting in free solar energy.
For these reasons, their design optimization challenge is more complex than many other building components and systems.
Developing windows with reduced weight and costs and with optimum thermal features, able to control and harvest energy, it's of paramount importance such they will have a high impact in the window industry and reduce harmful emissions and could be used for both new constructions or for the retrofitting of existing buildings. Therefore, properly intervene in the design of glazing systems represent a key opportunity for building sector in order to control energy requirements, helping to move toward the goals of the European energy agenda.

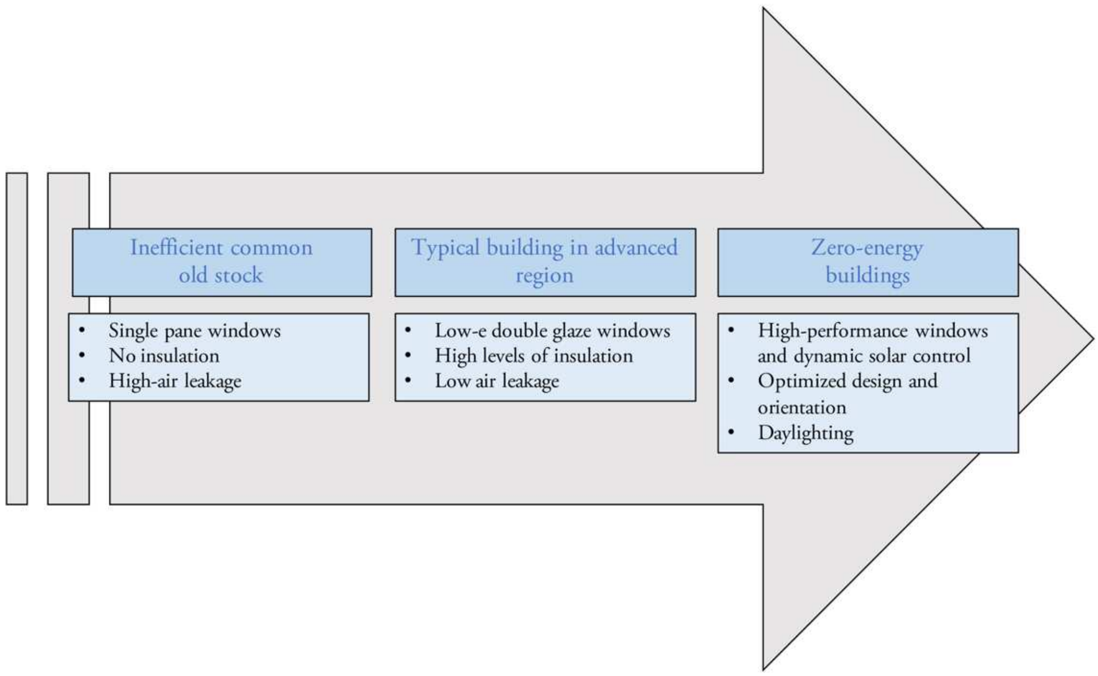


Fig. 04 – Building sector needs to change the way in designing, renovating and building, to shift from an inefficient old building stock towards zero-energy buildings.

5.2. Windows' design features

The most common material employed to realize transparent building components is glass due to its unique characteristic of light-transmission.
For thousands of years, artists and architects have worked with it because of how it forms, feels, and handles light; also craftsmen have used glass for practical applications because of its stability, waterproofing and transparency[3].
Even if first glass building applications appeared quite 2,000 years ago, used to seal off entrances to structures, the use of glass in buildings did not become widespread until a few centuries ago, with the development of the modern trend in architecture, and it was not until the 20th century that glass performance began to evolve significantly for residential housing and commercial buildings.
In the last century – since the development of float glass' process in the 1950s – scientists have made extraordinary advances in the characterization and fabrication of glass, leading to innovative applications in diverse fields such as architecture, transportation, electronics, communications, and medicine.

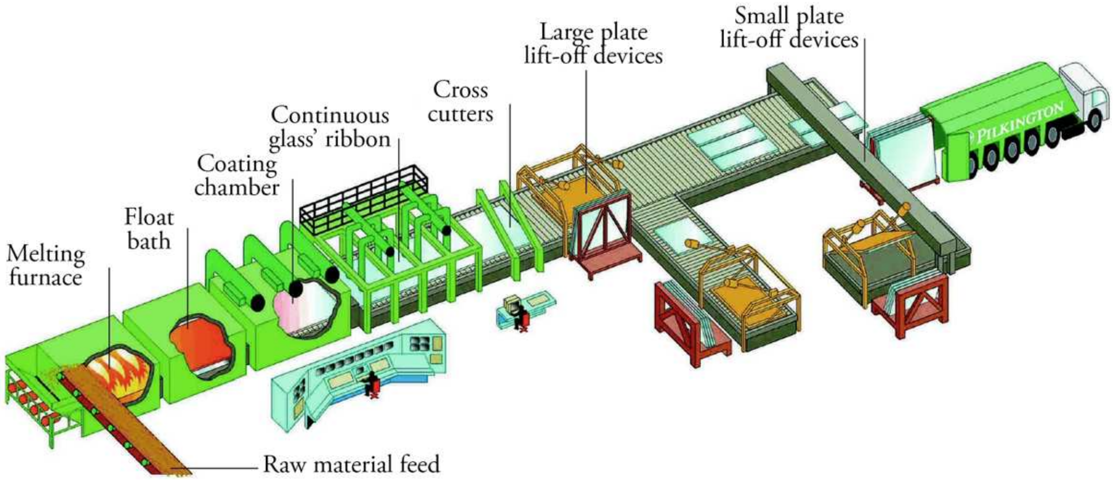


Fig. 05 – Float glass' production plant

5.2.1. Characteristics of glass products

Generally, glazed surfaces suitable for building applications are primarily made of silica (SiO2). However, light-nature, as well as transmission/absorption variations determined by different materials, entail the use of different kind of glasses, with different performance and application characteristics from an optical, mechanical and energetic point of view (Tucci, 2006). Clear common glasses have light-transmission coefficient included between 60% and 80%, for radiations with wavelengths approximately between 400 and 2500 nm, even if intervening on glazing chemical composition, varying its mixture, allow to modify this limit or affecting other performances.
The presence of different chemical components in glass mixture indeed influences glass basic performances such as transparency / light-transmission / selective-absorption capacity.
As stated before, glass amorphous structure is commonly obtained from the fusion of silica with oxides, inorganic compounds that can be identified as grid- or network-former, the so-called vitrifying, able to confer chemical stability to final products. The basic product used is silica

[3] Morse, D.L. and Evenson, J.W. (2016), Welcome to the Glass Age, *International Journal of Applied Glass Science*, 7 [4], pp. 409-412.

(silicon dioxide or silicon sand – SiO_2 for 69% to 74%) or boric oxide[4], generally introduced in the mixture in the form of sand. This compound, through the heat action, gives the glass its texture, transforming it from a crystalline form to a vitreous, amorphous form.
Other compounds are those defined grid- or network-modifiers, and are:

- **melting agents**; which have the purpose of lowering the melting temperature of silica mass from about 1700°C to 1550°C. The more used melting agent is sodium oxide (Na_2O for 10% to 16%), introduced as sodium carbonate to homogenize the melting mixture of the vitreous paste, even if it can lead to the detriment of glass chemical resistance. Soda can be replaced also with potassium oxide (K_2O) or potash, with more energetic melting actions able to make glass more brilliant and colourless, even if facing higher costs. Their use is limited to special glasses' realizations;
- **stabilizers**, that improve material chemical hardness and resistance. The most common stabilizer is calcium oxide (but also aluminium, magnesium and zinc oxide are used), introduced into the mixture as calcium carbonate to limit the solubility of the molten mass, making it less plastic in favour of greater chemical stability and a lower expansion coefficient, thus providing to it better atmospheric agents- and mechanic-resistance. Also magnesia (MgO), sulphur dioxide (SO_3) and iron (Fe_2O_3) can be used as stabilizers;
- **refining agents**, materials that ensure glass' consistence, releasing gases and standardizing quality, thus adjusting it physical and chemical properties avoiding the formation of air bubbles (generally during moulting process). They could be sodium sulphate ($NaSO_3$), sodium nitrate ($NaNO_3$), sodium chloride ($NaCl$), arsenic oxide (As_2O_3), calcium fluoride (CaF_2) or carbon (C). Compounds that give glasses additional performances are also: aluminium oxide (Al2O3), introduced as alumina to extend the workability range as well as chemical and mechanical resistance of material; lead oxide (PbO), to obtain crystal because it confers extreme clarity and high-glare index to glass; zinc oxide (ZnO_3), introduced as trace, to obtain a glass resistance to thermal shocks and chemical corrosion. The introduction of metal compounds dissolved in the mass confers to glass particular selective light-absorption properties;
- **matting agents**, that act on glass' transmission properties;
- **colorants**, able to influence glass' spectral transmission. They can be used also to discolour and optically neutralize the coloration determined by ferrous compounds. The most employed colorants are feldspars (as manganese dioxide – MnO_2). Decolorized glasses have a higher energy absorption coefficient with respect to a glass with a high concentration of metal oxides.

Conventional industrial glazing employed in architecture are generally:

- **Soda-lime glasses**, produced through the floating process and mainly composed for the 71-75% by silica dioxide (SiO_2), for the 12-16% by sodium oxide (Na2O) and for the 10-15% Lime (CaO) plus a small number of other materials (Al2O3, CaO, MgO), employed for adding glass special properties.
- **Quartz glasses**, able to support sudden temperature leaps because of their low expansion coefficient. They are formed almost exclusively of silica and therefore difficult to process. Quartz glazed products are primarily employed for laboratory objects and applications.
- **Borosilicate glasses**, very resistant to chemical corrosion, they have low thermal expansion coefficient and high thermal-resistance that increase the shock-resistance ability. Due to

[4] The use of boric oxide instead of silica determines the lowering of mass melting point coupled with a greater fluidity of the vitreous paste. Thus determine also a higher resistance toward chemical attack and a lower expansion coefficient that makes glass suitable to endure high-temperature and thermal shock.

their quite high costs, they are rather exceptional in construction; the commercial product that represents this type of glasses is Pyrex©.

- **Lead glasses**, very glossy, with high-glare index and low softening temperature. To this category belongs crystals.
- **Silica glasses**, high thermal- and chemical-resistance glasses, characterized by a less silica percentage than quartz glasses. They are employed for special chemical or optical productions because of the difficulty in processing silica.

5.2.2. Glass' general properties

Chemical properties - Glass' chemical resistance generally refers to performances offered by panes' surfaces, different in each vitreous mass due to the friction with the machinery employed for production processes that can determine small superficial fragments leakage[5].
Compounds that mostly affect glass' chemical resistance are alumina (Al_2O_3) and magnesia oxide (MgO).
Glass' chemical properties are also determined by melting time, because lower melting times determine inhomogeneous panes at the sub-microscopic scale, therefore more susceptible to be borrowed by aggressive chemical compounds.
In general, it can be said that glass chemical resistance depends on the attack which its subjected to. Subjected to an acid attack, glass suffers very little damage because the corrosive actions do not explicit on the siloxane glass chain but through an ion exchange between acid ions H+ and the vitreous ions Na+ and Ca+. Pane's surface becomes in this way poor of alkali superficially present and the corrosive attack can continue if other alkaline ions migrate in the surface. Given that this migration process is very slow, the speed of the whole phenomenon has lowered down over time. The only exception is constituted by the hydrofluoric acid (HF) capable of notch the siloxane chain thus to cause serious damage to glass chemical structure.
Subjected to an alkaline attack, the OH ions react directly with the siloxane glass' chain, determining the grid-breakage up to the formation of silicic and soluble acid anions; this reaction causes the complete glass' dissolution. Furthermore, its solubility increases the pH of the etching solution. The amount of glass dissolved by an alkaline agent linearly increases with time.
Caused by a sum of the previous attacks, *water attack* first determines the exchange between the H+ ion and the alkaline ion, and subsequently, due to the increase of the etching solution's pH, the pane undergoes alkaline corrosion. Water attack is dangerous especially in case of surface stagnant water on surfaces that, as a result of an evaporation process, progressively increases its acidity, attacking glass with alkaline reaction.
In general, surface corrosion effects occur with iridescent area whose transparency is characterized by diffusing light effect.
To improve glass chemical resistance, its surface can be made resistance to corrosive agents by varying the percentages of vitreous mixture compounds as with the alumina (in calcium-sodium glasses) or by treating it with gaseous SO2 or, again, with fluorinated compounds able to cause the removal of residual alkali from the surface, making the glass less attackable[6].
Glasses with higher chemical performance are boron-silicate ones, used for producing additive containers for medicines' storage and characterized by chemical neutrality.

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[5] In a pane just laminated, the percentage of sodium present in the surface layers is considerably lower than the one of bulk glass (about 100 Å). In float glass, this difference is even more evident. The two surfaces result both pressed because of alkali- and alkaline-earth oxides loss. On the face in contact with the tin bath there are also missing OH groups, partially replaced through a migration of SnO and Sn^{2+}, transferred from the molten metal which causes an imbalance of pane's internal forces because less compressed than the opposite face.
[6] Surfaces treated in this way are more resistant due to the impossibility to cede additional alkali ions because their superficial layers are devoid of these elements.

Physical properties - Glass is a material with excellent heat-conduction characteristics. Heat-transmission takes place according to three processes that can be superimposed: conduction, convection and radiation.

Conduction is a phenomenon which occurs between solid substances in contact with each other due to a thermal difference. Heat flows from the hot body to the colder body without mass exchanges but only with energy exchanges at the molecular scale, driven by thermal- excitation. The extent of the phenomenon depends on the material's chemical-physical characteristics.
Convection is a phenomenon that occurs between a solid and a fluid (gas) or vice versa by way of a temperature difference that implies also a movement of the fluid itself. If the movement is determined by the density difference (and therefore by a temperature delta), the convection is defined as natural, otherwise, if the movement is induced by external forces, the convection is defined forced.
Radiation does require physical contact between two bodies, thus can also occur in the presence of vacuum. The energy transmitted by irradiance from a body to another is propagated with electromagnetic waves with frequency dependent on the issuing body temperature. The energy transmitted by a body per unit area and in time unit is called emittance and it is proportional to the fourth power of the body's absolute temperature.

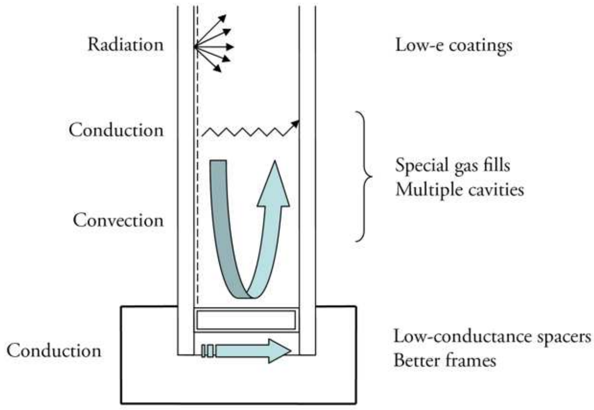

Fig. 06 – Heat transmission phenomena which occur through a window system

Therefore, the emissive power of a material depends on the material that constitutes is, on its temperature as well as on its geometric-superficial conformation; rough surfaces, for instance, have generally a greater emissive power than smooth ones. The lower is the emittance, the higher is the reflectance in the long infrared frequency thus the performance in terms of reduction of thermal-losses of building envelope. Materials that have better characteristics of low emissivity are: gold, silver, copper and iridium, whose oxides if applied as superficially deposit on glazed surfaces are able to significantly reduce their emissivity.

Acoustic properties - The acoustic attenuation offered by glass – even defined Sound Insulation Capacity or Sound Transmission Loss – varies according to the frequency considered. SIC is defined as the difference between the sound pressure level in the room where the emission source is placed and the sound pressure level in the disturbed environment.

Being the glass a homogeneous material, its SIC is a linear function of the product of the mass of the superficial unit multiplied for frequency. Due to its high weigh, glass' SIC its quite fair however there is performance's decay due to the phenomena of resonance, detectable at low frequencies, and of coincidence, that occurs at high frequencies when the sound wavelengths correspond with walls' inflectional wavelengths. Glass' SIC increases when resonance and coincidence phenomena decrease.

In determining this value are also involved the reduction index of any eventual air leaks, the SIC of frames, the nature of gaskets and sealants as well as the overall tightness of the whole window system.

Mechanical properties - Glass is a fragile material with different kind of qualities, as for instance its stresses-resistance, variable due to loads. Inevitably, its stresses-resistance decrease while loads and their application time increase.
Generally, its mechanical performance is reduced mainly due to a stress-corrosive phenomenon linked to environmental humidity that affects glass' silica-chain, resulting in the breakage of bonds Si-O-Si. During the vitrification stage also micro-cracks[7] can occur, responsible for a reduction of glass strength to values comprised among 70 and 350 N/mm^2. A further reduction can be determined by major micro-fractures, generally visible, caused by mechanical shocks during processing phases.
Glass' mechanical resistance depends also from its superficial quality as well as from the size of the stressed area. This feature can be corrected or improved with tempering or stratification processes that involve more consisting layers of the pane, as well as with cleaning processes that treat glass' outer surface with hydrofluoric acid solutions, capable of significantly reinforce it.
In float glasses, the imbalance of mechanical performances between the two panes determines different degree of compression, thus different mechanical resistance between the two surfaces: the less compressed surface will have greater mechanical resistance while the more compressed determines a further lowering of the admissible-breaking-load.
Additional mechanical requirements imposed by Italian regulations are those connected with wind- or snow-stresses-resistance and safety. Another feature is thermal-shock resistance. Even temperature differences in different points of the plate, determined by non-uniform irradiation, can determine different strains, sometimes higher to those admissible.

Properties	Symbol	Unit of measurement	Value
Density (at 18°C)	ρ	[kg/m^3]	2500
Hardness (Knoop)	$HJ_{0,1/20}$	Gpa	6
Young module (Elasticity module)	E	[MPa]	70000
Poisson coefficient	μ	[-]	0,2
Bend resistance	$f_{g,k}$	[MPa]	45
Specific thermal capacity	C	[J/(kgK)]	720
Average linear expansion coefficient (20 – 300 °C)	α	[1/K]	$9x10^{-6}$
Resistance towards the temperature gap		[K]	40
Thermal conductivity	λ	[W/(mK)]	1
Average refraction index towards visible radiation	N	[-]	1,5
Emissivity	ε	[-]	0,837

Tab. 01 – Main glass' mechanical and thermal features.

Thanks to the advancement of the technological progress as well as of the industrial techniques, glass is nowadays available in various forms and compositions, generally distinguished on the basis of the manufacturing process that generated them.

[7] Those micro-cracks (of elliptical form with microscopic axial length) are capable of providing in a fragile body such as the glass' pane the trigger of fractures because tensile stresses that are concentrated thus exceed acceptable ones, bringing the pane towards its breakage.

5.2.3. Window panes

Despite the classification of glass employable in fenestration systems from an energetic point of view, windows' panes can be divided depending on their manufacturing process, distinguish between **basic products** – intended as those subjected only to one manufacturing (such as annealed glass) and **secondary manufactured** products, such as toughened glass, laminated glass[8] and coated glass.
Other glazing products are listed below, according to the manufacturing they are subjected to.

Pressed glass – Products obtained by pressing and hot-moulding the liquefied glass paste into a metal mould. Through this manufacturing process can be obtained glass-bricks, building product able to guarantee structural performance, a distinctive feature of opaque walls, without sacrificing glass' light transmission. Pressed glass products can be formed as a massive slab, hand-woven with multi-prismatic surfaces, hollows and air chamber. With this technology also coloured-paste vitreous tiles for floors and claddings can be obtained, put in place with adhesives or special mortars.
Blown glass – Produced with ancient traditional techniques (mouth-blown) that allow obtaining products with a wide range of shades and different chromatic intensity. Blown glass products are characterized by imperfections due to the craftsmanship of the processing; the few plates produced with this technology are mainly used in art glasses.
Sheet glass – Obtained by the mechanical circulation of the molten mass, this kind of glasses have discontinuous thickness due to undulations of their surfaces, more or less accentuated because of the processing technique that can determine glass' optical deformation. Today, this processing is out of practice and it is replaced by the float technology that produces glass with better physical-chemical properties and identical light transmission factor.
Molten glass – Defined also laminated glasses, molten glasses are produced by the continuous drain of the vitreous mass from a basin-oven by rolling on a thin layer of sand. This technology is used for producing slabs of great thickness. Molten glass products are opal and translucent crystals.
Wire glass – Subfamily of molten glasses, wired glasses - produced by draining - transmit light in a diffused way. They incorporate within the mass of fluid glass a welded steel mesh (with real armour function) which has the task of retaining glassy fragments consequent to a possible breakage of the plate. These kinds of products have high fire performance while their downsides are, on the other side, a low mechanical strength – solvable intervening on glass-metal bond – and the possible presence of gas bubbles inside the slab[9].
Profiled U-glass (channelled) – Commercially called U-GLAS, profiled or channelled glasses are produced as drained glasses: the glass ribbon, after the melting tank, is conducted on moulds which bend upward its edges. The final product has resistant self-supporting U-section which permits its fastening directly on supporting structures without needing any other metal supporting frames, allowing to obtain large glass surfaces. They can also be reinforced with stainless steel wires – placed longitudinally – able to increase the mechanical strength of the plate. The seal between planks is ensured by the use of plastic or silicone structural sealants.
Screen-printed glass – Glass panes decorated with drawings, signs or graphics of various type obtained through photographic reproduction techniques by means of the construction of a screen printing frame; the engraved image is then fixed through a vitrification process induced by high-temperature firing.
Ground glass (Etched glass) – Obtained through a process that confers translucency properties to the glass pane by means of two different techniques: sanding and polishing. In the first case, the glazed surface is machined with a sand jet that makes it opaque and rough; in the second case, the pane is treated with acids that confer it variable degrees of opacity.

[8] Made of two or more panes of glass sealed together with an interposed plastic layer (typically a PVB, that has qualities of transparency, elasticity, toughness and cohesion to the glass panes) that can prevent the fall-out of glass shards after fractures. The presence of the plastic layer as well as the alternation of different components' thicknesses provides also protection from UV rays and gives the system good acoustic feature.

[9] To fix this problem can be employed low carbon steels due to the contents of pearlite and cementite in their structure able avoid the formation of gas bubbles.

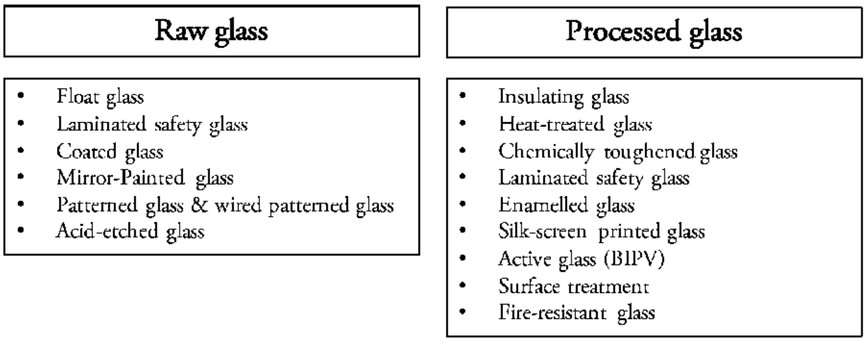

Fig. 07 – Overview of the main raw glass and processed glass products.

Talking in performance terms instead, glasses can be used for fenestration purpose as single pane or in multilayer solution, otherwise called Insulated Glass Units. While single-pane solutions are, by now, obsolete – due to the fact that they are not able to guarantee minimum regulations' standards – IGUs are even more widespread, thanks to their cost-effectiveness[10].

Insulated Glass Units are basically glazed panels made by two or more panes sealed together along the perimeter and filled in the interspace between them with fixed air or low-emissive gas. Different kinds of IGUs are identifiable depending on: *a*) the type of glass panes employed, *b*) the frame materials, *c*) the width of the interspace, *d*) the nature of the gas contained in it, *e*) the desiccant inserted in the spacer and *f*) the type of sealant employed[11].

The thermal performance of such systems is basically determined by the number and type of panes and of the gas inserted between them; interspace as well plays a significant role in reducing heat-exchanges through the glazed surfaces even if there is a maximum dimension beyond which performance improvement is not remarkable. As a matter of fact, over a certain dimension, gas convective motions within the interspace would induce heat-losses; this is the reason why the employed insulating gases are generally heavier than air and with lower tendency to move (e.g. Argon), capable of slowing down heat-flow through the glass pane from inside to outside[12].

Moreover, the duration and consequently, the effectiveness of an IGU, are strictly connected with sealants' quality, often weak point of the system capable of affecting the insulation provided by the air-gap. Two types of sealants are generally used: two-component sealants, which chemically react as a result of their application, and sealants applicable in a stable form.

In general, sealants have to be elastic enough to allow mutual movements between plates and the spacer, subjected to thermal variations or mechanical stresses, as well as their chemical components must be compatible with gases contained in the interspace. To neutralize vapors that may persist inside the interspace during the assembly phase, or which may seep later through sealants – and thus capable to affect the glazing characteristics with condensation phenomena – dehydrated salts are inserted inside the spacer with the task of selectively absorbing the gas contained in the gap. Generally, salts used are silica gels or molecular metals.

[10] A. Roos and B. Karlsson (1994), "Optical and thermal characterization of multiple glazed windows with low U-values", *Sol. Energy,* 52, pp. 315-325. http://dx.doi.org/10.1016/0038-092X(94)90138-4

[11] S. D . Rezaei, S. Shannigrahi and S. Ramakrishna (2017), "A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment", *Solar Energy Materials & Solar Cells,* 159, pp.26-51. http://dx.doi.org/10.1016/j.solmat.2016.08.026

[12] H. Karabay and M. Arici (2012), "Multiple pane window applications in various climatic regions of Turkey", *Energy Build.*, 45, pp. 67-71. http://dx.doi.org/10.1016/j.enbuild.2011.10.020

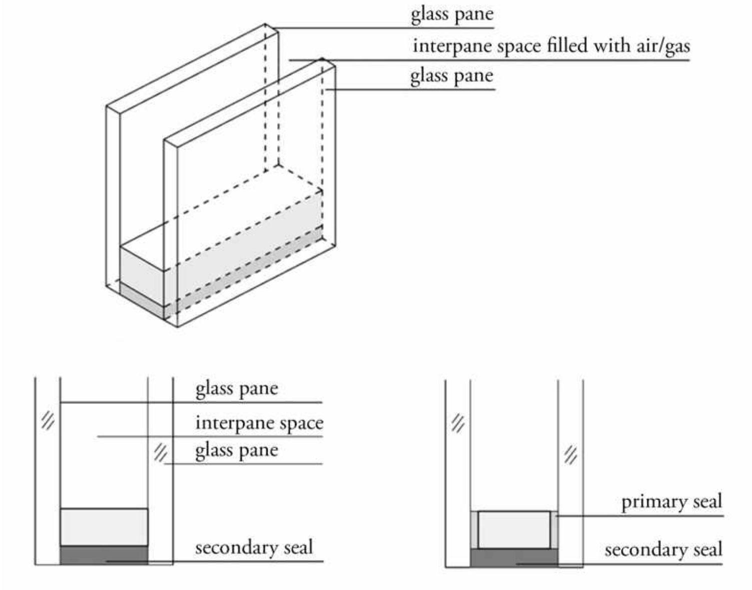

Fig. 08 – Composition and geometry of a double-pane IG unit.

5.2.4. Frames, spacers and other devices

Significantly responsible for the thermal performance of the whole window performances, *frames* constitute up to 30% of the exposed surface of fenestration[13].
Existing frames can be made of various materials, both in single as in coupled solutions. Major of fenestration frames are today made of wood (55%), followed by aluminium (24%), PVC (11) and other material solutions.

Fig. 09 – Different kind of windows' frame: from left to right, a wooden frame, a PVC frame and a metal frame.

Traditional frame's material is wood, due to its good insulation properties[14] coupled with a fair mechanical resistance, even if with some maintenance issues (in the untreated version). A compromise for obtaining a frame with the same aesthetic quality of a wooden one could be a two-component frame, in which wood clads the interior face while aluminium or vinyl face the outside, creating a permanent weather-resistant surface.
However, these mixed solutions need expedient to avoid thermal losses through them, due to the combination of two different materials. These resources, called thermal break solutions, consist of the insertion of plastic material with low thermal conductivity within the frame

[13] Conato F. and Frighi, V. (2016), *Metodi della Progettazione ambientale. Approccio integrato multi-scala per il controllo della qualità ambientale*, 2016, Milano: Franco Angeli Editore.

[14] Frame U-factor stands in the range of 1,70 to 2,80 W/m^2K.

section in order to divide the cold side from the hot side, thus avoiding the thermal transmission between indoor spaces and the outside[15]. Sometimes, thermal breaks present cavities which in turn can be filled with insulation materials, increasing in this way their action.

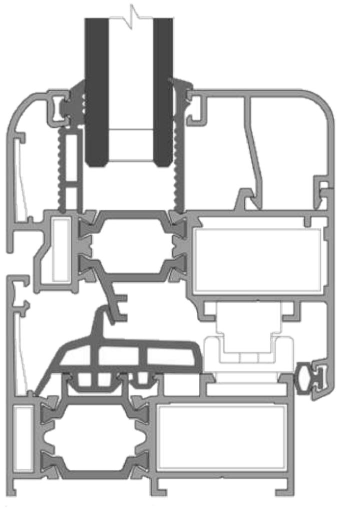

Fig. 10 – Vertical section of an aluminium window's frame with thermal break

The best window frames normally employ materials with a low thermal conductivity as thermal breaks, reaching U-factors between 0,6 and 0,8 W/m^2 K. Further steps foresee the integration of innovative materials (such as aerogel) within frames to improve thermal breaks features. *Aluprof* for instance, a Poland company, inserted aerogel bars inside an aluminium frame achieving in this way a U-value of 0,57 W/m^2 K[16].
Another variation could be obtained with composite frame, in which wood particle and resins are compressed and extruded into shapes for window frame; the advantages of such technology is great stability, coupled with structural and thermal properties even better than those of a conventional wooden frame, with better moisture resistance and more decay resistance; in addition, they can be textured or painted as desired.
Other employed materials are metals, used for their resistance, lightness and durability, especially if anodized, coupled with the ease to extrude them in shapes required for windows' parts.
These solutions are certainly less qualitative in terms of thermal insulation rather than wooden ones unless they are provided of the thermal break. Generally, aluminium frames are utilized in large elements due to their good stability, cost-effectiveness and low maintenance needs. The different surficial treatments they can have is to compensate for the irregular oxidation of the natural material.
Steel frames, on the other hand, are commonly used in industrial applications even if they present few installation problems due to their extremely high weight.
Other common solutions are plastic frames, made of polyvinyl chloride (PVC), a light, a convenient and economical plastic material with good insulating value. PVC frames have a hollow section (with single or multi-chamber) with various shapes that help in reduce convection exchanges; they can include or not a metal stiffener to strengthen their mechanical resistance. Negative issues of such technologies, on the other hand, can be their dimensional stability and the durability of their whiteness over time.
Regarding *spacers*, to the author's knowledge, there are basically two kinds of existing spacers: traditional solutions, made of wood, aluminium and steel or, on the other hand, solutions with

[15] Current technology with standard thermal breaks has decreased aluminum frame U-factors from roughly 11,35 to about 5,6 W/m^{2}K.

[16] Casini, M. (2016), *Smart Buildings. Advanced Materials and nanotechnology to Improve Energy-Efficiency and Environmental Performance*, Woodhead Publishing.

improved thermal performances.
A spacer is basically a device employed to join the glass panes along the perimeter, whose main function is to determine the width of the interspace between the two glass sheets, avoiding the formation of condensation by means of the presence, within it, of a desiccant agent (generally dehydrated salts).
In addition, the spacer system must serve a number of function, included to accommodate stress induced by thermal expansion and pressure differences, to provide a moisture barrier that prevents the passage of water or water vapor that would fog the unit as well as to provide a gas-tight seal that prevents the loss of any special low-conductance gas in the air space.
Standard spacer solution has a hollow section and it is generally made by metal, typically aluminium, even if stainless steel spacers exist and have lower thermal conductivity and, sometimes, different cross-sectional shape.
Another approach is to replace metal with better insulating materials, such as foam or thermoplastic resins. Foam spacers (pre-desiccated and made of structural foam) are generally equipped with improved thermal properties, compared with aluminium ones, for this reasons are defined Warm Edge spacers[17]. The more significant benefit resulting from their application is the increasing of interior surface temperature (at window's bottom edge) which is most subject to condensation.

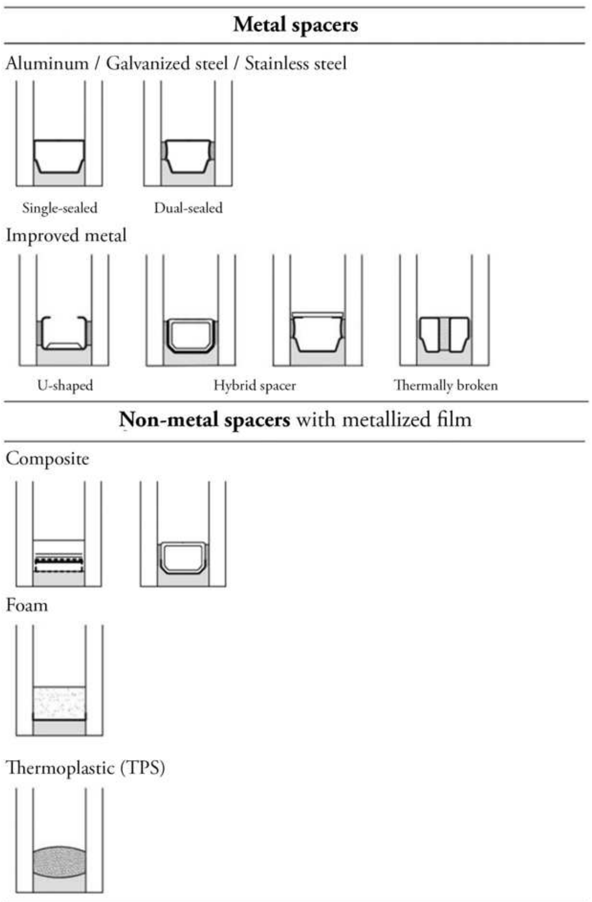

Fig. 11 – Categorization and representation of spacer systems.

Finally, many other products and components useful for assuring correct laying operation and installing of window systems are available on the market in multiple ways and with several features according to different application contexts.

[17] A.H. Elmahdy (2003), "Effects of improved spacer bar design on window performance", *Construction Technology Update*, N. 58, National Research Council of Canada.

Nevertheless, the general common devices, that can be recognized in almost all current installations, are:

- the **counter-frame**, employed to fasten through its application the window frame to the wall square;
- the **windows' ledge,** used where necessary, to appropriately finish the bottom edge of the interface and to avoid water penetration that can compromise installation;
- all the devices employed to ensure occupants' privacy such as blinds, roller shutter, and solar control devices.

To ensure a correct "*posa in opera*" (installation), have recently been developed components that try to integrate with a single product multiple functionalities, to avoid criticalities that the interface among heterogeneous component could imply.

Generally, the element which gathers the whole abovementioned issues is the counter-frame, as connection element among the window and the wall. Counter-frames spread in current building practice are of different typologies, due to the fact that they have to adapt to different needs and shapes, as well as to the various types of windows adopted. The most traditional solution is the one that employs counter-frames entirely made of wood simply joint together with nails; they are generally fastened to the wall through metal brackets, fixed with dowels, even if different kinds of fastening can be adopted according to the type of wall support. Other common counter-frames typologies employ metal, PVC or composite materials even if, recently, to overcome potential critical issues related to the adoption of such basic solutions, new improved versions of them have been developed. Generally defined as mono-block, these prefabricated systems – already thermo-insulated – allow resolving the whole interface, simplifying the installation phase of a window thanks to the several advantages they offer, such as simplified design phases, enhanced reliability during installation, compatibility with other devices, effective insulation and elimination of geometrical thermal bridges due to the continuity of the insulation layer on the external façade of the wall.

Fig. 12 – Thermo-insulating mono-block for windows.

Generally, they present a jamb shape to embrace gaskets and wires to avoid crevices. In addition, they help to align the stile to the block, contributing in a significant way to the regulation of the wall-square.
Clearly, the main advantage of such system is their ability to integrate into a single component different functions such as shading systems, screens and other devices, resolving at the same time the dimensional issue caused by the presence of two distinct elements while ensuring a valuable thermal and acoustic insulation level.
With the same principles, **windows' ledges** and **window' stiles** are existing, generally made of insulating expanded polystyrene (High-density EPS) to avoid thermal bridges in correspondence of such interface, allowing a durable and resistant connection coupled with excellent insulation properties and simple and fast installation.

Fig. 13 – Examples of commercial windows' ledges and windows' stiles in EPS.

As well explained in the Appendix, to obtain a window proper installation, sealants, gaskets, fastenings and accessory products are essential.
As a general rule, components and window's accessory products must be chosen according to the field of application as well as to their intended use, the environmental stresses to which they will be exposed and the type of users that will manage them and their selection must be consistent with the design of the building envelope system in its whole.

5.3. Glass' energy performance features

5.3.1. Introduction to light and color

The first and main feature of glass is **light-transmission**, allowed by glass' transparency and determined by the interactions among light photons and the atomic glass' structure, able to modify it between reflection or absorption phenomena.
In general, glazed support transmits most of the incident solar radiation depending on the substances that compose it and/or the surface treatments which its subject.
The sun, the main power source of radiant energy, generates light and heat in the form of electromagnetic waves, characterized from a wavelength (λ) and a wave amplitude (Δ).
Light, coupled with thermal radiations, represents more than 90% of the energy transmitted by the entire solar spectrum, producing, in turn, a set of radiation of wavelength between 0,3 and 3 μ. Within this amount, only a narrow band of solar rays reach the earth surface that is the quantity among 380 nm – ultraviolet – and 780 nm – infrared –, visible to the naked eye, that does not perceive radiations with lower wavelength.

Type of radiation	Wavelength (nm)	Proportion of energy
UV	280 to 380	approx. 5%
Visible	380 to 780	approx. 50%
IR	780 to 2500	approx. 45%

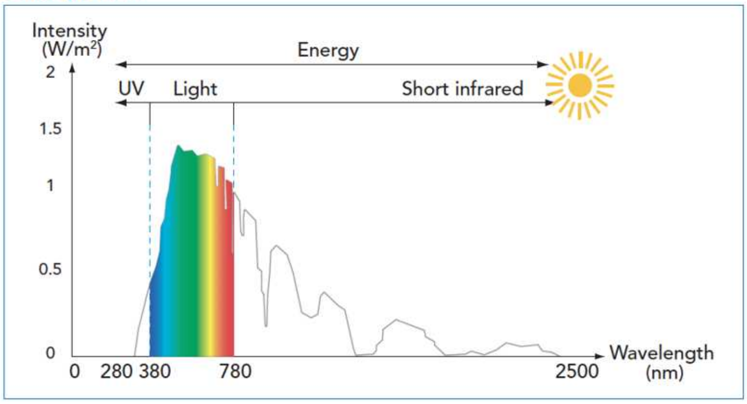

Fig. 14 – Solar spectrum and its composition.

Within the whole solar spectrum, three sections are those that affect internal building environments, being transmitted by the glass, which is Ultra Violet (UV), Visible Light (VL) and Infrared Energy (IE), that lies between the visible-section and the microwave-section of the electromagnetic spectrum. UV light is in turn, separable into three categories; two of them are rejected by the earth's atmosphere and float glass as well.
UV-A is the only amount of energy able to pass through it, primarily responsible for fading and deterioration of interiors' furniture, even if it can be blocked through coatings or films able to reflect or absorb this spectrum.
IE represents the radiant heat energy emitted by the sun added to an internal environment; to act on this transmission means reducing the heat inside rooms, thus prevent possible over-heating during the summer season. The more IR a glass pane is able to prevent, the more energy and cost can be saved.
Finally, VL is the amount of light visible to the human eye and consists of natural daylight; it can generate problems connected to unwanted glare and eye strain. Generally, windows can reduce VL by acting on tints.

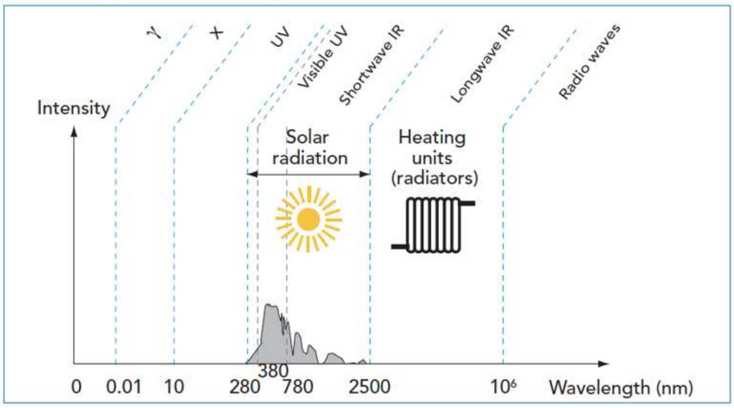

Fig. 15 – Different types of electromagnetic waves that compose the solar spectrum.

With respect of the visible wavelengths, glass is almost completely transparent while in respect of radiations with wavelength superior to 3 μ (infrared) it is opaque; this is the cause of the so-called **greenhouse effect** due to which, bodies located in a space protected by glass surfaces, increase their temperature as a result of direct irradiation, re-emitting energy converted into sensible heat as infrared radiations that remain confined within the space.

In general, incident infrared solar radiation on glass' surface can be **reflected**, **transmitted** or **absorbed**.

In normal incidence conditions, the reflected energy is the quantity of solar radiation reflected back by the glass into the atmosphere; the transmitted energy is the amount of solar radiation directly transmitted through glass' surface while the absorbed amount expresses the quantity of solar radiation absorbed by glass, responsible for its temperature's increase. Further, the pane will redraw the energy stored, partially inward and partially outward depending on boundary conditions.

The relations between the above-mentioned energy quantities, are expressed through the **reflection coefficient** (r or ρ), the **transmission coefficient** (t or τ) and the **absorption coefficient** (α), whose sum determines the total amount of the incident solar energy.

Reflection coefficient expresses the ratio between the reflected energy flow and the incident energy flow; in the same way, absorption and transmission coefficients express the relationship between the absorbed and transmitted flow and the incident one. The sum of these three factors is equal to one.

Total transmission instead, represents the total amount of solar radiation that, in normal incidence conditions, is transmitted through the glass; it is composed of the direct transmission (short-wave component) and of the component dissipated inward for radiation and convection (long-wave component).

The ability of a surface to absorb or emit electromagnetic radiation is reflected by the **emissivity value**.

By its own nature, glass has a high emissivity. Particular coatings are existing, able to act on this feature, reflecting heat back inside buildings and thus reducing heat losses through windows. With a low-E coating on its surface, glass does not absorb energetic radiation by means of its reflection inside the room, reducing heat transfer through the glass and increasing in this way the U-value of the system.

Heat-transmission through Transparent Building Components		
Heat-transfer	from the inside surfaces towards glass surface	Transmission mode that occurs whenever the inner glass' surface has a lower temperature than the internal operating temperature. Heat is transferred: • by radiation between the internal walls' surfaces and the glass' surface; • by conduction and convection of air in contact with inner glass' surface.
	through glass	Transmission that occurs when the single glass pane is not able to offer adequate resistance to heat-transfer. By the addition of an interspace – filled with air – it is possible to reduce such heat-exchange due to the air low-conductivity compared to glass' one. The resistance can also be increased by the increasing of the interspace up to a limit beyond which occur convective motions able to make self-defeating thickness increase. The use of low-e coatings allows to reduce radiative exchanges though glass; interposing them in fact it is possible to reduce such exchange of about three quarters of its entity.
	from the outer glass' surface to the external environment	Transmission process that occurs by radiation, conduction and convection. It depends on the external weather conditions, on wind-exposure and on the amount of rain precipitation to which it is subjected.

Fig. 16 – Heat transmission modes through transparent building components.

5.3.2. Reference parameters for windows' performance evaluation

As we so so far, the transparency feature of glass is function of the interaction of light photons with the material's atomic structure. This property is the one that allows visible light-transmission as a consequence of glass direct irradiations. Besides, radiant energy emitted by the sun as electromagnetic waves comprises also heat-transmission, in the form of infrared energy.

Generally, glass transmits most of the incident solar radiation depending on its composition and on the surface treatments which is subjected. In normal incidence conditions, the **reflected energy** is the quantity of solar radiation reflected back by the glass into the atmosphere; the **transmitted energy** is the amount of solar radiation directly transmitted through a glass surface, while the **absorbed energy** is the quantity of solar radiation absorbed by glass, responsible for pane's temperature increase. This magnitude of energy will further be redrawn by the pane, partially inward and partially outward, depending on boundary conditions.

The relations between these energy quantities are expressed through their relative coefficients: reflection coefficient (r or ρ), transmission coefficient (t or τ) and absorption coefficient (α), whose sum determines the total amount of incident solar energy. Reflection coefficient expresses the ratio between the reflected energy flow and the incident energy flow and, in the same way, absorption and transmission coefficients express the relationship between the absorbed and transmitted flows and the incident one. The sum of these three factors is equal to one.

Total transmission represents the total amount of solar radiation transmitted through the glass; it is composed by the direct transmission component and by the component dissipated inward for radiation and convection. While absorption or reflection abilities depend on glass' features, transmission though transparent building components is highly influenced by boundary conditions and occurs by means of conduction, convection and radiation phenomena.

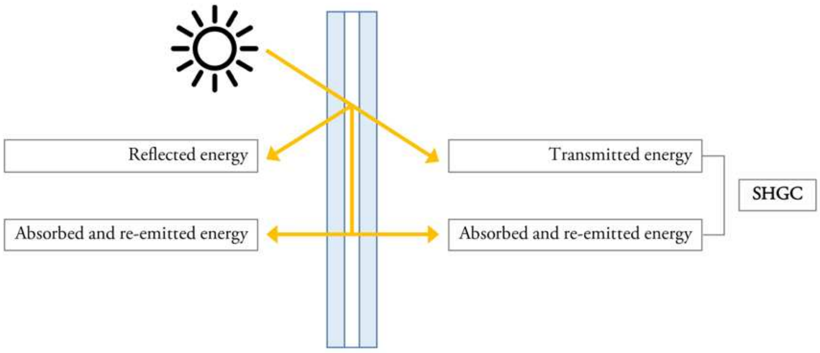

Fig. 17 – Light transmitted, reflected and absorbed through a common glass' pane.

Therefore, the definition and description of the energy performance of glazed components is quite complex due to the fact that they can interact with incident solar radiation. For these reasons, transparent building components must be endowed with precise requirements and, accordingly with Cuce E. et al.[18], have to be described in terms of both thermal and optical parameters.
Basically, the parameters through which a glazed component is evaluated, in performance terms, attained to thermal control – expressed through the thermal insulation capacity of the system – and to the lighting and solar control, expressed through glass' ability in contrasting lighting and heating flux, thus controlling the amount of solar energy entering in rooms.
So, the relative reference parameters commonly used in windows rating methods that influence the total energy consumption, and the indoor environmental comfort as well, are:

- **Thermal transmittance**, or Heat Transfer Coefficient (also called U-factor), that is the rate at which a window conducts non-solar heat flow. The lower the U-factor, the more energy-efficient the window is. Currently, over 40% of fenestration systems in EU have thermal transmittance higher than 5,5, $W/m^2 K$[19], thus resulting in important heat losses through glazing.

CLIMATIC ZONE	FENESTRATION THERMAL TRANSMITTANCE U (W/m^2K) (from the 1st of July 2015)	FENESTRATION THERMAL TRANSMITTANCE U (W/m^2K) (from the 1st of January 2021)
A e B	3,2	3
C	2,4	2,0
D	2,1	1,8
E	1,9	1,4
F	1,7	1,0

Tab. 02 – Minimum U-Value for fenestration in case of energy refurbishment as stated in Appendix B, Tab. 4 of the Decrees 26th of June 2015 "Buildings minimum requirements".

- **Solar Heat Gain Coefficient** (SHGC), or g-value. It expresses the fraction of incident solar radiation admitted through a fenestration product, either directly transmitted or absorbed and subsequently released as heat inside an indoor environment. The lower the SHGC, the less solar-heat the glazed component transmits and the greater is its shading ability. Fenestration products with high SHGC are more effective in collecting solar heat during winter while windows with low SHGC are more effective in reducing cooling loads during summer by blocking heat gain from the sun.

[18] Cuce, E. and Riffat, S. B. (2015), A state-of-the-art review on innovative glazing technologies, *Renewable and Sustainable Energy Reviews* 41, pp. 695–714. http://dx.doi.org/10.1016/j.rser.2014.08.084
[19] TNO Built Environment and Geosciences, "Glazing type distribution in the EU building stock", TNO Report TNO-60-DTM-201-0038. The Hague (NL):TNO; 2011.

CLIMATIC ZONE	D.P.R. 59/2009	Decree 26 of June 2015
all zones	g (SHGC) = 0,50	g_{gl+sh}= 0,35

Tab. 03 – Maximum g-value allowed for building under energy refurbishment.

- **Visible Light Transmittance**, or light-transmission coefficient (τl), is the fraction of the visible sunlight spectrum perceived by the human eye and transmitted through the glazing. It is expressed by a number comprised between 0 and 1: a high VLT value means more visible light transmitted.

Another important parameter to evaluate the energy performance of glazed systems is the **Light to Solar Gain** ratio, that measures the spectral selectivity of a glass system as an expression of the efficiency of different glass types in transmitting daylight while blocking heat gains. It is expressed by the ratio of the VLT to the SHGC; the higher the number, the more light is transmitted without adding excessive amounts of heat. A higher LSG ratio indeed means sunlight entering the room is more efficient for daylighting, especially in summer where more light is desired with less solar gain. So, the higher the LSG number, the brighter the room is without adding an excessive amount of heat.

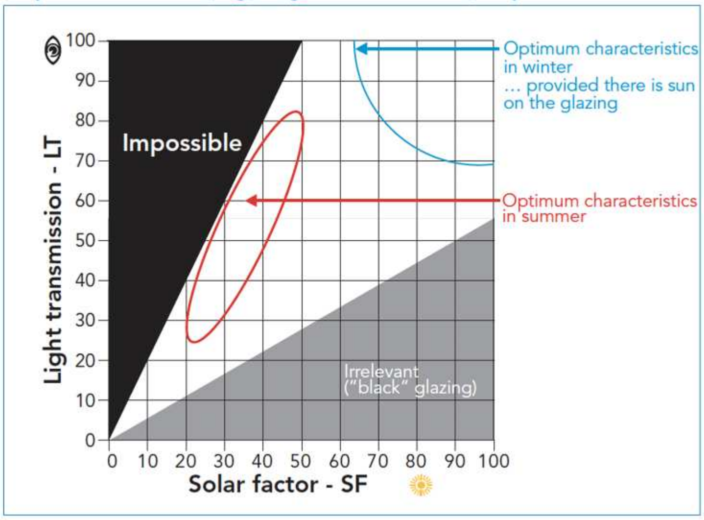

Fig. 18 – Relationship among SHGC and LT coefficient.

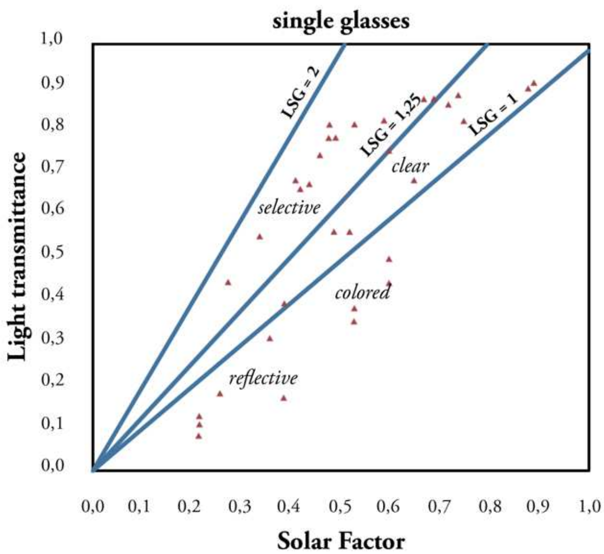

Fig. 19 – LSG value for different glazed technologies

DEVELOPMENT AND IMPLEMENTATION
Results and sources

The technological progress' advancement that led to the enhancement of glass' production techniques, coupled with the development of applied researches as well as of innovative material, has allowed the realization of new products with extremely high performance – if compared with the basic glass product – able to overcome the simplification of traditional elements, thus leading, in some cases, to the development of buildings with brave new shapes.
However, even if buildings with a great amount of glazed surface are often been considered "green" or "sustainable", these constructions are actually very energivorous, encountering severe indoor climate problems and large energy bills.
So, it is undeniable the fact that glazing still constitutes a very clear design problem, which requires the balance of thermal comfort, energy efficiency, light quality, view, daylight and relationships with the outdoor environment.

6.1. Smart Windows: types and features

To face the abovementioned well-known challenges, glazed systems with different abilities have been developed, transforming glass, a material that once performed only the function to allow the entrance of light, in a dynamic filter, able to play a more active role in regulating internal buildings' conditions.
These special glasses have been made possible thanks to the evolution of different production techniques that permitted to effectively act on properties like solar radiation control, thermal insulation, passive solar-heat-gain, glare control, privacy, maximization of natural lighting and other parameters responsible for internal comfort and energy costs and consumption.

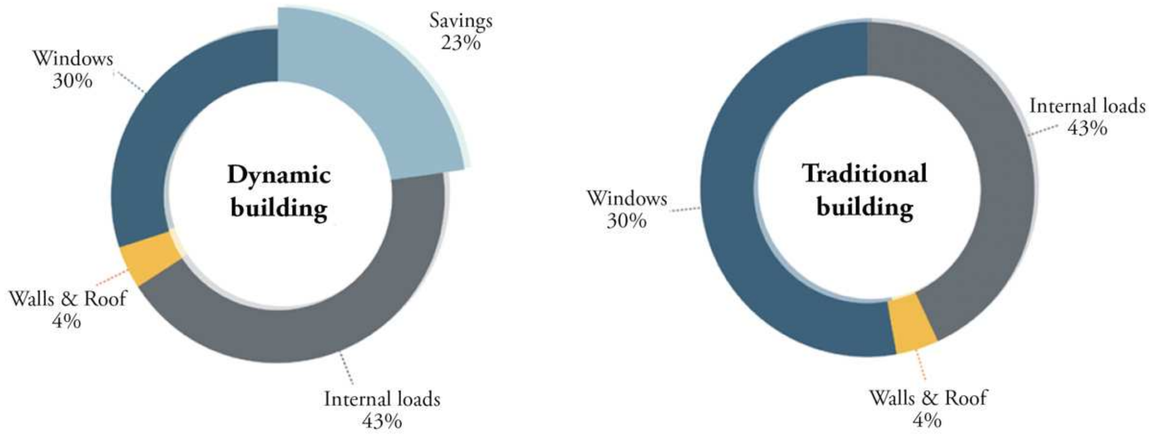

Fig. 01 – Peak Load Comparison between a traditional building with Low-E glazing installed, and a building in which fenestrations are dynamic glasses: in dynamic building cooling peak loads are reduced by 23%.

Several types of experimental, innovative glasses, that cover a wide range of functions and application cases, are today on-the-market available or, at least, under development, having different features under many points of view.
This group includes the so-called "dynamic glazing" [1], fenestration products able to change

[1] A definition of dynamic glazing products comes from the *Energy Star product specification for Residential Windows, Doors and Skylights. Eligibility Criteria*, Version 6.0, that recognize as dynamic «any fenestration

their performance properties[2] by modifying their characteristics of transparency, gloss, coloration and solar radiation screen while keeping unchanged glass structural properties.
Dynamic glasses, otherwise defined "Smart Windows"[3], can be controlled through a variety of means such as automatic photo-sensors and motion-detectors, smartphone applications or integration with intelligent building systems, allowing end-users to control daylighting inside rooms by switching their aspect, managing the control of the interactions that take place between the external conditions and the internal environment, thus creating, in this way, smart adaptive building envelope with the ability to save costs for heating, cooling and lighting.
Therefore, it is clear that the advantages deriving from the massive adoption in the building sector of this kind of technologies could lead to significant reductions in energy consumptions and, through the elimination of all the attached devices needed to control incident solar radiation, also in costs, maximizing at his best natural daylight while minimizing glare and heating-cooling requirements.
To fully understand the potential of this special category of glazing components a **classification** of the most promising glazing technologies (on-the-market available or under development) has here been drowned up, taking into account the most recent literature on such topics. The technologies investigated have been distinguished by classifying them based on their performance properties, whether they are **passive** – intended as equipped with static performance – or **active**, able to dynamically respond to external inputs of various nature. At the end of the chapter, also new emerging technological solutions have been taken into consideration to finally conclude with a brief comparison of the discussed technologies.
For each kind of "passive" and "active" windows' technologies, a commercial products representative of each category has been analyzed in-depth, in order to have rigorous and reliable performance data on which base further analysis and considerations. For synthesis purpose, only one product per category has been taken into account even if for further implementation of the present work more product could have been analyzed to obtain performance ranges that can be used as a reference, according to the requirements' framework that can vary case by case and according to the different and specific contexts of application.
Clearly, not all of the technologies under investigation are equally widespread in the current market, especially with regards of those still under development or in a research stage – such as the emerging technologies previously mentioned – for which the treatise is limited to present them in general terms.
The aim of this second-level analysis is to define main properties of actual transparent building components within current application context (referring to a real product), understanding their strength and weaknesses in the smart buildings' viewpoint.
Such classification and cataloguing of commercial products have been made on the basis of their **main features**, defining common terms and performance evaluation criteria to compare products with different characteristics.

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product that has the fully reversible ability to change its performance properties, including U-Factor, Solar Heat Gain Coefficient (SHGC) or Visual Transmittances. This includes, but is not limited to, shading systems between the glazing layers and Chromogenic Glazing».

[2] Allen, K. et al. (2017), Smart windows – Dynamic control of building energy performance, Energy and Buildings n. 139, pp. 535-546. http://dx.doi.org/10.1016/j.enbuild.2016.12.093

[3] Wikipedia defines smart or switchable those windows whose light transmission proprieties are altered when when voltage, light or heat is applied. Generally, glass changes from translucent to transparent, changing from blocking some wavelengths of light to letting light pass through.

The **parameters** took into consideration descend from the main performance requirements of the building envelope[4] (identified within previous chapters); they have been defined as follow:

- **U-value,** or thermal transmittance of the system, expressed in W/m^2K.
- **Solar Heat Gain Coefficient, Visual Light Transmittance** and **Light-to-Solar Gain**, calculated as the ratio among the previous two.
- **Sound Insulation Capacity** of the system (if available), expressed in Decibel [Db] by the Rw value.
- **Power** of the system (in case of energy generation features), expressed in Watt [W].
- appropriateness to the **Climate** (*Tropical* | *Dry/Desertic* | *Temperate* | *Continental* | *Polar*)
- **Operation type** (*Extrinsic* | *Intrinsic* | *Self-adjusting* | *Users' control*)
- **Degree of adaptability** (*on/off* | *gradual*)
- **Trigger** – if relevant (*Thermal* | *Electromagnetic* | *Optical* | *Air quality* | *Occupants* | *Other*)
- **Purpose,** that led to the adoption of such a particular kind of technology (*Thermal comfort* | *Visual performance* | *Acoustic comfort* | *Energy management* | *Energy generation* | *IAQ* | *Interaction* | *Other*)
- **Adaptive function** – if relevant (*Collect and storage* | *Control* | *Prevent/reject* | *Interaction*)
- **Operation mode** (*passive or active*)
- ability to get integrated with *BMS*
- **Light transmission mode** (*fixed* | *variable*)

In addition to these parameters, other complementary data are reported, such as:

- the trade name and the manufacturing;
- a product's brief description;
- the use for which it is suggested (*Residential* | *Service/industry* | *Specialized*)
- the bibliographic references.

Finally, a synthetic comprehensive judgement has been provided, which take into consideration the general performance features of the examined product, its applicative potentialities and the cost/benefits ratio.
The assessment has been expressed in a qualitative way thanks to three indicators which express the appropriateness of the product to specific requirements: the lower one (red box) expresses the total absence of such requirements – or very low value – while the highest one (green box) expresses the complete resolution of the critical issues identified – or very high value.

POOR (lack of compliance)	(red)
FAIR	(yellow)
GOOD (complete fulfillment)	(green)

[4] *Thermal control*, defined as the thermal insulation capacity of the system; *Visual performance*, intended as the coupling of solar control ability of the system – defined as the ability to oppose the heat flux, limiting undesired gain during summer – and its light transmission control ability – intended as the ability of the system in obstruct the solar radiation within the visible spectrum –; *Acoustic comfort*, defined as the sound insulation capacity of the system; *Energy management or energy generation abilities* and *Interaction and user control.*

6.2. Passive | Static windows' technologies

6.2.1. Tinted glasses

Tinted glasses are mass-colored glasses obtained thought the addition of metal oxides to a base-clear product during the production process.
The applied oxides are able to vary color and optical properties of glass, conferring to the glass pane the property to absorb certain portions of incident solar radiation, thereby reducing the percentage that passes through them.

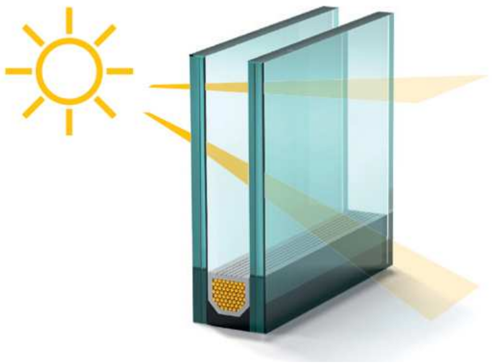


Fig. 02 – Schematic functioning of a tinted absorbent IGU glass system.

Usually, the coloration is obtained with ionic or phase-dispersed colorants made by particles' aggregates that determine the attenuation of transparency, caused by diffraction and reflection phenomena of light due to the particles dispersed in the vitreous mass.
An absorbent tinted glass with discrete properties should intercept the energy of the solar spectrum between 800 and 2000 nm as a result of glass chromatic alteration, without excessively lowering visible transmission.
The adoption of tinted glasses is quite effective in reducing the amount of incident solar radiation entering within a room: according to the results obtained by Chow et al. (2010) indeed, thermal transmission in a room with tinted glazing can be reduced more than 20%; their effectiveness and color-intensity grow proportionally with pane's thickness and, in an inversely way, with its light transmission.
As a reaction of their selective capacity, the high absorption coefficient of these products can easily cause the heating of the slab, resulting in a weakening of its mechanical strength.
Because of their modest energy-selective capacity, absorbent glasses can be used coupled with reflective metal coatings to allow the combination between absorbent and selective abilities.

Color	Thickness (mm)	VLT	SHGC	U (W/m^2K)
Bronze	4	0,60	0,68	5,8
	6	0,49	0,60	5,7
	8	0,40	0,53	5,6
	10	0,33	0,48	5,6
Green	4	0,79	0,63	5,8
	6	0,73	0,55	5,7
	8	0,68	0,50	5,6
	10	0,63	0,46	5,6
Gray	4	0,55	0,66	5,8
	6	0,43	0,57	5,7
	8	0,34	0,50	5,6
	10	0,26	0,45	5,6

Tab. 01 – Specifications of most common tinted glass on-the-market-available.

Passive | Static	TINTED GLASS	ID 6.2.1.

Pilkington Arctic Blue™

Blue body-tinted float glass able to ensure high daylight transmittance. The blue color provides solar control, thus offering aesthetics possibilities also where a low reflection is required.
The solar control properties as well as the color density vary depending on the pane's thickness.
Such tinted glasses can be embedded in stratified safety glass' systems, heat strengthened, curved and enameled; they can be used in monolithic single solution of in IGUs, even coupled with a low-emissivity glass in order to increase thermal insulation performance of the system.

General performance

Use	Service | Industry, Specialized
Climate	Generally cooling dominant climates
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	-
Purpose	Thermal comfort, Visual performance
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	5,7	U-value	2,8	U-value	1,1
SHGC	50	SHGC	41	SHGC	33
VLT	54	VLT	48	VLT	48
LSG	1,08	LSG	1,17	LSG	1,45

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Gamma Pilkington Optifloat tint, factsheet, available at: www.pilkington.com
2) Global Glass Handbook 2012, Architectural Products, Pilkington, available at: www.pilkington.com
3) Glass Handbook 2018, France, Pilkington, available at: www.pilkington.com

6.2.2. Reflective (solar control) glasses

Reflective glasses are systems obtained through the application of metallic oxides in the form of coating (placed on the outer glazing of an IGU) that increase pane's reflection towards near-infrared radiations, reducing the transmission through them without shading the infrared waves.

Also defined solar control glasses, they are characterized by a predetermined selective reflection towards solar radiation and by a low SHGC. Compared to tinted glazing, reflective glasses have a much greater impact on the reduction of solar transmission.

To obtain them, different types of surface deposits can be made, with various deposition techniques, such as additives methods, subtractive methods, cathode sputtering or vacuum evaporation, thermal spraying or pyrolysis and chemical deposition. The most employed are **pyrolysis** and **sputtering** which generate different performance glazing. The first deposition technique consists of the deposition of metallic coatings through a vitrification process at very high temperatures (about 600-650°C); this process takes place continuously on the production line, during the annealing phase of glass; therefore, it is rather inexpensive and guarantees an excellent fastening of the oxides to the support, giving also to the coating a high resistance towards external atmospheric agents. On the other side, the number of usable oxides is limited as well as the production line does not guarantee a constant thickness of the deposit.

Instead, products obtained through magnetron sputtering deposition technique[5] (also defined cathodic pulverization process) are treated after the conclusion of the base glass production, thus having higher costs but allowing a greater range of colors than the previous glasses, better homogeneity of coatings and greater optical uniformity, although they are more delicate and the layer must be applied on face 2 or 3 to prevent the aggressive action of the atmospheric agents which can damage the metallic deposit.

In general, the reflectivity of such systems increases when the thickness of the film increases, while light transmission decreases.

The chance to outer install the surface-treated glass allows to obtain glazed products with high lighting reflection values in the visible range (RL about 35/40%) and low in the infrared range; this feature, combined with a fairly high solar factor, recommends the use of reflective glasses in climate contexts in which solar gains' reduction is fundamental (cooling dominated climates). However, it has to be underlined that these type of glasses allow a one-way view, which means visual transparency only from the less enlightened space towards the brighter one.

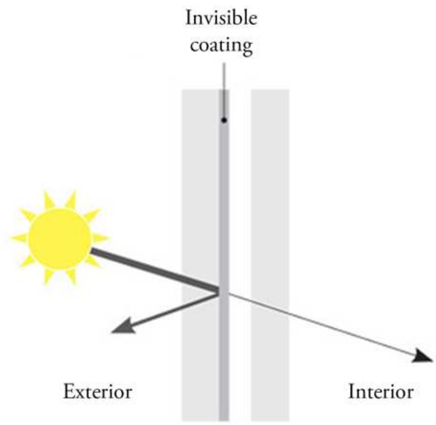


Fig. 03 – Operating principles of a reflective glazing system in a double insulated unit solution

[5] Process carried out under high vacuum in an electromagnetic field.

Passive | Static	REFLECTIVE GLASS	ID 6.2.2.

Pilkington Reflite™ Clear

Pyrolytic on-line coated reflective solar control glasses, available in different color (generally clear, bronze and grey); they offer low light transmittance and medium light reflectance, providing privacy to interior spaces while allowing the view to the outside.
Such glasses combine a low SHGC with a good reflectivity, reducing in this way the need for air-conditioning.
They can be used in single glazing applications as well as in insulating glass units, even combined with low emissivity glass; they can also be laminated, heat strengthened, toughened and curved.

General performance

Use	Service | Industry, Specialized
Climate	Generally cooling dominant climates
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	-
Purpose	Thermal comfort, Visual performance
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	5,7	U-value	2,8	U-value	2,6
SHGC	55	SHGC	46	SHGC	46
VLT	33	VLT	30	VLT	30
LSG	0,6	LSG	0,65	LSG	0,65

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Pilkington Reflite, Solar Control, factsheet, available at: www.pilkington.com

Fig. 04 – Office building with reflective glasses for solar control.

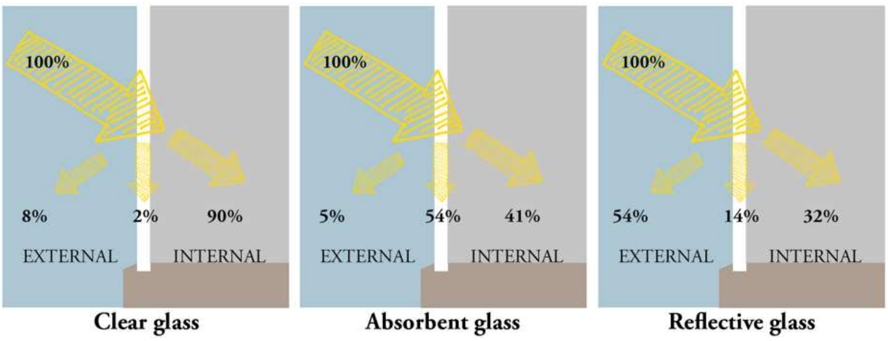
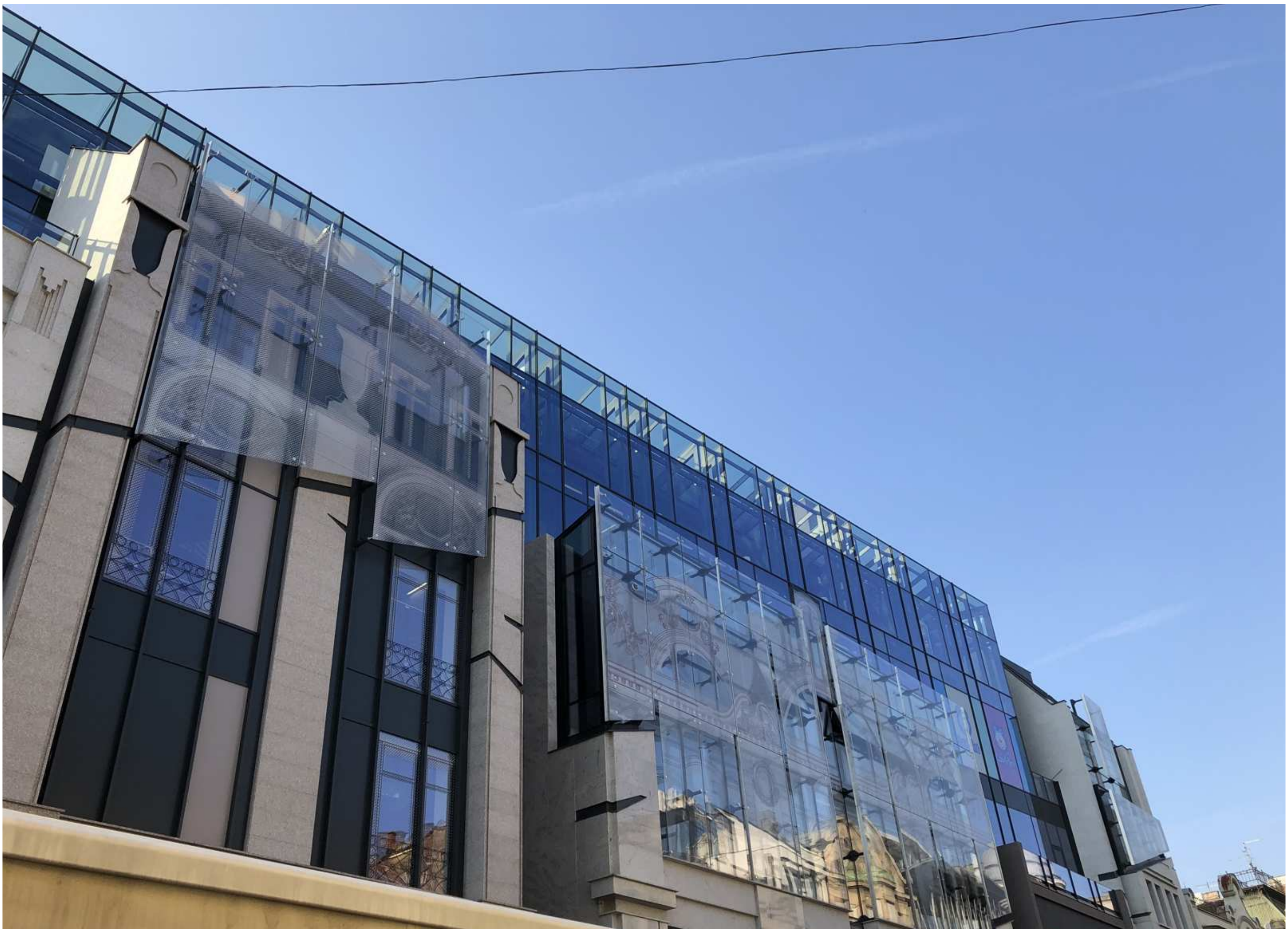


Fig. 05 – Different percentage of incident solar radiation entering through a glass surface on the basis of the type of glazed technology installed.

Fig. 06 (pag. 257) – Use of both tinted and reflective glasses in a commercial building in Belgrade, Serbia.



6.2.3. Selective glasses

Selective glasses employ coatings made of metallic oxides and dielectric materials, generally applied on the outer glazing, to block incoming infrared radiation, avoiding in this way entering in indoor environments. They maintain discrete light transmission levels, limiting, at the same time, the solar factor's value. The selective coatings have indeed the function of filtering the electromagnetic waves, admitting most of the incoming solar radiation in both visible and near-infrared spectra; instead, long-wave radiations (far-infrared), emitted from warm objects within rooms, are reflected into the room. In this way, during the winter season, the inclination of the solar rays – on average parallel to the thin glazed element – make radiations able to penetrate through the system thus triggering the greenhouse effect, exploited in passive thermal-energy strategies to reduce heating loads.
These systems couple thermal insulation characteristics, typical of low-emission glasses, with anti-solar properties of reflecting glasses.
The selective ability they provide is achievable even through the application of selective films to a common windowpane, typically in the form of a separate sheet that can be inserted between two or more glass' sheets.

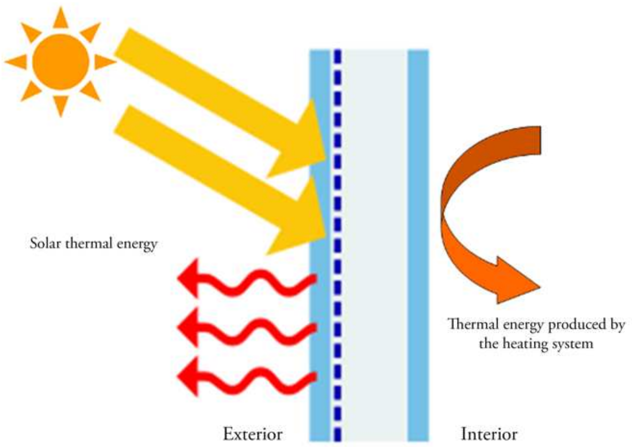


Fig. 07 – Operating principles of a selective glazing system in a double insulated unit solution.

A variation of traditional selective glasses is **angular selective glasses**, traditionally equipped with a series of very small louvres in the air gap among the two glass' panes. A novelty recently introduced and currently available only in the USA (CFR. Fig. 07) are angular selective devices that embed in the air gap a special honeycomb insert; this structure, combined with a proprietary polymer composition, provides the advantage of dynamic performance – increasing solar heat protection at peak hours – without the invisible light reduction that generally occurs with other dynamic technologies.

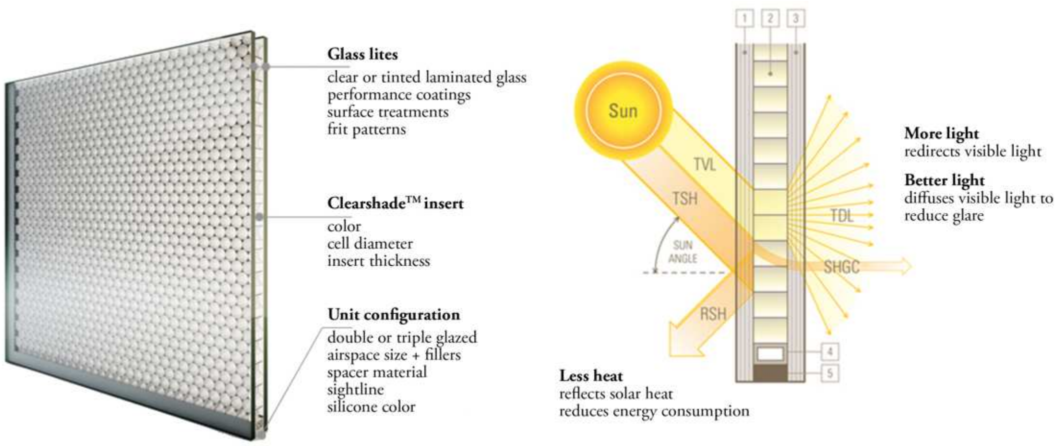


Fig. 08 – Schematic functioning of the angular selective technology produced by PANELITE, called ClearShade.

Passive | Static	SELECTIVE GLASS	ID 6.2.3.

AGC Stopray Vision 60

High-performance glasses coated with a double silver-layer magnetron-selective coating, to provide thermal insulation and solar protection, applied through cathodic pulverization vacuum.
Available in several color and level of solar control, light transmission and reflection, this product provides high-light transmission, low SHGC and very good selectivity due to the VLT ratio always lower or equal to 2.
They are available in a wide range of different transmission and light-reflection level and colors, able to combine solar protection during summer and thermal insulation during winter.

General performance

Use	Mainly Service | Industry, Specialized
Climate	Any
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	-
Purpose	Thermal comfort, Visual performance
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	2,77	U-value	1
SHGC	-	SHGC	43	SHGC	43
VLT	-	VLT	59	VLT	60
LSG	-	LSG	1,37	LSG	1,39
Rw	31	Rw	-	Rw	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Architectural Glass brochure (2013 Italian Edition), available at: https://www.yourglass.com
2) AGC Technical Data Sheet – Stopray, V. 04/2014, available at: http://www.agc-glass.eu/en
3) AGC Stopray Infosheet, available at: https://www.infobuildenergia.it/Allegati/2418.pdf

6.2.4. Low-emissive glasses

Glasses with low-emissive treatments to reduce heat-exchanges through them, without compromising their transparency. Indeed, low-emissive glasses are transparent towards solar-thermal radiations (capable of penetrating inside thermal environments) but reflective regarding infrared radiations; this results in an increase of the greenhouse effect due to their capacity in preventing the loss of the radiation emitted by the internal heating elements, allowing in this way its reflection towards the indoor spaces with consequent savings in energy costs for air conditioning.

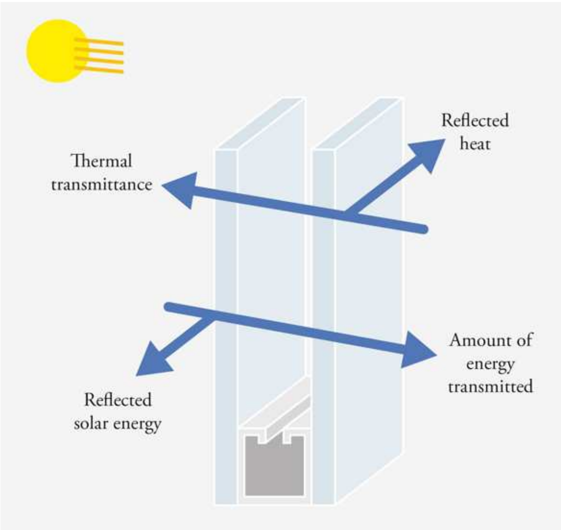


Fig. 09 – Operating principles of a Low-Emittance system in double-glazing solution.

These systems are generally composed of a double-glazing unit filled with dried air or with a noble gas and made reflective through the deposition of metals or semi-conductive metal salts, obtained by pyrolysis or by sputtering. This feature is also obtainable through the insertion in the air-gap between the two panes of a plastic film, onto which a thin deposit of metal oxides is applied[6].

A weak point of these systems is that multiplying the effect of thermal solar radiation they increase overheating as well; for this reason, they are particularly suitable to be applied in heating-dominate climates (rigid climatic contexts) where high solar factor (SHGC) is required, as well as a low thermal transmittance coefficient (U-factor).

Low-E devices have total optical transparency and high light- and energy-transmission capacity. However, the delicacy of metal oxide deposits, implies that they have to be installed in double-glazing insulation systems, with the treated side toward the inside due to its sensitivity towards moisture. The best effectiveness of the system is ensured sandwiching the film between thin dielectric layers, able to reduce the reflectance of the coated glass in the solar spectral range.

Today, low-E coatings are employed in all major IGUs; depending on the thickness of the cavity and on the filling gas type they allow to obtain thermal transmittance values between 1,7 and 1,0 W/m^2K, for double glazing, and lower than 0,7 W/m^2K for triple glazing. Recent researches[7] shown that with the adoption of these technologies the solar heat gain through windows can be reduced up to 48%.

[6] To provide low-e coatings, two approaches are possible: hard-coatings, durable, less expensive but generally also less effective, and soft-coatings, with better thermal performance but more expensive and subject to oxidation during the manufacturing stage.

[7] Liu, H. (2012), *The development of novel window systems towards low carbon buildings* (PhD thesis), The University of Nottingham.

Passive | Static	LOW-EMISSIVE GLASS	ID 6.2.4.

Pilkington Optitherm

Off-line coated glass able to reflect the long wavelength-energy generated back into the buildings. The transparent, low-emissive coating permits the transmission of the short wavelength originating from the sun.

The main features of such systems are: high light transmission, neutral color and good thermal insulation. Such products must be assembled in IGU and clearly can be combined with other glazed technologies to maximize their performance in terms of safety or acoustic insulation.

General performance

Use	Any
Climate	Generally heating dominant-climates
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	-
Purpose	Thermal comfort
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,6	U-value	1,0
SHGC	-	SHGC	59	SHGC	49
VLT	-	VLT	78	VLT	70
LSG	-	LSG	1,32	LSG	1,42

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Pilkington Optitherm S1, Factsheet, available at: www.pilkington.com
2) Global Glass Handbook 2012, Architectural Products, Pilkington, available at: www.pilkington.com
3) Glass Handbook 2018, France, Pilkington, available at: www.pilkington.com

6.2.5. Vacuum insulated glasses

Introduced at the beginning of the century (Zoller, 1924), vacuum insulated glazing was no produced until 1989; today, they are almost fully available on the market, produced by Pilkington[8], even if with quite a high cost.
Standard vacuum insulating glazing products consist of two glass panes, generally low-emissive, separated by a vacuum space in which supporting and separating pillars stand, to avoid the collapse of the system. The pillars, made of indium and disposed to properly react to atmospheric compressive stresses imposed by the pressure within the two panes (of about 10^{-2} mbar) have a very small dimension so they have no impact on the vision towards outside.
The advantage of such technology is that it combines an extremely small thickness with very good qualities of thermal insulation due to the vacuum between the glass panes that avoid convective exchanges between them; also radiative exchanges are much lower, as long as the presence of selective coatings reduces thermal losses.
In past years, several authors carried out experimental researches to evaluate the thermal performance of vacuum glazing, as accurately reported by Cuce (2016); last developments in this field are pointed towards sealants and spacers with high-performances, to increase the internal pressure of these systems to reach for a U-value of about 0,4 W/m^{2}K.
However, such a kind of window assemblies still presents many shortcomings, for instance, the resistance to the variable pressures caused by wind and vibration that can affect windows' flat surface, or, again, the maintenance of an airtight seal around the edge to avoid the re-establish of conduction to its normal value.

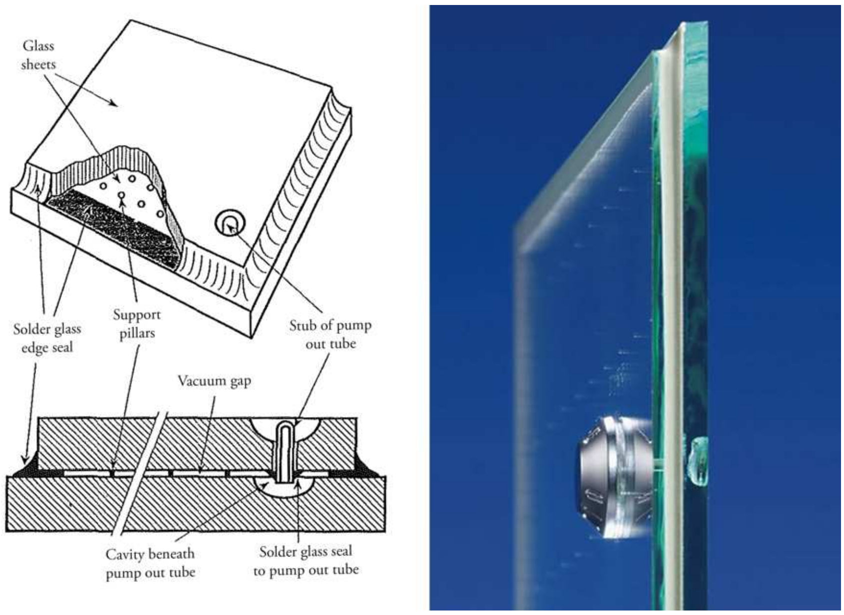


Fig. 10 – On the left: schematic diagram of the vacuum glazing system; on the right: Pilkington Spacia commercial product.

[8] Pilkington. Pilkington Spacia [available at: http://www.pilkington.com/en-GB/uk].

Passive | Static	VACUUM INSULATED GLASS	ID 6.2.5.

Pilkington Spacia

All purposes glass which combines a very low thickness with the thermal performance of a conventional double glazing. VIG (Vacuum Insulated Glazing) reaches now better performance than standard triple glazing, being suitable to be installed in almost the totality of climate regions.
They are particularly suitable for all the cases in which there is the need to balance historical preservation issues with comfort and actual environmental requirements and, in general, for all the contexts in which a thinner low weight glazing is desirable; such systems indeed, have the gap between the two panes reduced to 0,2 mm.
In addition, they presents improved sound reduction performance if compared to a standard double glazed unit.

General performance

Use	Any
Climate	Any
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	-
Purpose	Thermal comfort
Adaptive function *(if relevant)*	Control
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	1,1	U-value	-	U-value	-
SHGC	67	SHGC	-	SHGC	-
VLT	78	VLT	-	VLT	-
LSG	1,16	LSG	-	LSG	-
Rw	36	Rw	-	Rw	-

General assessment

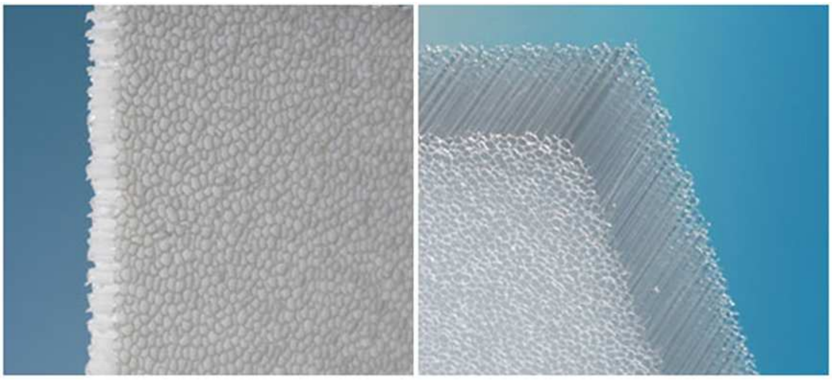
Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Global Glass Handbook 2012, Architectural Products, Pilkington, available at: www.pilkington.com
2) Glass Handbook 2018, France, Pilkington, available at: www.pilkington.com

6.2.6. TIM glasses

Discovered in Germany in the 80s (Tucci, 2006), TIM glasses are generally plastic or glazed components which comprise, in the space between the two panes, a transparent or translucent insulating materials (Al-Obaidi et al., 2014). Their main advantage is that they combine diffused lighting features with very limited thermal losses that usually characterize glass curtain walls (Qu et al., 2014).
TIM glazed systems allow to reduce energy flows through the casing and, being translucent (SHGC is equal to that of a common IGU), they permit the diffusion of natural light – both direct as diffuse – in environments where there isn't the need to ensure the complete visual transparency towards the outside, preventing in this way glare phenomena.
These systems exploit TIMs' main characteristic – that is their particular geometrical structure – to reduce radiative and convective heat exchanges through them.
Therefore, based on their geometrical structure, transparent insulation materials can be divided in: a) **multiple-parallel-structured materials**, in which the insulation capacity of the material increases with the number of the elements and of the internal reflections (reducing in this way also the solar radiation transmission), and b) **glazed-upright-structured materials**, able to directing radiation through the inside. To this group belong capillary structures with parallel fibers and honeycomb structures with perpendicular fibers. Both honeycomb or parallel-fiber panels have to be applied with the structure direction perpendicular to the facade plane (parallel to the direction of incident solar radiation), to limit the number of internal reflections through structures.



Fig, 11 – On the left: Okapane technology made of a capillary panel with free crystal tubes and honeycomb geometry, fiberglass coated. On the right: Kapilux Panels in which the translucent capillary tubes placed within the air gap between two glass sheets divide incident solar radiation, allowing the diffuse lighting in confined spaces. Glazed transmission can be chosen specifically according to different needs. In both the technologies the small cavities among capillary produce a sort of insulating air buffer able to stop the heat-convection; for this reason, increasing the capillary tubes within the panels means improving its thermal transmittance.
In general, these panels offer an excellent thermal insulation level with U_g value lower than 0,7-0,8 W/m^{2}K

Glazing TIM systems generally employ plastic capillaries or honeycomb structures insulating materials, that can be made of **polycarbonate** or **poly-methyl-methacrylate** (honeycomb structured compound of organic nature), equipped with excellent light-transmission and heat-insulation properties (90% for normal incidence), or of **aerogel**, an inorganic material (with porous and hygroscopic structure) made for more than 90% of air and, for the remaining percentage, of silica-dioxide particles, with very low thermal conductivity (lower than 0,013 W/m^{2}K) (Baetens et al., 2011).
Aerogel, due to the high percentage of air contained in it, presents very low density and very interesting thermal characteristics; extremely fragile and very moisture-sensitive, it is available in different forms: the most commons are **monolithic** and **granular** forms (Buratti and Moretti, 2011). Monolithic aerogels are panes of thickness between 8 and 20 mm, with

density between 3 and 500 kg/mc; they can be directly used to replace traditional glazing even if their high-cost, coupled with the small available size of the panes, makes them of difficult application. Glazed systems produced with this material – appeared on the market in 2005 – have a high-solar-transmission coefficient (up to 80%) and a very low heat transmission coefficient; for these reasons they are suitable to be used both in cooling as in heating dominant climates.
Aerogel in granular form instead, made of spheres with variable diameter, can be easily used in IGUs even if it has a very low light-transmittance. In general, this kind of devices allows to obtain very thin window systems, with U-value lower than 0,50 W/m^2K and without diminishing the solar factor nor considerably reducing VLT.

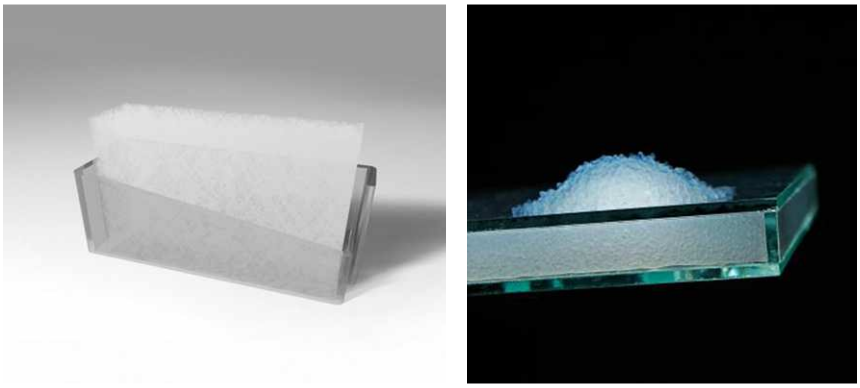


Fig. 12 and 13 – Section of TIM glasses with aerogel in the air gap within the two panes.

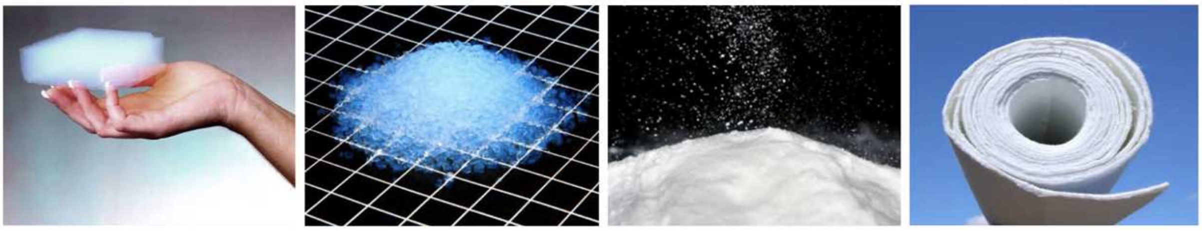


Fig. 14 – Different forms of Aerogels, from left to right: in monolith tiles, in granules, in powder and fiber composite. Composites are obtained including the fiber in the gelation process or pressing the granules into the fiber composite.

Fig. 15 (pag. 266) – Pilkington Aerogel application in an office building

Passive | Static	TIM GLASS	ID 6.2.6.

Okalux Kapilux T

IGU in which a transparent capillary slabs, inserted in the cavity, allow for a light-diffusing illumination, providing, at the same time, very good sun and glare protection. Similarly, the heat-insulation capacity of the system is improved by the capillary tubes.
On the contrary, one of the weakness point is that the structure of the capillary tubes is visible from both sides, thus preventing the complete view towards outside (they are indeed, only partially transparent).
In general terms, TIM glasses permit a high-light transmission, a good heat and sound insulation, even if they partially reduce the view towards outside.

General performance

Use	Mainly Service | Industry, Specialized
Climate	Any, even if mainly heating dominant climates
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	-
Purpose	Thermal comfort
Adaptive function *(if relevant)*	Control
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,28	U-value	-
SHGC	-	SHGC	64	SHGC	-
VLT	-	VLT	68	VLT	-
LSG	-	LSG	1,06	LSG	-

General assessment

Performance features	(orange)
Potentiality and applicability	(orange)
Integrability with BMS	(red)
Costs/benefits ratio	(orange)

References

1) Brochure OKALUX + KAPILUX, available at: https://www.okalux.com/products/product-finder/products/kapilux/detail/kapilux-t/
2) Infotext KAPILUX T, available at: https://www.okalux.com/products/product-finder/products/kapilux/detail/kapilux-t/
3) Tender Specification KAPILUX T, available at: https://www.okalux.com/products/product-finder/products/kapilux/detail/kapilux-t/

6.2.7. Self-cleaning glasses

Self-cleaning glasses exploit technologies and formulations able to transform glass' surficial properties by penetrating in the micro-pores of the glazed surfaces. These applications have the advantages to reduce maintenance needs while controlling solar radiation by diminishing depositions on the glass surface.

Fig. 16 – Difference between a non-treated glass and a glass with self-cleaning treatment.

Two categories of self-cleaning treatments can be identified: **hydrophobic** (water repellent) and **hydrophilic** (water attractive) surfaces. A solid surface with contact angle (between itself and a water droplet) higher than 90 degrees is considered hydrophobic, whereas a contact angle lower than 90 degrees makes it hydrophilic. If this angle exceeds the 120 degrees, the surface is considered super-hydrophobic (also defined Easy-To-Clean surface); similarly, when the angle is lower than 60 degrees, the surface is called super-hydrophilic.
Self-cleaning hydrophobic surfaces have surficial treatments of nano-technological nature, capable of reacting with silica's molecular chain of glass, thus eliminating its micro-porosity (Mellot et al., 2006). These formulations transform glass' surface properties, uniformly arranging molecules, thus developing a surface layer capable of letting water and surface deposits flow, in a perfectly smooth and compact way and in contrast with the natural surface of common glass, which has, on the contrary, imperfections that led it to accumulate water, corrosive substances or dirt. These surfaces are also defined **lotus-effect surfaces** (Midtdal and Jelle, 2013) and, thanks to the reduction of surface adhesion, can reduce cleaning requirements, obtaining water repellent systems in which contamination is washed off by water droplets.

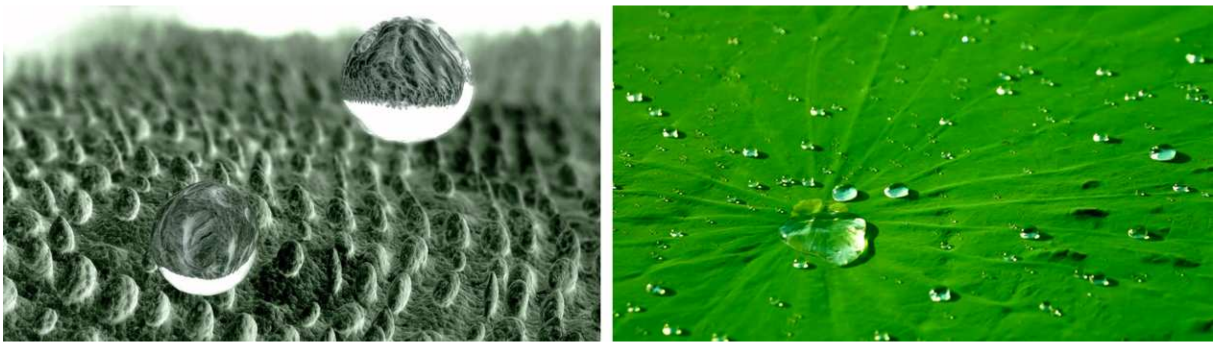


Fig. 17 – Schematic functioning of the so-called lotus effect.

On the other hand, hydrophilic glasses are generally obtained through the deposition of metallic oxide layers (generally TiO_2, ZnO or WO_3) on their surfaces; commercial manufacturing products are mostly made with atmospheric pressure chemical vapor deposition techniques (APCVD) or with other various techniques such as PVC, CVD, sol-gel, electrospinning and dip-coating.

The treated surfaces, due to the photocatalytic properties of the metal-oxide-based nanoparticles, decompose the organic contamination using UV radiation. The coating interacting with UV rays through a photocatalytic process, provides the decay of organic pollutants and nitrogen oxides, allowing rainwater to wash away dirt. The photocatalytic properties long last until the irradiation continue; while after illumination stops, the hydrophilic behavior remains for about two days.

Nowadays, exist on the market also super-hydrophilic devices that employ nanoscale polymers or silica nanoparticles to provide a perfectly smooth surface, able to perform also an antifogging function.

The difference between photocatalytic self-cleaning surfaces and ETC systems is that ETCs do not require UV light to function and that their hydrophobic properties – on the contrary of hydrophilic devices – determine the runoff of water droplets rather than form a hydrophilic film on them. Both these kinds of glazing are particularly suitable for difficult-to-reach surfaces.

Thanks to the reduction of dirt on their surfaces, self-cleaning systems improve light transition through them, reducing energy costs for lighting accordingly.

The ratio decontamination to contamination expresses the efficiency of the glazing.

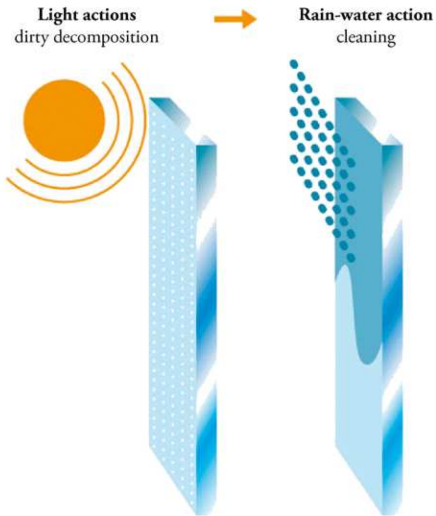


Fig. 18 – Sunlight action on a photocatalytic glass

Fig. 19 and 20 – Applications of Self-cleaning glasses.

Passive | Static	SELF-CLEANING GLASS	ID 6.2.7.

Pilkington Activ

Float glass in which a particular, neutral coating is dropped off through a pyrolytic (on-line) process; the coating contains catalyst elements able to activate both the photocatalytic and hydrophilic action. Thanks to this particular treatment, these glasses are able to exploit solar radiation to decompose organic sediments and let them run off when rain water droplets hit the surface, reducing cleaning and maintaining needs and related costs.
This range of glasses can be laminated with both PVB or resins, heat-strengthened, curved and enameled with standard techniques; they can be used in a monolithic form or as IGU (with the self-cleaning coating facing the outside).

General performance

Use	Any
Climate	Any
Operation type	Extrinsic
Degree of adaptability	On/Off
Trigger *(if relevant)*	Optical
Purpose	Other
Adaptive function *(if relevant)*	---
Operation mode	Passive
BMS	No
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	5,7	U-value	2,7	U-value	2,6
SHGC	79	SHGC	72	SHGC	75
VLT	89	VLT	76	VLT	77
LSG	1,12	LSG	1,06	LSG	1,02

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Glass Handbook 2018, France, Pilkington, available at: www.pilkington.com
2) Pilkington Activ Technical Data (available online at: https://www.pilkington.com/it-it/it/prodotti/categorie-prodotti/autopulente/pilkington-activ-la-gamma#documentazione)
3) Pilkington Activ Global Brochure (available online at: https://www.pilkington.com/it-it/it/prodotti/categorie-prodotti/autopulente/pilkington-activ-la-gamma#documentazione)
4) Self-cleaning glasses range. Guidelines for use (available online at: https://www.pilkington.com/it-it/it/prodotti/categorie-prodotti/autopulente/pilkington-activ-la-gamma#documentazione)

6.2.8. Heating glasses

Heating glasses represent a pretty promising smart windows technology because they seem able to contain heat and gain losses through the transparent surface by adding to the interior pane of an IGU a metallic coating, electrically connected (generally made of aluminium oxide), that, when a low voltage is applied, warms up and directs the heat to the interior, avoiding heat exchanges through the room and the external environment.
Systems of such a kind completely remove the risk of condensation between glass' panes, contributing also to the heating system of the entire building (since they generate about 0,42 Kw/m^2).

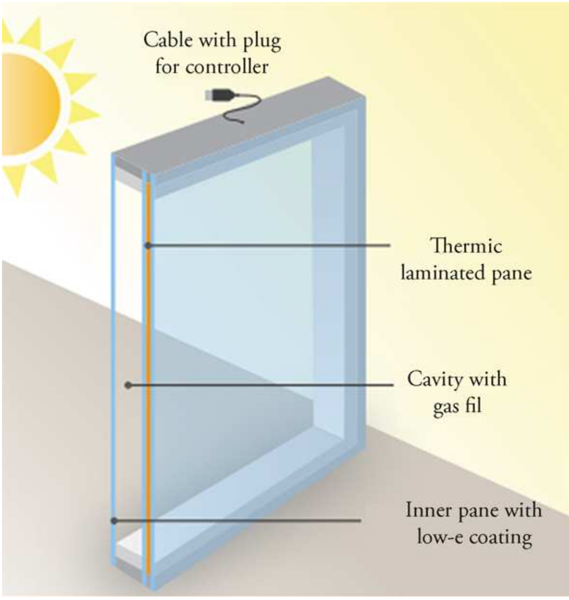


Fig. 21 – Schematization and functioning of a heating glass

Normally, heating glasses require 100-300 W/m^2 to work, providing a pane temperature of about 40°C; if used only for condensation-prevention purposes, their operation power can be halved.
Further improvements of such technology include the development of new high-conductive oxide coatings with nanoparticle for faster heating rates, lower consumption and higher color neutrality, that means increased VLT.
Appeared on the market only in 1980, and firstly in Finland, now heating glasses are produced by several companies all over the world (e.g. Saint Gobain, Quantum E-glas, American Vitrius Technology, WarmGlass, etc.). Among the other, significant is the device produced by Vitrius Technology since it can re-calibrate and re-program itself in real-time, improving its performance based on end-users' needs.

Passive | Static	HEATING GLASS	ID 6.2.8.

WG Crystal WarmGlass

WG Crystal presents a metallic surficial treatment that allow pane's electrical stimulation; by applying an electrical current, the coating on the glass surface transforms the energy into heat, emitted in the form of long-wave infrared rays. According to the coating deposition, it is possible to heat both the internal or the external pane.

The requested power supply is about 230 v – 50 hz (to reach a surficial temperature of about 60-65° C) and the surficial temperature is completely adjustable according to users' demands. Moreover, it is possible to add to this system, devices for the electronic management of its functioning, such as timers, thermostats, chrono-thermostats, temperature controls, automation systems, wireless systems, etc.

The glass pane, in addition to the heating treatment, can be designed to suit other functions such as self-cleaning functions, solar control, additional sound insulation capacity, blind insertion, etc.

General performance

Use	All
Climate	Any, even if mainly heating dominant climates
Operation type	Users' control
Degree of adaptability	Gradual
Trigger *(if relevant)*	Electromagnetic
Purpose	Thermal comfort
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Active
BMS	Yes
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	2,8	U-value	1,3
SHGC	-	SHGC	50	SHGC	50
VLT	-	VLT	72	VLT	74
LSG	-	LSG	1,44	LSG	1,48
W (if relevant)	-	W (if relevant)	50-100 (m^2)	W (if relevant)	50-100 (m^2)

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Warmglass website (https://www.warmglass.it)

6.2.9. Photovoltaic glasses

Photovoltaic glasses embed photovoltaic cells or panels into the system to transform solar energy into electrical energy, acting in the same way as sunscreen.

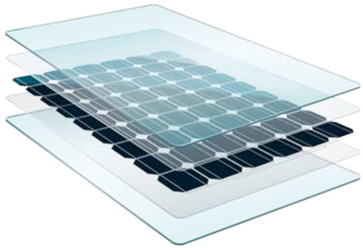


Fig. 22 – Composition of a photovoltaic glass; the PV cells are embedded within the two glass panes.

To the author's knowledge, several types of products are on-the-market available, using different photovoltaic elements, although silicon (Si) still remains the prevalent semiconductor employed in solar cells production. It is used in the form of **crystalline silicon,** mono- or poly-crystalline, or of **non-crystalline** cells, produced by **amorphous silicon**; non-crystalline cells have low average efficiency (around 9%) even if they are available in both opaque or semi-transparent modules. Otherwise, mono-crystalline cells are blue-, dark grey- or black-colored opaque elements with a degree of efficiency of about 15% (Jelle et al., 2012). Finally, poly-crystalline cells are blue opaque and made with silicon drained blocks and are the less efficient (their degree of efficiency is about 12%); they are produced with panes' thickness of 0,4 mm and sizes of 10x10 cm or 15x15 cm, combined into modules and placed in IGUs' air-gap using resin.

Fig. 23 – Semi-transparent PV modules

Other PVs' glasses are those produced using **thin-film organic materials** – semiconductors, cheaper than inorganics, like Si, but still sensitive concerning degradation – or **Dye-Sensitized Solar Cells** (DSSCs), covered by a thin-film and constituted by a photo-sensitized anode and an electrolyte. DSSCs presents low cost but very poor energy conversion efficiency (Cuce, 2016).

Fig. 24 – Sunscreen of the EPFL QUARTIER NORD SwissTech Convention Center Retail and Student Housing (Richter Dahl Rocha & Associés, 2014, Ecublens, Switzerland) made with DSSCs device.

Dimension	Features	VLT	SHGC	U (W/m²K)
980x950 mm	Efficiency | *8,02 %* PV technology | *a-Si* Assembly | *Single pane laminated*	0,0917	0,289	5,08
1300x1100 mm	Efficiency | *5,90 %* PV technology | *μc – Si* Assembly | *Single pane laminated*	0,0519	0,413	4,80
1300x1100 mm	Efficiency | *3,32 %* PV technology | *μc – Si* Assembly | *Single pane laminated*	0,0184	0,298	5,08
1300x1100 mm	Efficiency | *4,43 %* PV technology | *μc – Si* Assembly | *Single pane laminated*	0,0417	0,387	5,10
989x930 mm	Efficiency | *5,01 %* PV technology | *a-Si* Assembly | *Double pane unit*	0,0691	0,154	1,67
980x950 mm	Efficiency | *4,75 %* PV technology | *a-Si* Assembly | *Double pane unit*	0,0734	0,123	2,14

Tab. 02 – Different specifications for six semi-transparent PV modules.

To overcome the major weak point of these systems (that is the lack of visible transmittance), researchers of the Michigan State University have recently developed a PV technology that uses a particular kind of plastic to produce electricity, if directly irradiated (Peschel, 2015). It is called **Transparent Luminescent Solar Collector** and it can be placed over windows to absorb specific non-visible wavelengths.

This new harvesting system has been developed using organic molecules that absorb UV and NI wavelengths and transporting thin strips of photovoltaic cells on plastic, to convert light into electricity. Due to the fact that absorbed wavelengths are not visible to the human eye, the material looks transparent, opening new interesting possibilities for the world of WIPVs. However, despite its many upsides, the real shortcoming of this technology is its low energy efficiency, still around 1%.

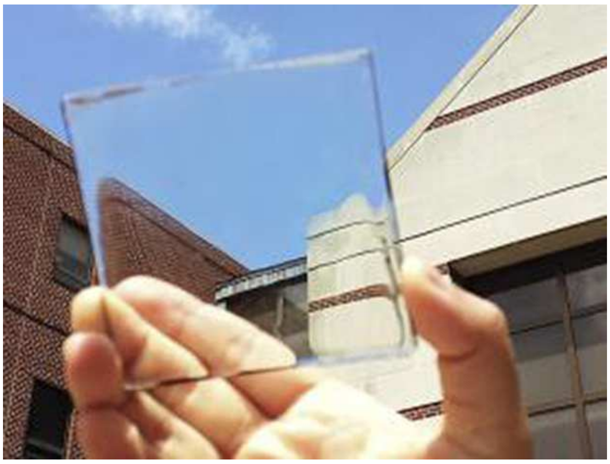


Fig. 25 – Sample of Transparent Luminescent Solar Contractor developed at the MSU, able to absorb sunlight without losing transparency. Photo of Yimu Zhao.

Also an Italian research team has tried to develop the first transparent photovoltaic glass with the introduction of graphene, a material tougher than diamonds, totally transparent, able to conduct the electricity even if employed in thickness comparable to that of an atom and with considerably reduced costs, if compared to traditional materials.

In the study[9], the platinum normally presents in a PV panel (based on dye-sensitized solar cell technology (DSSC) has been entirely replaced by graphene, in the form of ink, applied to the panel by spray deposition.

The advantage of this technology is that it can further be implemented with higher energy performance and that the production techniques of graphene panels could easily be produced industrially.

[9] Giucastro, F.G.S. (2017), "Smart windows of the future. The introduction of graphene in transparent photovoltaic". Paper presented at the 12th International Symposium on Renewable Energy Education - ISREE 2017, held from the 19 to 21 June in Strömstad Sweden, and published in the proceedings [ISBN 978-91-86607-37-1], available online at: http://www.stromstadakademi.se/sa_pdf/AAS-33.pdf

Passive | Static	PHOTOVOLTAIC GLASS	ID 6.2.9.
	ONYX Solar Photovoltaic	

Devices that exploit a quite simple technology to capture the light of the sun and transform it into electricity.
They are made of two or more panes – heat strengthened – which embed photovoltaic cells; different power capacities are determined by the solar cell density (cells' numbers per module).
The systems can be customized to adapt each project's needs in terms of thermal insulation, solar factor and other configurations.

General performance

Use	All, even if mainly Service | Industry or Specialized
Climate	Any
Operation type	-
Degree of adaptability	-
Trigger *(if relevant)*	(Optical)
Purpose	Energy generation
Adaptive function *(if relevant)*	Collect and storage
Operation mode	Passive (Active)
BMS	Yes
Light transmission mode	Fixed

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	2,7	U-value	1,2
SHGC	-	SHGC	19	SHGC	17
VLT	-	VLT	30	VLT	30
LSG	-	LSG	1,58	LSG	1,76
W (if relevant)	-	W (if relevant)	28 (m^2)	W (if relevant)	28 (m^2)

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Onyx Solar website (https://www.onyxsolar.com/product-services/technical-specifications)

6.3. Active | Dynamic windows' technologies

Suitable to be inserted within the category of **chromogenic**, glazing systems of such a kind are characterized by properties of variable transmittance. Such ability is obtained through the integration, within the system, of chromogenic materials, or of materials capable of changing their optical properties, according to external stimuli or after the application of an electric field. Chromogenic indeed, exploit chemical-physical properties of some technologies to change their status, making the glass to become from highly transparent, partially reflecting. Even if, in the first state, the glass pane allows high visible transmittance and solar heat gain factor, in the colored state these two values are expected to be as low as possible.
According to the technologies they employ, thus of their behavior, chromogenic glasses can be **self-regulating** (thermal and photochromic) or **electronically activated** (on the basis, for instance, of users' demands) (electro-chromic).
To the author's knowledge, nowadays chromic-materials-based smart windows are the most reliable technologies for producing smart adaptive glazing systems; however, even if such technologies are almost fully exploited, they still do not provide full control of direct sunlight, due to the fact that they directly turn from a transparent state to a tinted one, without intermediate transparency levels.

6.3.1. PCM glasses

PCM systems embed Phase Change Materials to control incoming solar loads, decrease building energy loads in peak hours and impede building temperature swing[10]. We can say that such kind of systems integrates four functions in a single functional unit: 1) the insulating function, 2) the overheating control function, 3) the energy conversion function and the 4) storage function, thanks to the presence of the PCM.
Different materials are suitable to be employed as PCMs, exploiting the principle of latent heat thermal storage (LHTS) (to absorb energy and release it at a different time) and changing their state from solid to liquid, allowing in this way the temperature control in a specific range, function of the material employed.
PCM glasses generally allow diffused natural lighting of spaces; at the solid state indeed, PCMs transmit about the 28% of visible light, while, when they are in a liquid state, VLT increases to over 40% (Goia, 2012).
Although translucent PCMs are available (Long et al., 2014), light quality transmittance of these technologies is still a weak point. Moreover, PCMs still have obvious limitations which need to be overcome to reach large-scale application, such as, for instance, issues related to the choice of the optimal melting temperature, flammability of paraffin and to the difficulty to thermally download the material after long "warm periods".

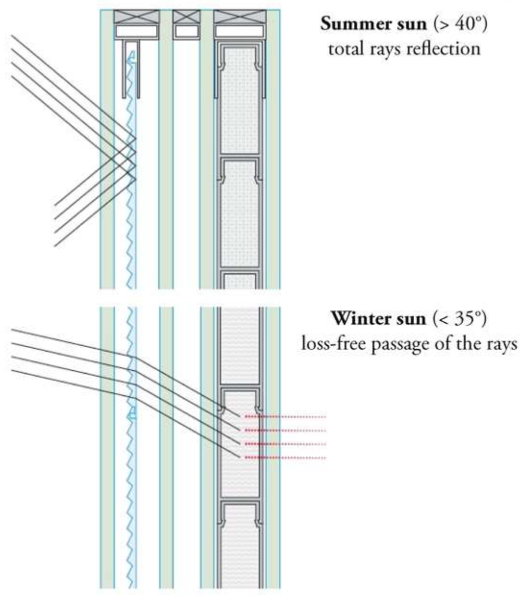


Fig. 26 –GLASSX PCM integrated system.

[10] In a study [Nghana B., Tariku F., "Phase Change Material's impacts on the energy performance and thermal comfort of buildings in a mild climate", *Build. Environ.* 99 (2016) 221-238] it was found that wall and indoor air temperature fluctuation is decreased by 2,7 °C and 1,4 °C respectively in a building that incorporates PCM; moreover, also energy demand was reduced by 57% during winter.

Active | Dynamic	PCM GLASS	ID 6.3.1.

GlassX Crystal

Triple insulated glass unit in which a prismatic pane is inserted in the outermost air-gap to reflect back high-angle sunlight while transmitting low-angle sunlight, offering a first (passive) solar-control level. The storage material – a salt hydrate PCM – is located in the inner air-gap, filled with sealed polycarbonate channels into which the translucent salt is encapsulated; this provides the system a storage capacity similar to 20 cm of concrete (about 1185 Mh/m^2). Such PCM melts and freezes in the temperature range of 26-30°C.
The U-value of the system thus obtained is about 0,48 W/m^{2}K, but its cost is still quite high (about \$550-970/m^2, according to the North American distribution), having a payback period of five to ten years.

General performance

Use	All, even if mainly Specialized
Climate	Any, even if mainly heating dominant climates
Operation type	Intrinsic
Degree of adaptability	Gradual
Trigger *(if relevant)*	Thermal
Purpose	Thermal comfort
Adaptive function *(if relevant)*	Collect and storage; Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	0,48	U-value	-
SHGC	-	SHGC	33 / 4-37	SHGC	-
VLT	-	VLT	8-28 / 12-44*	VLT	-
LSG	-	LSG	0,84 / 3-1,18	LSG	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) GlassX crystal, on Delta Engineering Services webpage (http://www.deltaes.it/glassx-crystal/)
2) GlassX crystal brochure, available online at: http://www.deltaes.it/glassx-crystal/#
3) GlasssX website (https://www.glassx.ch/en/products/glassx-crystal/)

* The values are referred to the two phases of the PCM: the first express the light transmission when PCM is crystalized while the second value refers to liquid PCM.

6.3.2. Suspended Particle Devices (SPDs) | Liquid Cristal Devices (LCDs)

SPDs are basically electroactive devices in which the application of an AC voltage makes the particles move from a random pattern to an align-oriented one, becoming the window transparent. Without an electrical charge, SP windows absorb light, thus decrease light transmission through them.
Generally, in SPDs, transparency depends on fluid film thickness and on particles density; in addition, they can be tuned at different levels quite quickly even if with pretty high energy consumption.
Typical ranges of light transmission and SHGC in these devices – in the transparent and opaque state – are, respectively, for VLT: 60-0,5%, and, for SHGC: 0,57-0,06%, with switching times of some seconds. They require about 100 V AC to operate from the tinted state to the transparent state and can be modulated via intermediate states; power requirements are about 5 W/m^2 for switching and 0,55 W/m^2 for maintaining constant transmission.

On the other hand, LCDs employ materials with a bars-molecular structure that, when a voltage is applied, allow to vary systems' light transmission properties; most of the LCDs indeed, scatter light, becoming white and translucent (Rezaei et al., 2017). These materials, discovered by Gray in Great Britain during 70s, are defined **nematic** if they are align-oriented but can shift each other, or **smettic** if they are stratified.
Different kind of LCDs become smettic at low temperatures while nematic if heated, and usually fluid when they reach a very high temperature. Most common LCDs use crossed-nematic devices, whose polymers form chains that round between polarized plates.
LCDs are generally composed by a layer of droplets dispersed in a polymer matrix; the particles are inserted between two transparent electrodes made of ITO-covered polyester. When the voltage is off, they scatter light due to the mismatch between the matrix and droplets refractive index.
These systems, unlike SPDs, are mainly employed for privacy purposes (Kim et al., 2015) and require current electrical energy to maintain operation.
The light transmittance of liquid crystal glazing, in the active state, does not exceed the 70%, while, in the off state, it is about 50%; they spread direct incident solar radiation but do not block it enough to reduce SHGC, that lays generally between 0,69 and 0,55.

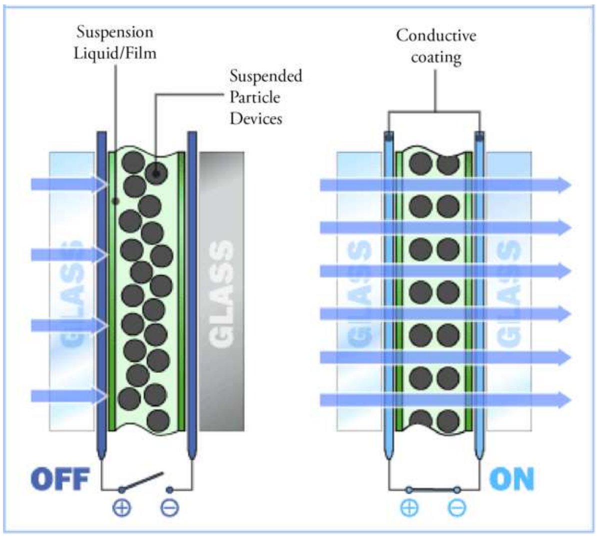


Fig. 27 – Operation mode of a Suspended Particle Device

Active | Dynamic	SPD GLASS	ID 6.3.2.a

Solar Smartglass

Device in which the particles inserted within the thin laminated film, sandwiched between the two glass' layers, react to an electric current: when no energy is applied, the particles are randomly orientated, absorbing light (so the glass appears completely opaque or colored); otherwise, when voltage is applied the particles align, reporting glass to its initial translucent state.
Their particular feature is the fact that such film is not limited to regular shaped flat glass thus allowing its employ with custom shaped components.
Additionally, this SPD glass can be manually or automatically tuned to control the amount of light, glare and heat passing through a window, reducing as well the need for conditioning.

General performance

Use	Any
Climate	Any
Operation type	Intrinsic, Users' control
Degree of adaptability	Gradual
Trigger *(if relevant)*	Electromagnetic
Purpose	Visual performance
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Active
BMS	Yes
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,36	U-value	-
SHGC	-	SHGC	39 / 33	SHGC	-
VLT	-	VLT	22 / 1	VLT	-
LSG	-	LSG	0,56 / 0,03	LSG	-
Rw	-	Rw	37 dB	Rw	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Solar Smartglass website (http://www.smartglassinternational.com/switchable-glass/solar-smartglass/)
2) Solar Smarglass Technical Document, Version 1.8, March 2013 Revision, available at: http://smartglassinternational.com/wp-content/uploads/Solar-Smartglass-Technical-Specs.pdf
3) SPD SmartGlass™ Overview, available at: http://www.smartglassinternational.com/downloads/SPD_SmartGlass_Data.pdf

Performance	OFF state	ON state
VLT	0,65	0,01
SHGC	-	-
U (W/m²K)	-	-
Maximum power draw – 19,4 mA/m²; Switching time – 1-3 sec.		

Tab. 03 – SP window's specifications.

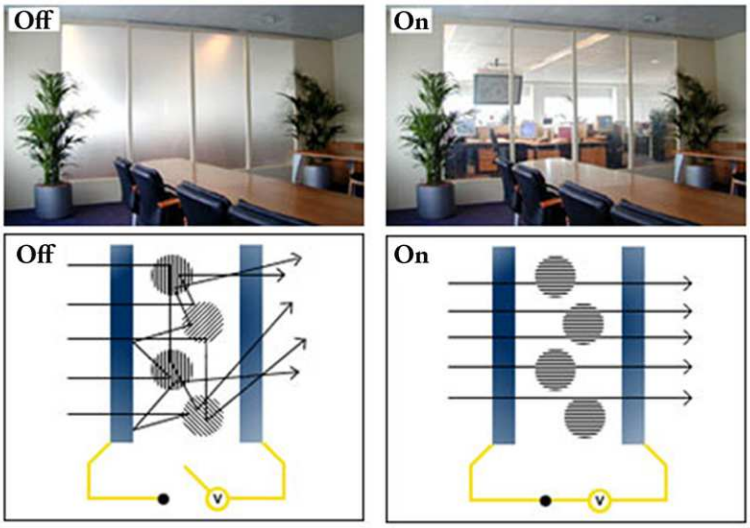


Fig. 28 – Operation mode of a Liquid Crystals device

Performance	OFF state	ON state
VLT	0,77	0,58
U (W/m²K)	1,59	1,59
	Operating voltage (AC)	120 V
	Power consumption	15,5 W/m²
	Switching time	0,1-0,4 s

Tab. 04 – LC privacy window specifications.

Active | Dynamic	LCD GLASS	ID 6.3.2.b

Innovative Glass – LC Privacy Glass

Suitable both for privacy and furniture purposes, these devices are able to frost on demand, changing from transparent to milky state. When powered indeed, panes are transparent, allowing full view and daylight, while when switched off view is obscured, providing complete privacy thus blocking about the 99% of UV rays. Their voltage of operation is 110/120 VAC.
Such systems are available with various configurations and IGU thicknesses, suitable for different purposes; moreover, they are fully compatible with every kind of domotics, being controllable by switch or through a voice command.

General performance

Use	All, even if mainly Service | Industry
Climate	Any
Operation type	Intrinsic, Users' control
Degree of adaptability	Gradual
Trigger *(if relevant)*	Electromagnetic
Purpose	Other
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Active
BMS	Yes
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,59	U-value	-
SHGC	-	SHGC	-	SHGC	-
VLT	-	VLT	75 / 51	VLT	-
LSG	-	LSG	-	LSG	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) LCPrivacyGlass (http://www.innovativeglasscorp.com/lc-privacy)

6.3.3. OLEDs

Slightly different if compared with the other glazed technologies analyzed so far, the OLED glasses fit in this category by virtue of their ability to change over time if an electrical input is applied.
Indeed, Organic Light Emitting Diodes are a new lighting technology consisting of two glass sheets on which, during production, thin layers of hydrocarbon-based chemicals are vapor-deposited. Unlike conventional LEDs and other light sources, OLEDs are able to emit their light across the entire surface; this feature makes them the first real flat area light source.
Due to the fact that their light is roughly comparable to the natural skylight and glare-free, and that they are very thin (measuring approximately among 1 and 2 mm), OLEDs are suitable for materials so far not appropriate for lighting applications, such as glass.
These devices are mirror-like in the switched state when a layer of aluminium is used as a cathode, while when it is replaced by silver they appear transparent, so it is clear that the possibility of emitting light from a seemingly transparent glass (without a visible light source when switched off) makes this technology a unique opportunity.
Even if engineers are working on special buildings applications of these technologies, many of them – unfortunately – have not developed beyond the prototype stage, thus means they are not yet market-ready because of too high material and installation costs coupled with too short service life.

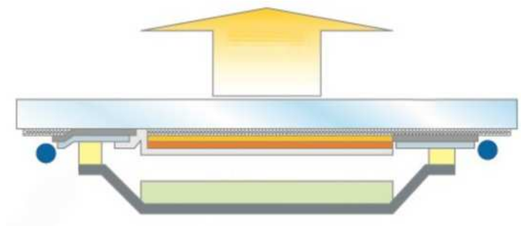


Fig. 29 – OLEDs functioning scheme.

6.3.4. Electrochromic glasses

Part of the so-called **chromogenic** devices (Granqvist, 2006; Granqvist et al., 2009 and 2010; Tavares et al., 2014; Carmody et al., 2014), electrochromic glasses are systems able to vary their light transmission properties (generally by varying their color and optical features) after the application of an electric field.

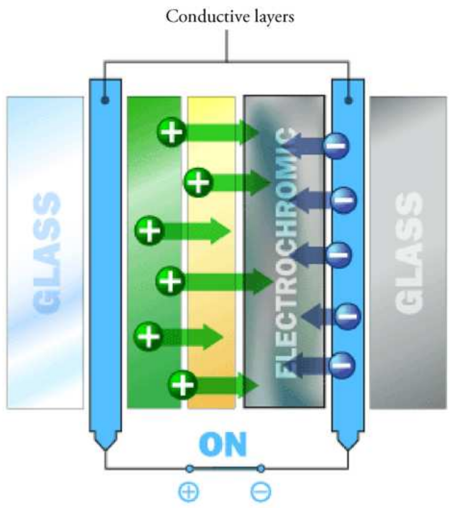


Fig. 30 – On the left: Cross-section of an electrochromic device, showing its operation mode.

Electrochromics are obtained by interposing in the gap between two glass' panes a layer of micro-liquid crystals[11], capable of ensuring reversible electrolytic reactions that, if subjected to a potential difference, can vary their coloration up to becoming transparent (Gorgolis and Karamanis, 2016).

EC systems are based on both *organic* and *inorganic* materials. Organic ECs are made of molecules that change their color during oxidation/reduction processes, while inorganic ECs are based on transition metal oxides (mostly W and Ni). Two types of metal oxides exist (cathodic and anodic) and they both are simultaneously employed in standard EC devices.

In EC systems, ions move through an electrolyte layer due to an external electric field induced between two transparent conductions (from one electrode to another); through this migration, a new state of aggregation is obtained, favoring a new glass color and modifying light-transmission of the system from about 1-4%, in the opaque state, to 60-63%, in the transparent state; the SHGC instead, stays between 0,06 and 0,46.

If, in the initial stage, crystals have a milky-white color – obstructing light-transmission through ray light deflection in different directions (by means of molecular disorder) –, after the application of an electric charge, crystals will be oriented in a different way, thus modulating system's optical behavior.

[11] Micro-liquid crystals are metals generally based on indium and silver oxide, WO_3 or MoO_3 Molybdenum Tungsten. The surface layer is applied with vacuum and physical deposit of vapors techniques (PVD).

Fig. 31 – From left to right, electrochromic windows under different operation mode.

Once the change has occurred, no electricity is needed for maintaining the shade that has been reached. Even the amount of energy required to activate these devices is minimum. Switching time of EC devices vary from seconds to minutes depending on the technologies employed and on window size as well.

Most of today available devices operate in on- or off-states only, although technologies that allow variable levels of transparency are easily applicable (Tavares et al., 2014).

Recent advancements in electrochromic materials concerning transition-metal hydride electrochromic have led to the development of reflective hybrids systems, which become reflective rather than absorbent and thus which switch state between transparent and mirror-like. These materials are based on the same concept of traditional electrochromic even if they go about the problem in a different way, that is by switching between a transparent state, when they are off, to a reflective state, when a voltage is applied.

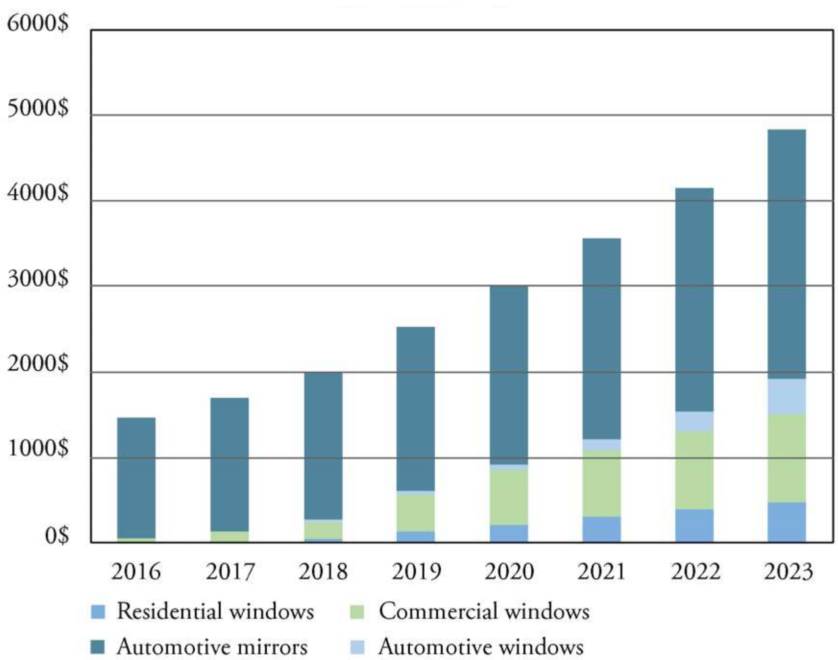


Fig. 32 – Forecasts for Electrochromic glass markets in terms of millions of dollars.

Additionally, a special type of electrochromic window has been developed at the Cockrell School of Engineering of the University of Austin, Texas (Llordés et al., 2016). This smart system employs two active electrochromic materials to choose between three different operation settings: one scenario admits the enter of light and solar radiation; another scenario blocks only infrared radiations while the last scenario prevents both light and heat entering. This is possible thanks to a double-band electrochromic material which incorporates elements for light-selective control, with different optical properties in very low switching time.
Recently, self-powered EC windows that employ PVs for being activated are under development (Cannavale et al., 2015) even if their transparency is very low due to the presence of the PV layer. These devices employ sputtered titanium and tungsten oxide films as an electrochromic layer, coupled with a photoactive layer made of dye solar cells (generally made of dye-sensitized titanium oxide – TiO_2) (Bogati et al., 2017).
Photo-electrochromic devices are able to provide a twofold behavior, being able to generate energy and, at the same time, to switch their transparency and light-transmission mode (Cannavale et al., 2016).
Despite their increasing development and appeal, these devices still lack in visual transmittance (still about 61,5% - in the bleached state - and 11,2% in the colored state).

Performance	OFF state	ON state
VLT	0,60	0,01
SHGC	0,41	0,09
U (W/m^2K)	1,59	1,59

Tab. 05 - Specifications for a commercial EC window.

Fig. 33 – First electrochromic window prototype produced by Sage.

Active | Dynamic	ELECTROCHROMIC GLASS	ID 6.3.4.

VIEW – Dynamic glass

Windows that tint in response to the variations of outdoor conditions due to the presence of nano-layers of electrochromic coating on glass' surface, able to respond to a low voltage (about 100-240 VAC), 50/60 Hz. They can adjust their tint levels on the basis of the quantity of solar radiation allowed into room depending on buildings' heat load specifications, personal preferences or, again by calculating the sun position, thanks to light sensors and real time data on weather conditions.
Their control system consists of a panel which communicates to windows within which the master controller controls all critical and interface function.

General performance

Use	All, even if mainly Service | Industry or Specialized
Climate	Any, even if mainly cooling dominant climates
Operation type	Extrinsic, Users' control
Degree of adaptability	Gradual
Trigger *(if relevant)*	Electromagnetic
Purpose	Visual performance, Thermal comfort
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Active
BMS	Yes
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,81	U-value	1,58
SHGC	-	SHGC	41 / 9	SHGC	48 / 9
VLT	-	VLT	48 / 1	VLT	60 / 1
LSG	-	LSG	1,17 / 0,11	LSG	1,25 / 0,11
Rw	-	Rw	35 dB		-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) VIEW Dynamic glass website (http://viewglass.com)

6.3.5. Thermochromic glasses

Thermocromic are glazed systems in which a temperature variation triggers a reaction in the material, giving it a high reflective capacity thus making it more sensitive towards infrared radiation. This results in a light-radiation absorption variation as a function of the external surface temperature, making these devices opaque when a critical temperature (specific for each product) is reached.

The alteration of optical properties is obtained through the modification of the molecular balance, an induced chemical reaction or through the transition of the crystalline structure.

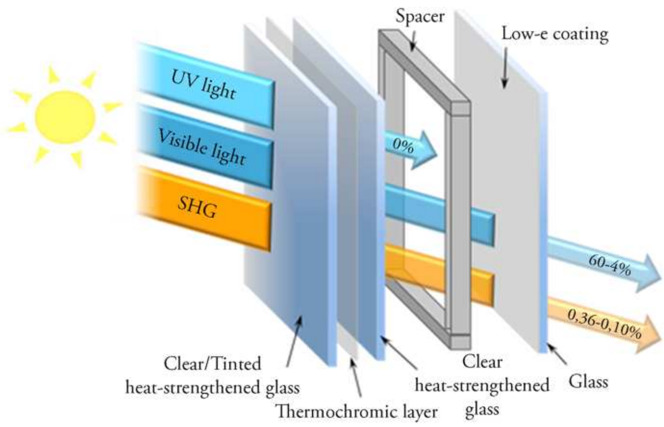


Fig. 34 (on the left) – Assembly of a commercial TC glazing.
Fig. 35 (on the right) –Thermochromic windows in the colored state.

In general, the most employed TC technology is the one that uses Tungsten trioxide or Vanadium dioxide coatings to obtain this totally reversible behavior (Hee et al., 2015). Vanadium dioxide (VO_2) is the most common material, despite its many shortcomings as the high transition temperature, comprised between 10°C and 65°C, so much higher than indoor temperatures (Li et al., 2012). To overcome these drawbacks, other materials, such as W and F, are added to VO_2 to decrease its transition temperature, or special gels are inserted between the two plastic-film layers. However, as a result, VLT of such devices is low; for this reason, anti-reflective coatings are used to increase it (Gorgolis and Karamanis, 2016).

Critical points of thermochromic technology are the non-gradual transition from transparency to opacity, as well as the vision that it produces, which seems to be not extremely clear. This feature makes thermochromic particularly suitable for applications in which visibility is not a priority, whilst is desirable privacy or a shielding effect.

To evaluate TC performance, the **solar modulation efficiency** is used (Rezaei et al., 2017); it is denoted by ΔT_{sol} that expresses the difference between the solar energy transmitted before and after the transition. Such value ranges from 0 to 1 and, for acceptable performance, it should exceed 0,1.

Performance	25 °C	65 °C
VLT	0,50	0,12
SHGC	0,29	0,13
U (W/m^{2}K)	1,36	1,36

Tab. 06 - Specifications for a Thermochromic window.

To overcome shortcomings of existing thermochromic devices, scientists of the U.S. Department of Energy's National Renewable Energy Laboratory (NERL) have developed a high-efficient window able to convert sunlight into electricity. Such a prototype employed perovskites and single-walled carbon nanotubes to respond to heat: during the transformation from transparent to tinted, the window darkens, generating electricity. The color changing is

driven by molecules (methylamine) that are reversibly absorbed into the device. When solar energy heats up the device, the molecules are driven out so it is darkened, while when the sun is not shining, the device is cooled back down, appearing transparent because the molecules re-absorb into it.
Such a device allows an average of 68% of VLT when it's in a transparent or bleached state while when the window colors, only 3% is allowed.
The aim of researchers was to develop a system able to perform a twofold behavior: from one side as solar cell – when there is a lot of solar radiation – and from the other as good window system when there is not. Results published in Nature Communications[12] showed a solar power conversion efficiency of the system of about 11,3%.
Such efforts were turned into production field within the Emerging Technologies program funded by the Department of Energy's Building Technologies Office, under the name of SwitchGlaze.

Fig. 36 –Thermochromic windows' transition during the day.

[12] Wheeler, L. et al., Switchable Photovoltaic Windows Enabled by Reversible Photothermal Complex Dissociation from Methylammonium Lead Iodide.

Fig. 37 – Application of solar responsive thermochromic glass to service industry building.

Active | Dynamic	THERMOCHROMIC GLASS	ID 6.3.5.

Sunintuitive Dynamic glass

Dynamic glasses that don't need for wires or controls due to the fact that they work only with the exposure to direct sunlight.
Indeed, thanks to the heats coming from sunlight, the thermocromic PVB layer within the glass' panes warms, tinting accordingly in a relationship of direct proportion to the intensity of the sun.
As the interlayer cools, the glass returns to a clear state.
Due to the fact that this device does not require power source nor control equipment, its installation is the same as conventional glass IGUs.

General performance

Use	All, even if mainly Service | Industry or Specialized
Climate	Any, even if mainly cooling dominant climates
Operation type	Extrinsic, Self-adjusting
Degree of adaptability	Gradual
Trigger *(if relevant)*	Thermal
Purpose	Visual performance, Thermal comfort
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,36	U-value	-
SHGC	-	SHGC	36 / 16	SHGC	-
VLT	-	VLT	54 / 8	VLT	-
LSG	-	LSG	1,5 / 0,5	LSG	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Sunintuitive glass website (https://suntuitiveglass.com)
2) Sunintuitive Technical Information brochure, available at: https://suntuitiveglass.com/wp-content/uploads/2019/01/Technical-Brochure_2019-1-1.pdf

6.3.6. Thermotropic glasses

Thermotropic glasses dynamically alter their solar and visible light transmittance and reflectance in response to window's temperature (Yao and Zhu, 2012). They differ from other types of chromogenic devices in two major aspects: they switch between a transparent and an opaque state, meaning that visibility is not retained in the "solar control" mode, and they react automatically to changes in the glazing temperature rather than being activated by an external switch. These two properties make this type of glazing particularly suitable for clerestory windows or skylights, where a direct view is not significant.

Their ability to change state is based on lower critical solution temperature (LCST) of a PCM (a two-component fluid[13]) inserted within the two glass' panes; up to a determined temperature (defined **switching** or **transition temperature**), the fluid remains in the form of a homogeneous, transparent mixture, while when it passes such temperature, it changes its configuration and, through the separation of the two components, makes the layer becoming white-opaque, reflecting and diffusing much of the light and thus decreasing the passage of light radiation. The switching process is reversible; if the outside temperature decreases below the switching temperature indeed, the glass becomes clear again.

The advantage in using such technology is that during winter it remains clear even if the sun is shining, so daylight can be maximized at its best as well as energy demands for heating and lighting can be minimized accordingly.

Thermotropic materials can be divided into different systems based on the mechanism by which they achieve a state of low visible- and solar-transmission, under the transition temperature. The three main groups are: **thermotropic hydrogels, thermotropic polymer blends** and **embedded thermotropic polymers within fixed domains**.

Recent researches (Allen et al., 2017) tried to develop and test new types of thermotropic windows where the TT layer, made of hydroxyl-propyl-cellulose (HPC), is sandwiched as a membrane between two glass' panes. Tests done on the HPC-based prototype showed that in the transparent state (below 40°C) it has VLT of 0,9 and solar transmittance of 0,75; while, above the transition temperature (over 50°C), it has VLT of 0,14 and solar transmittance of 0,11.

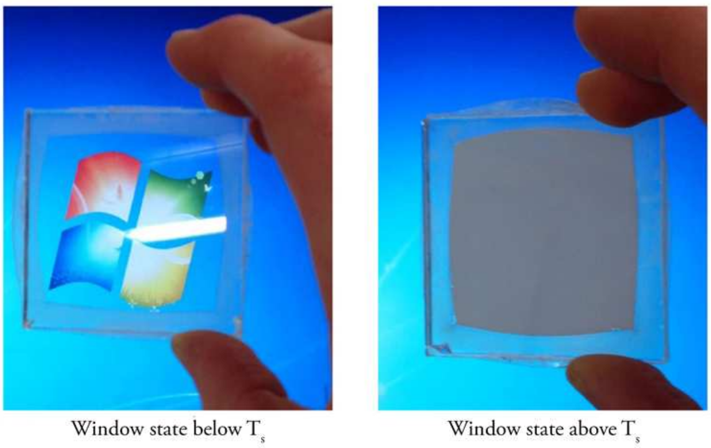


Fig. 38 – Prototype of the TT smart window developed at the University of Nottingham.

In general, it can be said that TT devices allow obtaining transmittance above the 85% in the transparent state (under the transition temperature) and below the 15% in the translucent state (above the transition temperature).

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[13] The basic mixture interposed between the glazed panes is generally composed of two components with different reflection index (e.g. water and plastic - hydrogel - different plastics - polymer mixture).

Active | Dynamic	THERMOTROPIC GLASS	ID 6.3.6.

Solardim ECO

Glass that adapts its light transmission to the external temperature: from a certain range it becomes lees clear, partly reflecting the sunlight (up to 50% depending on the level of doting); the remaining sunlight instead, enters the interior. The degree of light scattering as well as switching temperature can be varied

This technology doesn't need for electrical power source; it is very durable and compatible with existing conventional glazing system because no sealing frame are required. In addition, combination with an individual switching behavior is possible.

General performance

Use	All
Climate	Any
Operation type	Extrinsic, Self-adjusting
Degree of adaptability	Gradual
Trigger *(if relevant)*	Thermal
Purpose	Visual performance, Thermal comfort
Adaptive function *(if relevant)*	Prevent/reject
Operation mode	Passive
BMS	No
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	2,72	U-value	-
SHGC	-	SHGC	69 / 51	SHGC	-
VLT	-	VLT	90 / 35	VLT	-
LSG	-	LSG	1,3 / 0,68	LSG	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) Solardim Eco website, https://www.tilse.com/yacht-glass/solardim-eco/

2) SOLARDIM®-ECO, High Energy Savings Through A Self- Regulating Solar Protection Glazing, available at: https://www.iap.fraunhofer.de/content/dam/iap/en/documents/FB2/Solardim_ECO_Fraunhofer-IAP.pdf

6.3.7. Photochromic glasses

A particular type of chromogenic glasses which originated approximately in 1899 after the discovery of the phenomenon of discoloration of some crystalline substances, as a result of exposure to light radiation.

Photochromic glasses are capable of varying their optical properties due to external light-intensity variations by means of the presence of organic or inorganic compounds that act as optical sensitizers (Casini, 2016). The photochromic reaction indeed triggers an exchange between silver and copper ions, resulting in precipitation of silver metal which determines the coloring of the glass pane.

PCs behavior is reversible when radiation stops and this is possible thanks to the decomposition of micro-crystals of silver halide (chlorides, bromides, iodides), present in the glass paste and sensitive to UV rays.

In such systems, light transmission depends on the amount of light on glass surface because they modify their transmission-curve on the basis of the intensity, the duration and the nature of the incident solar radiation.

One of the limits of photochromic technology is the poor light-transmission during the winter season, thus decreasing SHG in internal environments.

Since photochromic glasses' coloring process is ambient-temperature-sensitive – being more intense at low temperatures and essentially null at higher temperatures – it follows that their use in buildings is very poor (Granqvist et al., 2009).

Fig. 39 – Photochromic glasses during various transition phases, from a tint one to a completely clear one.

Active | Dynamic	PHOTOCHROMIC GLASS	ID 6.3.7.

SmartGlass Dynamic

Photocromic glasses are able to darken gradually when heated from direct sunlight, automatically adjust their tint level in response to sun's intensity. Their switching process is reversible in a fully autonomous way.
However, the shortcoming of this technology is that they cannot control heat gain because often the amount of incident light on the window does not correspond to the amount of solar heat absorbed. So, for instance, the system could darken more in winter than in summer, due to the fact that sun rays may strike it more intensely due to their lower height in the sky during winter months.

General performance

Use	All
Climate	Any
Operation type	Extrinsic, Self-adjusting
Degree of adaptability	Gradual
Trigger *(if relevant)*	Optical
Purpose	Visual performance, Thermal comfort
Adaptive function *(if relevant)*	Control
Operation mode	Passive
BMS	No
Light transmission mode	Variable

Technical data

Monolithic, 6 mm		*6 mm + 12 mm Air + 4 mm*		*6 mm + 16 mm Ar + 4 mm*	
U-value	-	U-value	1,2	U-value	-
SHGC	-	SHGC	10 / 34	SHGC	-
VLT	-	VLT	6 / 60	VLT	-
LSG	-	LSG	0,6 / 1,76	LSG	-

General assessment

Performance features	
Potentiality and applicability	
Integrability with BMS	
Costs/benefits ratio	

References

1) SmartGlass Dynamic, website, available at: http://www.smart-glass.co.uk/products/smartglass-dynamic/

6.3.8. Gasochromic glasses

Glasses obtained by means of the incorporation of a gasochromic layer between two panes of an IGU (generally among the outer and the middle pane of a triple IGU), which, when exposed to diluted hydrogen gas (generally mixed with Ar gas), colors and changes system's transparency because of a catalytic reaction with the glass mixture (Wilson, 1995). The transparency level of such devices depends on the volume of hydrogen to which the gasochromic layer has been exposed. The second gas-filled cavity and the third pane, with low-emissive coating, ensure that the IGU has an Ug value of about 0,9 W/m^{2}K.

The most employed GC material is Tungsten oxide (Feng et al, 2016), coated with a thin catalyst layer, even if devices equipped with a thin layer of Wolfram are available[14]. In systems with W, the contact with a low concentration of hydrogen it's enough to confer to the panel a blue-color; when the contact occurs with oxygen instead, the film bleaches to the original transparent state.

The modification that occurs in glass transmission properties allows reducing visible and total solar energy transmittance values of a triple glazing unit from 0.63 and 0.49 to 0.20 and 0.17 respectively (when the indoor pane is coated with a standard low-E coating). If a solar-control coating is added, lower SHGC values can be obtained.

With GCs, clear visibility from inside to outside is retained in all switching states.

In contrast to conventional, external shading systems, gasochromic glazing can also be used in the upper floors of high-rise buildings even if they need of more control equipment; in addition to a gasochromic insulating glazing unit indeed, the system needs two further main components: a **gas supply unit** and a **control unit**. The gas supply unit consists of an electrolyzer and a pump, which is connected by pipes to the window in a closed-loop configuration. Ideally, the gas supply unit is integrated into the external building facade. One gas supply unit is able to provide sufficient gas to switch 10 m^2 of gasochromic glazing (Rezaei et al., 2017). The control unit instead, permits both manual and automatic control. The integration into a bus system allows the glazing to be switched, to optimize lighting conditions, thermal comfort and/or building energy consumption.

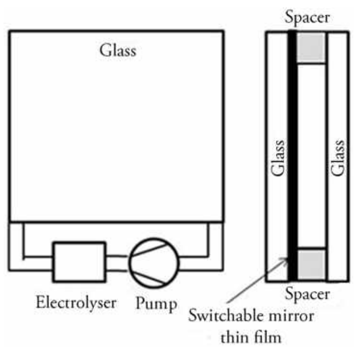


Fig. 40, on the left – Conceptual scheme that shows the operation mode of a gasochromic system.
Fig. 41, on the right – Specimen of gasochromic glass during transition phase.

[14] The optically active component of a gasochromic IGU is a film of WO_3, thick less than 1 μm, which is coated with a thin film of a catalyst. It is located on the inner surface of the outer pane of a triple IGU.

Fig. 42 – Gasochromic glass, installed at Fraunhofer ISE

6.3.9. Electrochemical glasses

Electro-chemical glasses are based on photovoltaics' technology; their functioning is ensured by the electro-chromic effect provided by titanium dioxide. Sunlight indeed, due to the photovoltaic effect, induces a current circulation within the material that causes dioxide's darkening. The opening of the circuit can be manually determined or by sensors reagent to the light intensity.

6.3.10. Electrothermal glasses

Devices obtained through the incorporation of a heatable transparent conductive film and bus bars – to activate the film – within a glass pane. Bars are connected to the edge of the conductive film, divided from them into regions.
The relative patent has been released in 2017 to Asahi Glass Company and was related to the invention of a plate for an ET window that includes a heatable transparent conductive film and multiple bus bars for feeding electric power to the transparent conductive film. When the transparent conductive film is energized, it generates heat.
These systems are still under development; to the author's knowledge indeed, current on-the-market-available devices are only addressed to the automotive sectors.

Status

on-the-market available | under development | research

Measurement unit

U-value (W/m²K) | VLT (%) | SHGC (%) | LSG | Max. dim. (mm)

	Clear float glass (6 mm thick)	Double IGU (4 | 12 | 4 mm)	Double IGU Argon (4 | 16 | 4 mm)	Triple IGU (4 | 12 | 4 | 12 | 4 mm)	Tinted glasses (IGU 6 | 12 | 6 mm)
U-value	5,8	2,8	1,2	1,5	2,8
VLT	90	80	81 (VL)	72	48
SHGC	87	70	73 (SHG)	50	41
LSG	1,03	1,14	1,10	1,44	1,17
Max. dim.	6000x3210	6000x3210	6000x3210	6000x3210	n.a.
Cost	16 €/m²	50 €/m²	65 €/m²	n.a.	200 €/m²

	Reflective glasses (6 mm thick, single pane)	Selective glasses Argon (6 | 16 | 4 mm)	Low-E glasses (IGU 6 | 12 | 6 mm)	Vacuum insulated (Pilkington Spacia)	TIM glasses (IGU– 4 | 20 | 4 mm)
U-value	5,7	1,0	1,9	1,4	0,5
VLT	31	67	53	76	70
SHGC	48	45	45	66	75
LSG	0,64	1,48	1,20	1,16	0,93
Max. dim.	6000x3210	6000x3210	3048x1778	2400x1350	n.a.
Cost	42 €/m²	148 €/m²	200 €/m²	n.a.	n.a.

	Self-cleaning glasses (Pilkington Active Clear)	Heating glasses (IGU 4 | 16 | 4 mm)	Photovoltaic glasses (IGU 4 | 12 | 4 mm)	PCM glasses (GLASSX Crystal)	LCD glasses (IGU 4 | 12 | 4 mm)
U-value	2,6	1,1	1,67	0,48	1,59
VLT	75	74	6	50-80	77-58
SHGC	71	53	12	n.a.	60
LSG	1,06	1,39	2	n.a.	~1,12
Max. dim.	n.a.	3210x2200	1000x600	2800x150	900x2600
Cost	n.a.	110 €/m²	340 €/m²	n.a.	1000 €/m²

	Electrochromic glasses	Thermochromics glasses	Thermotrophic glasses	Photochromic glasses	Gasochromic glasses
U-value	1,6	1,36	1,15	1,10	n.a.
VLT	58-1	50-12	72-23	25-62	n.a.
SHGC	41-9	29-13	48-15	22-27	n.a.
LSG	1,41-0,11	1,72-0,92	1,5	1,13-2,29	n.a.
Max. dim.	1828x3048	n.a.	n.a.	1000x2600	n.a.
Cost	n.a.	n.a.	n.a.	800 €/m²	n.a.

Fig. 43 – Comparison among mostly of Passive and Active glazing technologies investigated; performance values are referred to technologies considered in general terms and not to specific commercial products if not specified. For each technology is reported also its development status as indicated in the legend at the upper left of the image itself.

6.4. Emerging solutions

Common approaches recently adopted to improve glazing performance have fundamentally been four: the first is the traditional approach that acts on the interspace of multilayer glazing assembly (IGU), by using films, low-conductance gases or thermally improved edge spacers to improve insulation capacity of the system; the second is aimed at altering material composition (such as, for instance, what happened in tinted glazing); the third resorts to coatings application on the glass surface to modify its light reflection performance (such as selective, reflective or low-emittance coatings) while the fourth employs external inputs of various kind (whether passive or active) to change glass' optical features.
Although valid, the above-mentioned approaches still present some shortcomings; to overcome such issues, several research centres and institutes currently developed new emerging solutions. Here following are presented the most promising.

6.4.1. Bio-adaptive glasses

A new emerging family of energy generating glasses is one of the bio-adaptive glazed panels, realized employing algae bio-reactor panels (Kohlstedt, 2013).
These bio-reactors are able to produce biomasses which can subsequently be collected for energy generating purposes; at the same time, they can capture solar-thermal heat, providing an energy source used to power the building. So, solar energy can be absorbed and converted or deflected, when needed, by the semi-opaque panels. The micro-algae plants contained within the glass are continuously fed with liquid nutrients and carbon dioxide through a water circuit; sunlight aids the algae photosynthesis – driving a dynamic response to the percentage of solar shading required – making them growing until they can be harvested and used as biogas to heating water.
This technology, conceived and developed from Arup in cooperation with SSC (Strategic Science Consult of Germany), has been installed for the first time in the BIQ house during the International Building Exhibition in Hamburg in 2013. Despite this, to the author's knowledge, it's not currently spread in ordinary building applications.

Fig. 44 (pag. 301) – On the left: Arup and Slitterwerk, BIQ House - Algae Powered Building, Hamburg. On the right: microalgae panels' detail.

6.4.2. Heat insulation Solar Glass

HISG is a multi-functional glazing technology with a very promising U-value (Young et al., 2014, Cuce et al., 2014), resulted as a successful application of a transparent PV glazing.
The system, under investigation at the University of Nottingham (Cuce et al., 2016), combines several features such as power generation capacity, thermal insulation, self-cleaning and acoustic insulation properties although it is coupled with the detriment of SHG, reducing it up to 80%, and VLT (lowering it of about 7,15%), if compared to ordinary glazing.
Cuce et al. (2015) compared three typologies of conventional glazing technologies with thermal performance features of the HISG discovering that HISG has approximately a U-value of 1.10 W/m^{2}K; this means that this technology provides better performance than conventional IGUs, whereas thermal performance parameters of air-filled double glazed windows (low-E treated) and Argon filled double glazed window (low-E treated) are found to be similar.

6.4.3. Air-sandwich

Air Sandwich glazing systems are based on the idea of a set of plastic films, with spacers and air trapped in-between, used as insulation. The U-value of the glazing system resulting from the assembly of five air layers is 3,40 W/m^{2}K, while a system with seven layers allows obtaining a U-Value of 1.80 W/m^{2}K (Cuce and Riffat, 2015).

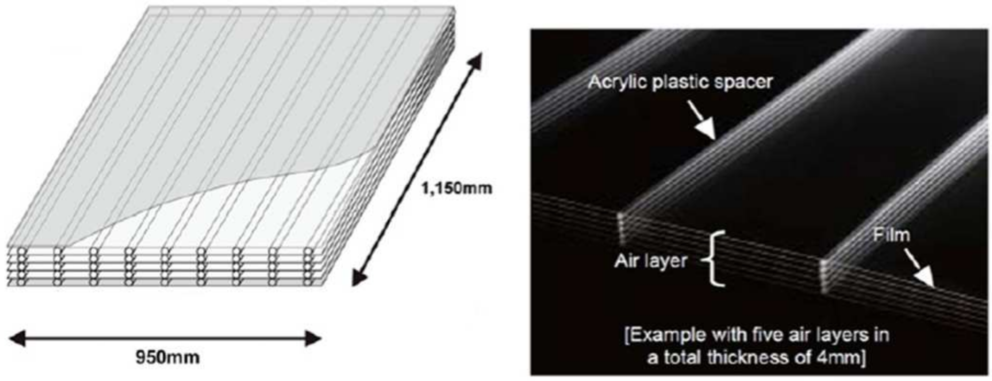


Fig. 45 – Air-sandwich prototype developed by Sekisui Company.

6.4.4. Vacuum Tube Window Technology

Vacuum Tube Window technology, early presented and discussed by Eames (2008) and Schultz and Jensen (2008), was further re-introduced by Cuce and Riffat in 2015 who developed a new concept of it that provided an optimized design suitable for new applications, such as, for instance, for existing buildings. This technology can be described as a combination of evacuated glass tubes and a glazed frame. The air-gap between tubes and glass' panes is filled with Argon.
The results obtained from the experimentations show that the thermal transmittance of these systems is a direct function of tubes' diameters, with values between 0,30 and 2,00 W/m^{2}K for diameters of 80 and 20 mm, respectively.
Therefore, Vacuum Tube Windows are cost-effective (with a cost lower than 100€ per square meter) and, with high-performance, they seem are able to mitigate energy consumption in buildings, providing an average U-value of 0,40 W/m^{2}K, with an entire thickness of 70 mm.

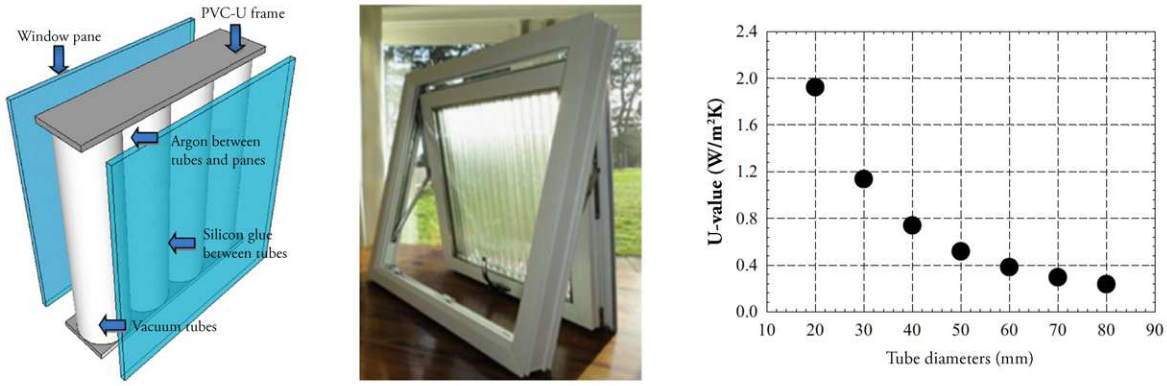
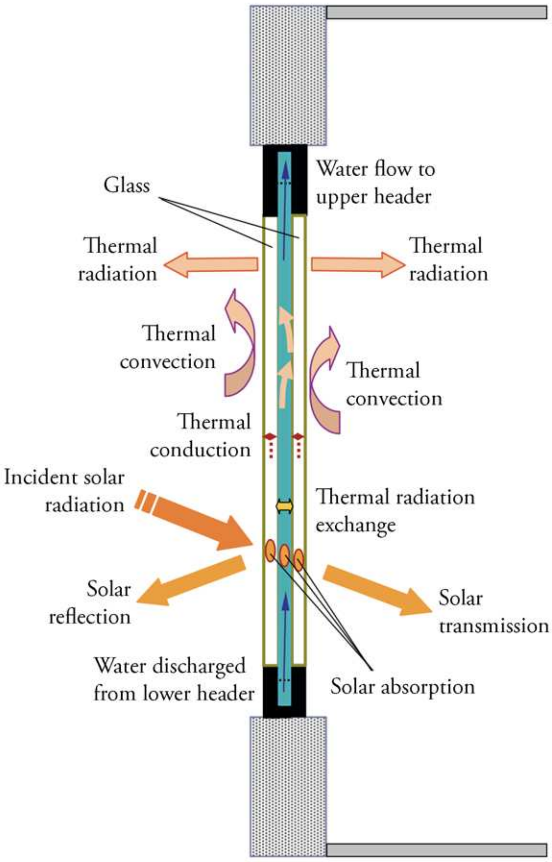


Fig. 46 – From left to right: Scheme of the Vacuum Tube Window glazing; Sample realized at the University of Nottingham; Relationship between tube diameters and system's U-Value.

6.4.5. Water-flow window



Introduced for the first time by Chow et al. (2010), Water-flow windows originated from the concept of removing the heat stored inside IGU's air-gap thanks to water flooding.
After simulations, achieved results indicate that the water flow can effectively reduce glass panes' temperature while reducing interior SGH as well as cooling energy demands.

Fig. 47 - Physical configuration and energy flow analysis of a water-flow double-pane window.

6.4.6. Solar-pond window

Solar Pond windows, developed at the University of Nottingham (Cuce and Riffat, 2015), aim to integrate into fenestration functions of lighting, heat collection, heat storage, heat preservation and photoperiod control.
They basically consist of a closed window-body equipped with transparent longitudinal sections inside. In such system, there are at least three completely isolated medium layers: the inner and the outer layers are filled with transparent thermal insulation liquid, while the interlayer is air, water or vacuum layer.
The developed prototype has air in the interlayer and an average U-value of about 0,40 W/m^{2}K (Cuce and Cuce, 2017).

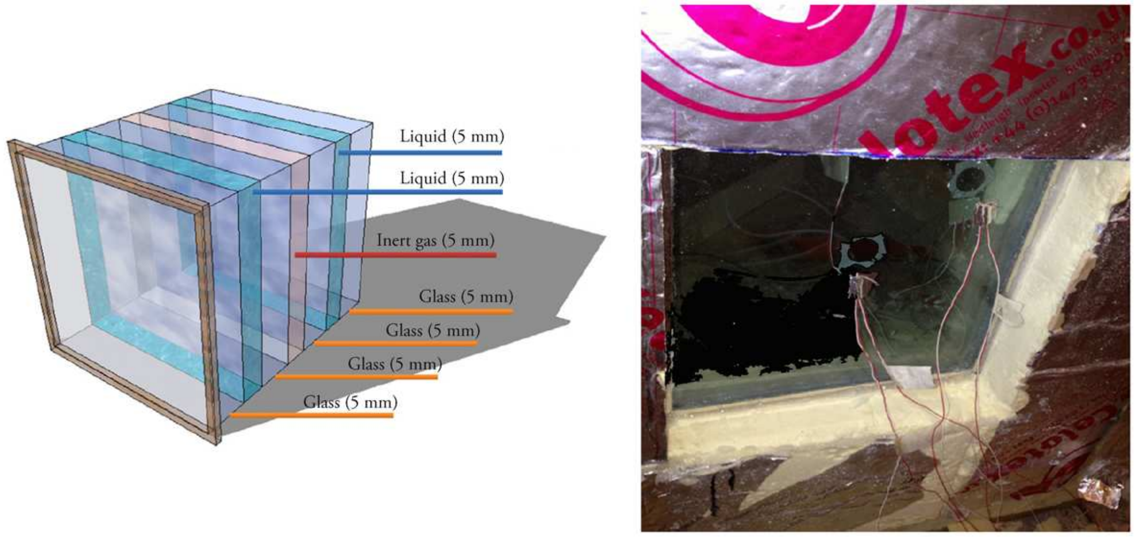


Fig. 48 – Solar Pond window technology, developed at the University of Nottingham.

6.4.7. Self-sufficient smart window

At the Nanyang Technological University of Singapore, Professor Xiaowei and his team developed a new smart window typology (Wang et al., 2014) able to regulate the amount of light that enters the buildings, varying its color from a transparent state to a blue state without adding energy electricity.
NTU's self-sufficient smart window is able to lower light penetration during the day of about 50%, going back to a transparent state during the night without energy consumption but rather producing it in surplus.
Such prototype contains a liquid electrolyte between the two glass panes, covered with Tin and Indium Oxide (ITO) commonly used in television technologies. One of the two sheets is covered with a layer of pigment called Prussian blue, while the other sheet is connected to a thin aluminium strip; these two compounds are linked with common electrical wires. When the electric circuit breaks, a chemical reaction between the Prussian blue and the electrolyte occurs, becoming the glass blue-colored, thus reducing building's energy needs for air-conditioning.

6.4.8. Electro-kinetic pixel window technology

Electro-kinetic pixel window technology, developed by researchers of the University of Cincinnati, allows to control light transmission – thanks to electro-kinetic pixels – and to fully altering color temperature of incoming visible light.
This is possible by using two electrodes which control an electrophoretic dispersion of complementary colors (usually blue/yellow in windows' applications) characterized by opposite electrical charges. The electric field created between them causes the flow of the color particles.
The interaction of light with each electrophoretic pixel (the electrodes) depends on the position of the particles in relation to them; when there are not electrodes charged and color particles are mixed in uniform dispersion the system is dark, while where the color particles are compact towards the perimeter and the lower electrode the system is clear.
By using more than two electrodes, and by altering the applied voltages between them, different color states are possible.

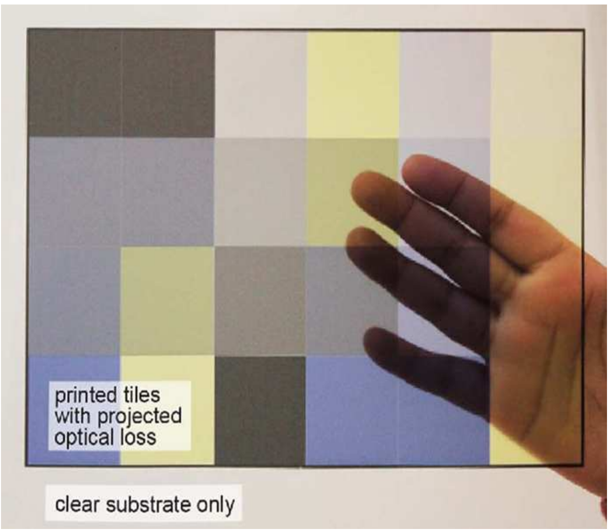


Fig. 49 – Specimen of the developed electro-kinetic pixel window technology which shows the different potential states the window tiles could operate in.

Electro-kinetic pixels can be easily integrated within IGU or applied to already existing windows by means of a roll-on coating consisting of a honeycomb of electrodes.
This patent-pending research seems able to lead to the development of low-cost window tinting, using existing e-ink technologies, that can provide a wide range of optical functionality, such as adjusting for color and brightness.

6.4.9. Elastomer-deformation tunable windows

Elastomer-deformation tunable windows are emerging glazing technology based on mechanical mechanism able to vary their state from a clear to a tinted opaque state, without blocking the diffusion of light.
This effect is produced by the insertion of a glass pane between two transparent dielectric elastomer layers, covered with a network of electrically conducting silver nanowires. Applying a voltage, the nanowires turn into electrodes moving towards each other, thus deforming the two elastomer layers. The irregular aspect of the surface due to the chaotic distribution of the nanowires determines the refraction of light and the decreasing of system's optical transmittance accordingly, leaving untouched the color of the pane.

	Smart windows' technologies			General performance											Technical data*						Assesment			
	ID	Category	Commercial product name	Status	Use	Climate	Operation	Adaptability	Trigger	Purpose	Adaptive function	Mode	BMS	Light transmission	U [W/m2K]	SHGC [%]	VLT [%]	LSG	Rw [dB]	W	1	2	3	4
Passive | Static	6.2.1	Tinted glasses	*Pilkington Arctic Blue*	Fully available	SI/Sp	T/C	not relevant	not relevant	not relevant	T/V	Prevent/Reject	Passive	No	Fixed	2,8	41	48	1,17	-	-	FAIR	FAIR	POOR	FAIR
	6.2.2	Reflective glasses	*Pilkington Reflite Clear*	Fully available	SI/Sp	T/C	not relevant	not relevant	not relevant	T/V	Prevent/Reject	Passive	No	Fixed	2,8	46	30	0,65	-	-	FAIR	FAIR	POOR	FAIR
	6.2.3	Selective glasses	*AGC Stopray Vision 60*	Fully available	SI/Sp	Any	not relevant	not relevant	not relevant	T/V	Prevent/Reject	Passive	No	Fixed	2,7	43	59	1,37	-	-	FAIR	FAIR	POOR	GOOD
	6.2.4	Low-emissive glasses	*Pilkington Optitherm*	Fully available	Any	Tr/DD/T	not relevant	not relevant	not relevant	T	Prevent/Reject	Passive	No	Fixed	1,6	59	78	1,32	-	-	GOOD	FAIR	POOR	GOOD
	6.2.5	Vacuum insulated glasses	*Pilkington Spacia*	Scarcely available	Any	Any	not relevant	not relevant	not relevant	T	Control	Passive	No	Fixed	1,1	67	78	1,16	36	-	GOOD	GOOD	POOR	FAIR
	6.2.6	TIM glasses	*Okalux Kapilux T*	Scarcely available	SI/Sp	T/C	not relevant	not relevant	not relevant	T	Control	Passive	No	Fixed	1,28	64	68	1,06	-	-	FAIR	FAIR	POOR	FAIR
	6.2.7	Self-cleaning glasses	*Pilkington Activ*	Fully available	Any	Any	Extrinsic	On/Off	Optical	other	not relevant	Passive	No	Fixed	2,7	72	76	1,06	-	-	FAIR	FAIR	POOR	GOOD
	6.2.8	Heating glasses	*WarmGlass – WG Crystal*	Fully available	Any	T/C/P	Users'Control	Gradual	Electromagnetic	T	Prevent/Reject	Active	Yes	Fixed	2,8	50	72	1,44	-	-	FAIR	GOOD	GOOD	FAIR
	6.2.9	Photovoltaic glasses	*ONYX Solar Photovoltaic*	Scarcely available	SI/Sp	Any	not relevant	not relevant	not relevant	E	Collect and Storage	Passive	Yes	Fixed	2,7	19	30	1,58	-	-	POOR	FAIR	FAIR	FAIR
Active | Dynamic	6.3.1	PCM glasses	*GlassX Crystal*	Scarcely available	Sp	T/C/P	Intrinsic	On/Off	Thermal	T	Collect/Prevent	Passive	No	Variable	0,48	33/4-37	8-28/12-44	0,84/3-1,18	-	-	FAIR	FAIR	POOR	FAIR
	6.3.2.a	SPDs	*Solar Smartglass*	Fully available	Any	Any	Intrinsic/UC	Gradual	Electromagnetic	V	Prevent/Reject	Active	Yes	Variable	1,36	39-33	22-1	0,56-0,03	37	-	FAIR	FAIR	GOOD	FAIR
	6.3.2.b	LCDs	*LC Privacy Glass*	Fully available	SI	Any	Intrinsic/UC	On/Off	Electromagnetic	other	Prevent/Reject	Active	Yes	Variable	1,59	-	75-51	-	-	-	FAIR	FAIR	GOOD	FAIR
	6.3.3	OLEDs	-	Scarcely available	SI/Sp	Any	-	On/Off	Electromagnetic	other	not relevant	Active	Yes	Variable	-	-	-	-	-	-	-	-	-	-
	6.3.4	Electrochromic glasses	*VIEW – Dynamic glass*	Scarcely available	SI/Sp	DD/T	Extrinsic/UC	Gradual	Electromagnetic	V/T	Prevent/Reject	Active	Yes	Variable	1,81	41-9	48-1	1,17-0,11	35	-	FAIR	GOOD	GOOD	FAIR
	6.3.5	Thermochromic glasses	*Suntuitive Dynamic glass*	Scarcely available	SI/Sp	DD/T	Extrinsic/SA	Gradual	Thermal	V/T	Prevent/Reject	Passive	No	Variable	1,36	36-16	54-8	1,5-0,5	-	-	FAIR	GOOD	POOR	FAIR
	6.3.6	Thermotrophic glasses	*Solardim ECO*	Develop./Protoype	Any	Any	Extrinsic/SA	Gradual	Thermal	V/T	Prevent/Reject	Passive	No	Variable	2,72	69-51	90-35	1,30-0,68	-	-	FAIR	FAIR	POOR	FAIR
	6.3.7	Photochromic glasses	*SmartGlass Dynamic*	Scarcely available	Any	Any	Extrinsic/SA	Gradual	Optical	V/T	Control	Passive	No	Variable	1,2	10-34	6-60	0,6-1,76	-	-	FAIR	FAIR	POOR	FAIR
	6.3.8	Gasochromic glasses	-	Develop./Protoype	-	-	Extrinsic/SA	Gradual	Other	V/T	Control	Passive	No	Variable	-	-	-	-	-	-	-	-	-	-
	6.3.9	Electrochemical glasses	-	Develop./Protoype	-	-	Extrinsic	Gradual	Electromagnetic	V/T	Control	Passive	Yes	Variable	-	-	-	-	-	-	-	-	-	-
	6.3.10	Electrothermal glasses	-	Develop./Protoype	-	-	Extrinsic	Gradual	Electromagnetic	V/T	Control	Passive	Yes	Variable	-	-	-	-	-	-	-	-	-	-
Emerging solutions	6.4.1	Bio-adaptive glasses	-	Develop./Protoype	-	-	not relevant	not relevant	Optical	T/V	Collect/Prevent	Passive	No	Variable	-	-	-	-	-	-	-	-	-	-
	6.4.2	Heat Insulation Solar Glass	-	Research	-	-	not relevant	not relevant	not relevant	T	Prevent/Reject	Passive	No	Fixed	-	-	-	-	-	-	-	-	-	-
	6.4.3	Air Sandwich device	-	Research	-	-	not relevant	not relevant	not relevant	T	Prevent/Reject	Passive	No	Fixed	-	-	-	-	-	-	-	-	-	-
	6.4.4	Vacuum tube window	-	Research	-	-	not relevant	not relevant	not relevant	T	Prevent/Reject	Passive	No	Fixed	-	-	-	-	-	-	-	-	-	-
	6.4.5	Water-flow window	-	Research	-	-	not relevant	not relevant	not relevant	T	Prevent/Reject	Passive	No	Fixed	-	-	-	-	-	-	-	-	-	-
	6.4.6	Solar pond window	-	Research	-	-	not relevant	not relevant	not relevant	T	Prevent/Reject	Passive	No	Fixed	-	-	-	-	-	-	-	-	-	-
	6.4.7	Self-sufficient window	-	Research	-	-	Extrinsic	Gradual	not relevant	V/T	Prevent/Reject	Passive	No	Variable	-	-	-	-	-	-	-	-	-	-
	6.4.8	Electrokinetic pixel window	-	Research	-	-	Extrinsic	Gradual	Electromagnetic	V/T	Control	Active	Yes	Variable	-	-	-	-	-	-	-	-	-	-
	6.4.9	Elastomer-def. tunable	-	Research	-	-	Intrinsic	Gradual	Electromagnetic	V/T	Control	Active	Yes	Variable	-	-	-	-	-	-	-	-	-	-

(red)	POOR
(yellow)	FAIR
(green)	GOOD

1	Performance features
2	Potentiality and applicability
3	Integrability with BMS
4	Costs/benefits ratio

Use	
SI	Service-Industry
Sp	Specialized
R	Residential

Climatic condition	
Tr	Tropical
DD	Dry/Desertic
T	Temperate
C	Continental
P	Polar

Purpose	
T	Thermal comfort
V	Visual performance
A	Acoustic comfort
E	Energy management
I	Interaction & Users' control

Fig. 50 – Summary chart of the investigated commercial products' performance. Data and consideration reported are coming from the sheets developed to conduct the analysis presented in the present chapter.
Values reported under the technical data set are referred to current widespread application of windows technologies (6mm + 12 Air + 4/6 mm)

6.5 Brief comparison and critical reasoning

Although the market offers different types of high-performance glazing systems and glass is ever more frequently enhanced with added functions to increase its whole performance response as building envelope components, smart windows and, in general, emerging technologies with outside-the-box performance are still in the early stage of development.
So far, transparent building components – even if equipped with quite high-performance – are the weakest point of building envelopes, especially in terms of thermal resistance.
In general, talking in performance terms about windows' essential features, it has to be said that to operate a real control on the criteria responsible for occupants' comfort, and building envelope performance as well, the most relevant parameters to be controlled are:

- the **heat transfer coefficient**, that has to be as lower as possible;
- the ability in modulating the total **Solar Heat Gain Coefficient**, expressed by the proportion of direct and indirect solar radiation transmitted through the glazing, and the portion of solar visible radiation transmitted through the glazing (that is the **Visible Light Transmission**).
  The VLT has to be as high as possible, even if it is associated with the increase of buildings' cooling load (Nilesh, 2016); differently, the SHGC should vary according to the external climate conditions. A high SHGC is recommended for cold climate (heating demand) in order to maximize solar gain, while a low SHGC is suggested for hot climate (cooler demand) in order to avoid overheating, especially during summer season (Kolokotsa et al., 2011).

To conclude the analysis carried out within the present chapter, some considerations on the different technologies investigated are here presented:

- Considerable researches have been invested in the development of low-energy window designs that contribute to buildings efficiency. Whilst significant progress has been made towards the development of cost-effective (super)insulating window designs, more limited progress has been made towards the development of cost-effective technologies for the control of solar heat gain.
- Most of the aforementioned technologies can reduce and control (passively or actively) light transmittance and SHGC.
- **Double** and **Triple IGUs** constitute the majority of glazed products on the market, due to their cost-effectiveness. The different types of gas inserted in the space between glass panes can significantly increase the thermal insulation performance of such products.
- Traditional **static solar-control-systems** are unsuitable for energy efficiency current requirements due to the fact that they reduce heat loads during summer – limiting glare phenomena – but they are not able to adapt to the variability of the external conditions.
- **Aerogel** and **multi-pane systems** have low overall heat-transfer coefficient; aerogel panels, in particular, have a high transmittance even if coupled with a reduced vision quality, due to the light scattering. This high transmittance in the infrared spectrum leads to an increase in cooling loads, especially in hot climates (Ihara et al., 2015).
- Most effective technologies within the domain of "static" glazing seem **Self-cleaning, Heating** and **Photovoltaic technologies** even if each of them presents some shortcomings: firsts act effectively on maintenance needs even if they are not able to operate a control on solar and visual transmittance; seconds seem able to provide a sort of control towards heat losses even if, similarly to previous ones, they do not operate a control on solar and light transmission, while thirds are generally limited in terms of

transparency, limiting – in some cases almost completely – the vision towards the outside.

- **Dynamic systems** can be effectively employed to achieve significant benefits in terms of energy efficiency, especially for climatic contexts in which the temperature variates and the weather experiences high-temperature differences. On the contrary, their high costs make them effective – in terms of cost-benefit ratio – only for great applications and/or in regions with higher energy costs, following a systemic approach (Adriaenssens et al., 2014, Xu and van Dessel, 2008).
- **Electrochromic, Suspended Particle Devices** and **Gasochromic** windows can be used in hot climates but they are not able to fully satisfy cool climate requirements; in addition, they still present too high costs for widespread applications: extra costs, if compared with traditional IGUs, are about 200 euros per square meter (Carmody et al., 2014), with a payback period between 26-33 years (DOE, 2014).
- **Thermochromic windows** with high VLT can satisfy general requirements for hot climates even if they fail in providing requirements for temperate and cool climates.
- **Photochromic glazing** has high costs; additionally, their complexity makes users unable to directly control them and to obtain a uniform distribution of substances. Another weak point of such devices is the gradual loss of process' reversibility over time.
- **Emerging solutions**, even if equipped with very interesting potentialities under several points of view, are currently at an early stage of development is only prototyped or tested in some small research reality; for this reason, they cannot be conceived as actually marketable solutions.

For all the above-mentioned reasons, fenestrations' design optimization challenge is more complex than for many other building components and systems.

Smart glass is still often neglected in architecture and buildings even though some functions would already be technically feasible.

Research is now focusing on strategies to improve windows' performance, reducing costs and favoring sensors and control-systems installation to increase operation efficiency, making them monitorable and reactive to various stimuli on the basis on predetermined inputs, quantifying at the same time benefits thus obtained.

Developing windows with reduced weight, cost and thermal features, able to control and harvest energy, is of paramount importance such they will have a high impact in the window industry.

The possibilities offered by advanced technologies presented coupled with the opportunities given by the incorporation in such systems of devices based on wireless data transmission – such as, for instance, intelligent sensors capable of detecting real-time data about environmental parameters, consumption, user behavior and operation of technical plants – make possible to concretely suppose the development of a new generation of products, even smarter than before, capable of autonomous and efficient management. Additionally, obtaining feedbacks and real-time information on fenestrations' operation will lead to more informed decision-makers and to the definition of more effective management strategies that will be reflected on a real implementation of the systems thus obtained.

	Glazing technologies	Advantages	Disadvantages
PASSIVE | STATIC GLAZING TECHNOLOGIES	**6.2.1. Tinted**	• Low glare	• Low VLT • Absorption of solar energy and release of heat into buildings.
	6.2.2. Reflective (solar control)	• Low glare • Reflection of NIRs	• Low VLT
	6.2.3. Selective	• Reduction of thermal loads in summer • Glare control	• Fixed coating without seasonal adaptability • Modification of indoor light colour
	6.2.4. Low-Emissive	• Reduced heat re-radiation by the window	• Low SHGC
	6.2.5. Vacuum insulated	• Good thermal insulation properties • Outside view • Glare control	• Not uniform light distribution • Ineffective in environment with temperatures' difference between internal and external greater than 35°C • Poor mechanical resistance
	6.2.6. TIM	• Low thermal conductivity • Glare reduction	• Lack of transparency • Fragile
	6.2.7. Self-cleaning	• High-visibility capacity maintained over time	• Low control of SHGC and VLT
	6.2.8. Heating	• No condensation in the interspace • Heat losses reduction • Outside view	• High cost if compared to traditional "static" technologies • Low control of SHGC and VLT
	6.2.9. Photovoltaic	• Solar modulation • Glare control • Self-powered	• Very low VLT
ACTIVE | DYNAMIC GLAZING TECHNOLOGIES	**6.3.1. PCM**	• Reduced building envelope thermal fluctuations	• Lack of transparency
	6.3.2.a. SPDs	• Solar modulation • Glare control • Faster responsive time • Vast transparency levels	• Need of electrical inputs for maintaining transparency levels • High electric power consumption • Relatively low SHGC • Reduction in intensity and visibility • Pretty expensive technologies
	6.3.2.b. LCDs	• Glare control	• Translucent (mainly for privacy applications) • Need of electric power for remaining transparency • Reduction in visibility • Lack of SHGC modulation: only on-off state • Limited to indoors • High cost
	6.3.4. Electrochromics	• Solar modulation • Glare control • Good switching time and low power consumption	• Still expensive • Limited modulation levels • Long response time • Need of electrical energy for very low transparent modulation • Low SHGC • Never completely opaque
	6.3.5. Thermochromics	• Reduced glare • Reduced NIRs • Reduced SHGC • Relatively low price and easy to integrated into IUGs	• Low visibility • High activation temperature
	6.3.7. Photochromics	• Seasonal adaptability • Glare control • External view • UV absorption • Solar and heat gain during winter	• Low absorption of IR • Light-colour altering • Total lack of user's control
	6.3.8. Gasochromics	• Solar modulation • Glare control • Faster responsive time • Simple layer structure	• Not fully commercial available • Need of special equipment and electrical energy for their operation

Fig. 51 – Comparison between the most frequent aforementioned glazing technologies.

ASSESSMENT AND DISCUSSION
Findings

7.1. The Tool(box)

To properly compare the glazing technologies indexed in the previous chapter, a **tool(box)** has been developed. Its final aim is to allow the set-up of a "**smart windows' configurator**" – a sort of open matrix for compiling and validating different technical solutions – for approaching design problems in complex building envelope systems, thus supporting design strategies of transparent building components within them.
The toolbox has been developed to provide a robust methodology **to asses building integration potential of technologies investigated**; its implementation started with the systematization of data gathered so far to define and resume windows' technologies main features, thus ease the understanding of their actual applications and potentialities within the smart buildings' viewpoint.
Unfortunately, not for all the technologies investigates data available are the same, especially when talking about emerging technologies or technologies still in a research state; for this reason, judgements have been supplied only concerning measurable requirements.

The toolbox developed is composed of a **balanced scorecard** and a **matrix**:

- the **balanced scorecard** born as a supporting tool, taking as example the role such tool plays in management techniques. Commonly used to translate missions and strategies in a coherent set of performance measures (to simplify their measurability), in this case, the balanced scorecard defines the set of actions to be undertaken to increase performance features of products evaluated, concerning predetermined requirements. It connects building envelope performance requirements previously identified (our strategic elements), with related objectives (what is expected in the domain of specific requirements) and the more operational elements, that are actions to be performed on the single component (continuous improvement activities) to obtain requirements' fulfilment, according to a top-down process.
  Within the scorecard, KPIs which track strategic performance, as well as targets to be reached (the desired level of performance) have been expressed. For each objective, at least one KPI should be identified and tracked to indicate progress towards a desirable outcome. They will allow to measure and monitor the progress of technologies identified toward strategic targets, determine the gap between actual and targeted performance (benchmark values from standards – basic control situation – vs. optimal strategy) thus aligning the actions to be undertaken with a shared comprehension of the objective to be reached.

Building envelope req.	Objective	Actions	KPI	Measure	Target
Performance requirements	*Description of the objective in the domain of the specific requirements*	*Action to be performed on the single components to obtain requirements' fulfilment*	*Key Performance Indicator*	*Measurement unit of the KPI*	*Benchmark value from regulations (if expected)*

Fig. 01 – Structure of the balanced scorecard built for the present dissertation; it defines the set of actions to be undertaken to increase performance features of products evaluated, concerning predetermined requirements.

- the **assessment matrix** instead, helps in systematize the measures depicted within the balanced scorecard with research objectives, to perform a Multi-Criteria Decision Analysis (MCDA). This tool aims to support designers in analysing complex situations by giving to each component analyzed a score, which considers the initial status of it based on parameters previously identified (the KPI) according to the specific requirements. Based on such assessment, the matrix recommends which kind of actions must be undertaken to overcome the simplification of traditional components.
  For each requirement, the score assigned correspond: to the **complete fulfillment** (4-5), to a **fair satisfaction** (2-3) or a **lack of compliance** (0); intermediate score could be possible as well.

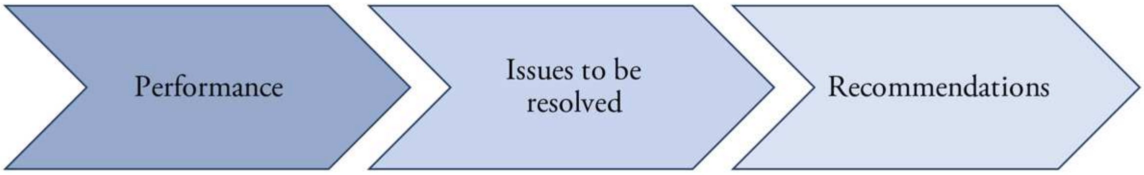


Fig. 02 – Central nucleus on which the structure of the toolbox is based.

Building envelope performance requirements	Parameters to be analyzed (KPI)	Glazing technology
		6.2.1.
THERMAL COMFORT	• Thermal transmittance • Appropriateness to the climate	5
VISUAL PERFORMANCE	• …	…
ACOUSTIC COMFORT	• …	…
ENERGY GENERATION	• …	…
…	• …	…
TOTAL SCORE		score

Tab. 01 – Structure of the assessment matrix built for the present dissertation; it helps in systematize the measures depicted within the balanced scorecard with research objectives, giving each component a score. Based on such assessment, the matrix recommends which kind of actions must be undertaken to overcome the simplification of traditional components.

Based on the global score achieved by each technology examined, the matrix will help in defining thresholds of intervention (operative solutions) to increase its global performance.
Three thresholds of intervention have been identified: **heavy**, which means that a hard intervention is needed, **medium**, which means that a soft intervention is needed and **ligh**t, which means that a low intervention is needed. A total score lower or equal to 10 correspond to the heavy threshold, which means that a **hard intervention** is needed; a global score comprised among 11 and 19 correspond to the medium threshold, which means that **soft intervention** is needed while a global score higher than 20 correspond to the light threshold, meaning that a **low intervention** is needed.

In general terms, for each threshold of intervention, suggestions regarding performance requirements that need for implementation have been here provided:

Building envelope performance requirements	THRESHOLD OF INTERVENTIONS		
	Heavy	Medium	Light
Thermal comfort	Total window's replacement (e.g. with double glazing or more performant IGU).	Frame's replacement with thermally broken frames. Draught proofing.	Draught proofing. Secondary glazing treatments (such as windows' tints and films).
Visual performance	Glass' replacement.	Secondary glazing treatments (such as windows' tints and films).	Shading devices
Acoustic comfort	Total windows' replacement.	Glass' replacement.	Acoustic devices.
Energy generation	Total windows' replacement.	BEMS' insertion.	Setting of optimized operational scenarios through BAS.
Interaction & users control	Total windows' replacement.	BMS' insertion.	

Fig. 03 – Suggestion regarding performance implementation needed about each threshold of intervention

7.1.1. Balanced scorecard

Building envelope req.	Objective	Actions	KPI	Measure	Target
Thermal comfort	to ensure an adequate level of thermal comfort avoiding significant heat losses through transparent building components.	• number of glass' panes • type of gas in the interspace • installing • thickness of the air gap • corrective within the interspace	Thermal Transmittance [U]	W/m²K	**Basic control situation** 1,5 ≤ u ≤ 2 **Optimal strategy** 1 ≤ u ≤ 1,5
Visual performance	to ensure an appropriate level of natural lightening within confined spaces avoiding undesired glare phenomena thus maintaining, where appropriate, the view towards outside.	• presence of shading devices • coatings • special treatments to modify optical or transmission features	Solar Control [SHGC] Light Transmission [VLT]	%	**Basic control situation** SHGC ≥ 40 | VLT ≥ 70 **Optimal strategy** SHGC ≤ 30 | VLT ≤ 60
Acoustic comfort	to ensure an adequate level of acoustic comfort preventing undesired noise especially in frail context of for particular intended uses.	• presence of shading devices • gas in the interspace • special treatments	Sound Insulation Capacity [Rw]	dB	**Basic control situation** Rw = 40 dB **Optimal strategy** Rw ≤ 38 dB
Energy generation	(if relevant) to produce energy without compromising basic functionalities of transparent building components.	• equipment or special devices	Power generated	W	
Interaction & users control	to allow users to interact and control the device installed under several point of view	• integration with BMS			
Performance requirements	*Description of the objective in the domain of the specific requirements*	*Action to be performed on the single components to obtain requirements' fulfilment*	*Key Performance Indicator*	*Measurement unit of the KPI*	*Benchmark value from regulations (if expected)*

Fig. 04 – Balance scorecard filled with data coherent with the purposes of the present dissertation; it defines the set of actions to be undertaken to increase performance features of products evaluated, in relation to predetermined requirements, connecting building envelope performance requirements previously identified (our strategic elements), with related objectives (what is expected in the domain of specific requirements) and the more operational elements, that are actions to be performed on the single component (continuous improvement activities) to obtain requirements' fulfilment, according to a top-down process.

7.1.2. Assessment matrix

Building envelope performance requirements	Parameters (criteria) to be analized (KPI)	Passive | Static glazing technologies								
		6.2.1.	6.2.2.	6.2.3.	6.2.4.	6.2.5.	6.2.6.	6.2.7.	6.2.8.	6.2.9.
THERMAL CONTROL	• Thermal transmittance • Appropriateness to the climate	3	3	3	5	5	5	3	5	3
VISUAL PERFORMANCE	• SHGC • VLT	3	2	5	4	4	0	3	4	1
ACOUSTIC COMFORT	• Rw	3	3	3	3	3	4	3	3	3
ENERGY GENERATION	• W	0	0	0	0	0	0	0	3	3
INTERACTION & USERS' CONTROL	• Trigger • Integration with BMS	0	0	0	0	0	0	0	4	0
TOTAL SCORE		9	8	11	12	12	9	9	19	10

Building envelope performance requirements	Parameters (criteria) to be analized (KPI)	Active | Dynamic glazing technologies										
		6.3.1.	6.3.2.a	6.3.2.b	6.3.3.	6.3.4	6.3.5.	6.3.6.	6.3.7.	6.3.8.	6.3.9.	6.3.10.
THERMAL CONTROL	• Thermal transmittance • Appropriateness to the climate	5	3	3	-	3	3	2	3	3	-	-
VISUAL PERFORMANCE	• SHGC • VLT	1	4	2	-	4	4	3	2	2	-	-
ACOUSTIC COMFORT	• Rw	3	4	3	-	3	3	3	3	3	-	-
ENERGY GENERATION	• W	0	0	0	-	0	0	0	0	0	-	-
INTERACTION & USERS' CONTROL	• Trigger • Integration with BMS	0	4	4	-	5	0	0	0	0	-	-
TOTAL SCORE		9	15	12	-	15	10	8	8	8	-	-

Building envelope performance requirements	Parameters (criteria) to be analized (KPI)	Emerging solutions								
		6.4.1.	6.4.2.	6.4.3.	6.4.4.	6.4.5.	6.4.6.	6.4.7.	6.4.8.	6.4.9.
THERMAL CONTROL	• Thermal transmittance • Appropriateness to the climate	5	4	3	4	4	4	3	3	3
VISUAL PERFORMANCE	• SHGC • VLT	1	1	1	1	3	3	4	4	4
ACOUSTIC COMFORT	• Rw	4	4	0	0	4	4	0	0	0
ENERGY GENERATION	• W	3	3	0	0	0	0	0	0	0
INTERACTION & USERS' CONTROL	• Trigger • Integration with BMS	0	0	0	0	0	0	3	4	4
TOTAL SCORE		13	12	4	5	11	11	10	11	11

*Values reported are referred to current widespread application (6mm + 12 Air + 4/6 mm)

SCORE:	
Complete fulfillment	4 - 5
Fair satisfaction	2 - 3
Lack of compliance	0

THRESHOLD:	
HEAVY	≤ 10
MEDIUM	11 - 18
LIGHT	19 - 24

Fig. 05 – Assessment matrix completed with data related to technologies investigated within previous chapters. Each technology has been assessed through a synthetic score which expresses its compliance with specific building envelope requirements. On the basis of the global score achieved by each technology examined, the matrix helps in defining thresholds of intervention to increase windows' technology global performance. Three thresholds of intervention have been identified and, for each of them, suggestions regarding performance requirements that need of implementation have been provided in Fig. 03.

7.2. SWC' s structure and workflow

The final item of the tool(box) introduced so far is the so-called (in a non-exhaustive way) "smart windows' configurator". It has been conceived like a sort of open matrix useful to help in compiling and validating different technical solutions, supporting the design of transparent building components towards the improvement of building envelope performance, fostering their conscious and effective integration within complex systems.

The methodology followed to conceive the "smart windows' configurator" starts with the work of cataloguing of smart windows' technologies done within the previous chapter, to understand their strengths and weaknesses thus to be aware of what specific implementation they need. Moreover, the analysis conducted on the case-studies, and more in general, on the reduced sampled of those attributable to the specific field of investigation of the present research, has allowed gathering data on the use of smart advanced technologies, monitoring systems, use of performance foils or coatings able to equip Transparent Building Components (TBC) with new unconventional features, helping in fine-tune the attention towards more common critical issues when dealing with the design of TBC. The "smart features" that emerged from such analysis have been drawn off this tool, providing useful sparks for the definition of parameters as well as for the elaboration of outcome strategies coming from the present configurator.

So, the second step for the SWC's definition has been the development of the toolbox of which such configurator is part of, based on the synergy among itself and the previously developed balance scorecard and assessment matrix (see the previous paragraph).

In the end, the third and last step concerned the fine-tuning of the tool workflow, according to the expected results, thus the actual development of the configurator, in the form of an open matrix.

Essentially, the configurator structure is based on the flowchart depicted in **Fig. 01** which provides for some input data to be assumed as starting point; then, the matrix helps in systematizing them with performance and technical data gathered so far concerning windows' technologies about specific building envelope performance requirements, giving – for each of them – a synthetic judgement.

Afterwards, concerning this assessment, output data are provided, related to possible alternative strategies to solve shortcoming identified, thus supplying possible technical solutions towards the implementation of the abovementioned requirements.

Therefore, such tool aims to provide, for each scenario hypothesized, a set of viable options to be applied.

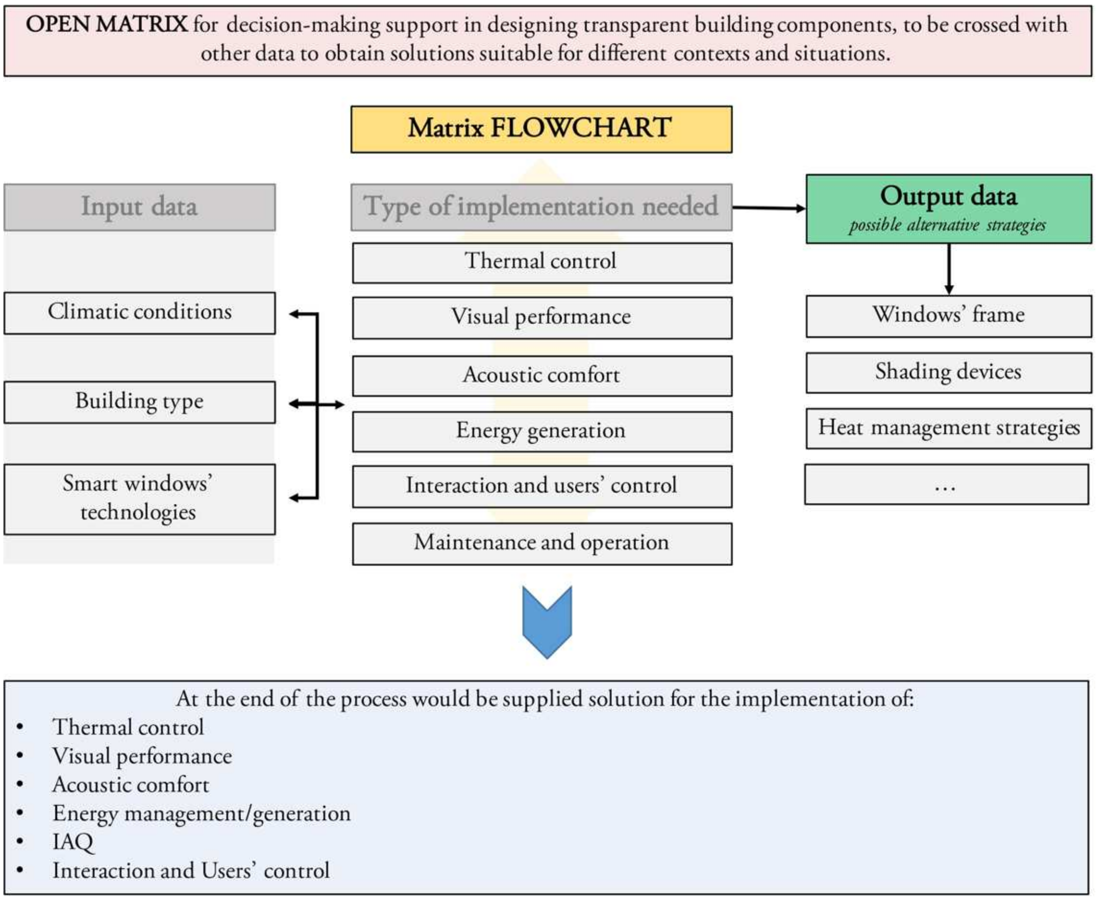


Fig. 06 – Flowchart for the design of the smart windows' configurator. The configurator's structure is based on some input data to be assumed as a starting point (in this specific case: climatic conditions, building type and smart windows 'technologies) to be crossed with performance and technical data gathered so far about specific building envelope performance requirements, to obtain as output data possible alternative strategies for each of them.

Input data on which the smart windows' configurator relies on – that are reported in the vertical column of the matrix (on the x-axis) – are:
1) **climate conditions**, as defined in Chapter 4 of the present dissertation in accordance with Köppen Climate Classification, that are Tropical (Tr) / Dry-Desertic (DD) / Temperate (Tp) / Continental (C) / Polar (P);
2) **building intended use**, distinguishing among residential building (R), service / industry building (SI) and specialized building (Sp);
3) **smart windows' technologies**, referring to the technologies investigated in Chapter 6. Within this selection, emergent solutions have been excluded due to their extremely experimental nature that made very difficult data collection on their performance.
On the horizontal line instead, have been depicted **building envelope performance requirements**, as defined in previous chapters, regrouped within the following "families": *a*) thermal control, *b*) visual performance, *c*) acoustic comfort, *d*) energy generation, *e*) interaction & users 'control and *f*) maintenance & operation.
For each combination among the climatic condition of the surrounding, the type of buildings on which the technology has to be applied, the selected technology and the specific requirements, the configurator gives a judgement able to depict in a synthetic way technology's behaviour towards each requirement (● poor / ● ● fair / ● ● ● good) and, respectively, an output strategy for its implementation. Such advice can be single, thus means referred to a single specific requirement [e.g. **TrRA1**, which refers to the recommendation for the implementation of thermal performance (*a*) of a tinted glazed technology (*1*) installed in a residential building (*R*) in tropical climate condition (*Tr*)] or general, thus means referred to the whole

implementation of the technology selected towards building envelope performance [e.g. TrR1, which refers to the recommendation for the implementation – in general terms – of a tinted glazed technology (*1*) installed in a residential building (*R*) in tropical climate condition (*Tr*)].

		TYPE OF IMPLEMENTATION NEEDED						
INPUT DATA		Thermal control	Visual performance	Acoustic comfrort	Energy generation	Interaction & users' control	Maintanance & operation	TOTAL
Climate conditions	Tr							
Building type	R							
Smart windows' technologies	*6.2.1.*	TrRA1	TrRB1	TrRC1	TrRD1	TrRE1	TrRF1	TrR1
	6.2.2.	TrRA2	TrRB2	TrRC2	TrRD2	TrRE2	TrRF2	TrR2
	6.2.3.	TrRA3	TrRB3	TrRC3	TrRD3	TrRE3	TrRF3	TrR3
	6.2.4.	TrRA4	TrRB4	TrRC4	TrRD4	TrRE4	TrRF4	TrR4
	6.2.5.	TrRA5	TrRB5	TrRC5	TrRD5	TrRE5	TrRF5	TrR5
	6.2.6.	TrRA6	TrRB6	TrRC6	TrRD6	TrRE6	TrRF6	TrR6
	6.2.7.	TrRA7	TrRB7	TrRC7	TrRD7	TrRE7	TrRF7	TrR7
	6.2.8.	TrRA8	TrRB8	TrRC8	TrRD8	TrRE8	TrRF8	TrR8
	6.2.9.	TrRA9	TrRB9	TrRC9	TrRD9	TrRE9	TrRF9	TrR9
	6.3.1.	TrRA10	TrRB10	TrRC10	TrRD10	TrRE10	TrRF10	TrR10
	6.3.2.a.	TrRA11	TrRB11	TrRC11	TrRD11	TrRE11	TrRF11	TrR11
	6.3.2.b.	TrRA12	TrRB12	TrRC12	TrRD12	TrRE12	TrRF12	TrR12
	6.3.3.	TrRA13	TrRB13	TrRC13	TrRD13	TrRE13	TrRF13	TrR13
	6.3.4.	TrRA14	TrRB14	TrRC14	TrRD14	TrRE14	TrRF14	TrR14
	6.3.5.	TrRA15	TrRB15	TrRC15	TrRD15	TrRE15	TrRF15	TrR15
	6.3.6.	TrRA16	TrRB16	TrRC16	TrRD16	TrRE16	TrRF16	TrR16
	6.3.7.	TrRA17	TrRB17	TrRC17	TrRD17	TrRE17	TrRF17	TrR17
	6.3.8.	TrRA18	TrRB18	TrRC18	TrRD18	TrRE18	TrRF18	TrR18
	6.3.9.	TrRA19	TrRB19	TrRC19	TrRD19	TrRE19	TrRF19	TrR19
	6.3.10.	TrRA20	TrRB20	TrRC20	TrRD20	TrRE20	TrRF20	TrR20

•	Bad
••	Fair
•••	Good

Smart windows' technologies	
6.2.1.	Tinted
6.2.2.	Reflective
6.2.3.	Selective
6.2.4.	Low-emissive
6.2.5.	Vacuum insulated
6.2.6.	TIM
6.2.7.	Self-cleaning
6.2.8.	Heating
6.2.9.	Photovoltaic
6.3.1.	PCM
6.3.2.a.	SPD
6.3.2.b.	LCD
6.3.3.	OLEDs
6.3.4.	Electrochromic
6.3.5.	Thermochromic
6.3.6.	Thermotrophic
6.3.7.	Photochromic
6.3.8.	Gasochromic
6.3.9.	Electrochemical
6.3.10.	Electrothermal

Climate conditions	
Tr	Tropical
DD	Dry-Desertic
Tp	Temperate
C	Continental
P	Polar

Building type	
R	Residential
SI	Service|Industry
Sp	Specialized

Fig. 07 – Structure of the smart windows' configurator for the first combination (Tropical climate condition, Residential building). On the x-axis are reported input data on which the configurator relies on, while on the horizontal line are depicted building envelope performance requirements.
For each combination, a judgement is provided – in consideration of technical data reported within the assessment matrix – able to depict in a synthetic way technology's behavior towards each requirement. Respectively, the code that refers to the output strategy for its implementation is depicted. At the end of each line instead, is given the code correspondent to the suggestion related to the whole implementation of the technology selected towards building envelope performance.

For synthesis purposes, in the present dissertation, only the combinations related to the Temperate climatic condition (Tp) and referred to Service / Industry buildings (SI) are taken in consideration, because identified as the most frequent within the case-studies' analysis performed within Chapter 4.
Moreover, particular attention is pointed towards the technologies that obtained the lower score within the assessment matrix, for which, specifically, output strategies have been provided.
For the same reason, final outputs are only provided in general terms due to their ability to comprehend even issues related to single requirements. They combine a set of viable configurations able to inform options for optimal integration of the technical systems identified, thus becoming useful guidelines to help designers in choosing possible alternatives to overcome shortcomings of the selected technological solutions.

7.3. The Smart Windows' Configurator

		TYPE OF IMPLEMENTATION NEEDED												
INPUT DATA		Thermal control		Visual performance		Acoustic comfrot		Energy generation		Interaction & users' control		Maintanance & operation		TOTAL
Climate conditions	Tp													
Building type	SI													
Smart windows' technologies	*6.2.1.*	••	TpSIA1	••	TpSIB1	••	TpSIC1	•	TpSID1	•	TpSIE1	••	TpSIF1	**TpSI1**
	6.2.2.	••	TPSIA2	••	TpSIB2	••	TpSIC2	•	TpSID2	•	TpSIE2	••	TpSIF2	**TpSI2**
	6.2.3.	••	TpSIA3	•••	TpSIB3	••	TpSIC3	•	TpSID3	•	TpSIE3	••	TpSIF3	**TpSI3**
	6.2.4.	•••	TpSIA4	•••	TpSIB4	••	TpSIC4	•	TpSID4	•	TpSIE4	••	TpSIF4	**TpSI4**
	6.2.5.	•••	TpSIA5	•••	TpSIB5	••	TpSIC5	•	TpSID5	•	TpSIE5	••	TpSIF5	**TpSI5**
	6.2.6.	•••	TpSIA6	•	TpSIB6	•••	TpSIC6	•	TpSID6	•	TpSIE6	••	TpSIF6	**TpSI6**
	6.2.7.	••	TpSIA7	••	TpSIB7	••	TpSIC7	•	TpSID7	•	TpSIE7	••	TpSIF7	**TpSI7**
	6.2.8.	•••	TpSIA8	•••	TpSIB8	••	TpSIC8	••	TpSID8	•••	TpSIE8	••	TpSIF8	**TpSI8**
	6.2.9.	••	TpSIA9	•	TpSIB9	••	TpSIC9	••	TpSID9	•	TpSIE9	••	TpSIF9	**TpSI9**
	6.3.1.	•••	TpSIA10	•	TpSIB10	••	TpSIC10	•	TpSID10	•	TpSIE10	••	TpSIF10	**TpSI10**
	6.3.2.a.	••	TpSIA11	•••	TpSIB11	••	TpSIC11	•	TpSID11	•••	TpSIE11	••	TpSIF11	**TpSI11**
	6.3.2.b.	••	TpSIA12	••	TpSIB12	••	TpSIC12	•	TpSID12	•••	TpSIE12	••	TpSIF12	**TpSI12**
	6.3.4.	••	TpSIA13	•••	TpSIB13	••	TpSIC13	•	TpSID13	•••	TpSIE13	••	TpSIF13	**TpSI13**
	6.3.5.	••	TpSIA14	•••	TpSIB14	••	TpSIC14	•	TpSID14	•	TpSIE14	••	TpSIF14	**TpSI14**
	6.3.6.	••	TpSIA15	••	TpSIB15	••	TpSIC15	•	TpSID15	•	TpSIE15	••	TpSIF15	**TpSI15**
	6.3.7.	••	TpSIA16	••	TpSIB16	••	TpSIC16	•	TpSID16	•	TpSIE16	••	TpSIF16	**TpSI16**
	6.3.8.	••	TpSIA17	••	TpSIB17	••	TpSIC17	•	TpSID17	•	TpSIE17	••	TpSIF17	**TpSI17**

•	Bad
••	Fair
•••	Good

Smart windows' technologies	
6.2.1.	Tinted
6.2.2.	Reflective
6.2.3.	Selective
6.2.4.	Low-emissive
6.2.5.	Vacuum insulated
6.2.6.	TIM
6.2.7.	Self-cleaning
6.2.8.	Heating
6.2.9.	Photovoltaic
6.3.1.	PCM
6.3.2.a.	SPD
6.3.2.b.	LCD
6.3.3.	OLEDs
6.3.4.	Electrochromic
6.3.5.	Thermochromic
6.3.6.	Thermotrophic
6.3.7.	Photochromic
6.3.8.	Gasochromic
6.3.9.	Electrochemical
6.3.10.	Electrothermal

Climate conditions	
Tr	Tropical
DD	Dry-Desertic
Tp	Temperate
C	Continental
P	Polar

Building type	
R	Residential
SI	Service|Industry
Sp	Specialized

Fig. 08 – Section of the smart windows' configurator considered in the present dissertation related to the combination for Service / Industry buildings (SI) in Temperate climate condition (Tp). For each technology examined[1], a judgement able to depict in a synthetic way technology's behavior towards each requirement is provided; clearly, it does not refer to commercial products investigated within Chapter 6, but rather it is based on the general description of technologies investigated, analyzed qualitatively, anyway enriched by knowledge acquired thanks to commercial products' analysis.
For each combination, the configurator gives an output strategy for the implementation of the specific window technology investigated, supporting the design of transparent building components thus fostering their integration within complex systems.
Such suggestion can be single, thus mean referred to a single specific requirement (e.g. TrRA1) or general, thus means referred to the whole implementation of the technology selected towards building envelope performance (e.g. TrR1).

Here following are presented the output strategies for the reduced sample considered for the present dissertation; as stated before, only combinations related to the Temperate climate condition (Tp) and referred to Service / Industry buildings (SI) are taken in consideration, as the most frequent within the case-studies analysis performed in Chapter 4.

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[1] *Emerging technologies, elechtrochemical and elechtrothermal technologies have been excluded due to their extremely experimental nature, thus for the impossibility to gather data on their performance and behaviors to elaborate further critical considerations.*

For synthesis purposes, within this framework, final considerations are provided in general terms only for technologies that obtained the lower score within the assessment matrix (**Fig. 04** and **05**) (see paragraph *6.6. Evaluation tools*), which means lower than 10, that are, specifically: tinted, reflective, TIM, Self-Cleaning, PCM, Thermotrophic, Photochromic and Gasochromic.

Building envelope performance requirements	Parameters (criteria) to be analized (KPI)	Passive | Static glazing technologies									Active | Dynamic glazing technologies										
		6.2.1.	6.2.2.	6.2.3.	6.2.4.	6.2.5.	6.2.6.	6.2.7.	6.2.8.	6.2.9.	6.3.1.	6.3.2.a	6.3.2.b	6.3.3.	6.3.4	6.3.5.	6.3.6.	6.3.7.	6.3.8.	6.3.9.	6.3.10.
THERMAL CONTROL	• Thermal transmittance • Appropriateness to the climate	3	3	3	5	5	5	3	5	3	5	3	3	-	3	3	2	3	3	-	-
VISUAL PERFORMANCE	• SHGC • VLT	3	2	5	4	4	0	3	4	1	1	4	2	-	4	4	3	2	2	-	-
ACOUSTIC COMFORT	• Rw	3	3	3	3	3	4	3	3	3	3	4	3	-	3	3	3	3	3	-	-
ENERGY GENERATION	• W	0	0	0	0	0	0	0	3	3	0	0	0	-	0	0	0	0	0	-	-
INTERACTION & USERS' CONTROL	• Trigger • Integration with BMS	0	0	0	0	0	0	0	4	0	0	4	4	-	5	0	0	0	0	-	-
TOTAL SCORE		9	8	11	12	12	9	9	19	10	9	15	12	-	15	10	8	8	8	-	-

Fig. 09 – Shred of the assessment matrix with enlightened the windows' technologies for which output strategies are provided; the selected technologies are those that obtained the lower score (lower than 10), thus for which a heavy intervention is needed.

INPUT DATA		TYPE OF IMPLEMENTATION NEEDED												
		Thermal control		Visual performance		Acoustic comfrort		Energy generation		Interaction & users' control		Maintanance & operation		TOTAL
Climate conditions	Tp													
Building type	SI													
Smart windows' technologies	*6.2.1.*	••	TpSIA1	••	TpSIB1	••	TpSIC1	•	TpSID1	•	TpSIE1	••	TpSIF1	**TpSI1**
	6.2.2.	••	TPSIA2	••	TpSIB2	••	TpSIC2	•	TpSID2	•	TpSIE2	••	TpSIF2	**TpSI2**
	6.2.3.	••	TpSIA3	•••	TpSIB3	••	TpSIC3	•	TpSID3	•	TpSIE3	••	TpSIF3	**TpSI3**
	6.2.4.	•••	TpSIA4	•••	TpSIB4	••	TpSIC4	•	TpSID4	•	TpSIE4	••	TpSIF4	**TpSI4**
	6.2.5.	•••	TpSIA5	•••	TpSIB5	••	TpSIC5	•	TpSID5	•	TpSIE5	••	TpSIF5	**TpSI5**
	6.2.6.	•••	TpSIA6	•	TpSIB6	•••	TpSIC6	•	TpSID6	•	TpSIE6	••	TpSIF6	**TpSI6**
	6.2.7.	••	TpSIA7	••	TpSIB7	••	TpSIC7	•	TpSID7	•	TpSIE7	••	TpSIF7	**TpSI7**
	6.2.8.	•••	TpSIA8	•••	TpSIB8	••	TpSIC8	••	TpSID8	•••	TpSIE8	••	TpSIF8	**TpSI8**
	6.2.9.	••	TpSIA9	•	TpSIB9	••	TpSIC9	••	TpSID9	•	TpSIE9	••	TpSIF9	**TpSI9**
	6.3.1.	•••	TpSIA10	•	TpSIB10	••	TpSIC10	•	TpSID10	•	TpSIE10	••	TpSIF10	**TpSI10**
	6.3.2.a.	••	TpSIA11	•••	TpSIB11	••	TpSIC11	•	TpSID11	•••	TpSIE11	••	TpSIF11	**TpSI11**
	6.3.2.b.	••	TpSIA12	••	TpSIB12	••	TpSIC12	•	TpSID12	•••	TpSIE12	••	TpSIF12	**TpSI12**
	6.3.4.	••	TpSIA13	•••	TpSIB13	••	TpSIC13	•	TpSID13	•••	TpSIE13	••	TpSIF13	**TpSI13**
	6.3.5.	••	TpSIA14	•••	TpSIB14	••	TpSIC14	•	TpSID14	•	TpSIE14	••	TpSIF14	**TpSI14**
	6.3.6.	••	TpSIA15	••	TpSIB15	••	TpSIC15	•	TpSID15	•	TpSIE15	••	TpSIF15	**TpSI15**
	6.3.7.	••	TpSIA16	••	TpSIB16	••	TpSIC16	•	TpSID16	•	TpSIE16	••	TpSIF16	**TpSI16**
	6.3.8.	••	TpSIA17	••	TpSIB17	••	TpSIC17	•	TpSID17	•	TpSIE17	••	TpSIF17	**TpSI17**

Fig. 10 – Shred of the smart windows' configurator with enlightened the configurations for which output strategies are provided.

OUTPUT STRATEGIES

Before providing general output strategies for each technology identified; some brief considerations about the specific combination under examination are needed.

First of all, it is worth remembering that glass' performance in temperate climate **must ensure solar control** thus **reducing overheating during summer**, **allowing a high visual transmittance** and **maintaining** – where possible – **benefits of passive solar heating**. Then, VLT and energy transmission can be higher than those requested in hot climate conditions.

To allow passive solar strategies, the **performance range** for each value should be:

- VLT among 35% and 90% (and ideally around 70%),
- SHGC among 20% and 70% (ideally around 50%),
- U value among 1 and 2 W/m^2K (anyway lower than 2,5 W/m^2K) with respect of specific local regulations on the subject.

Such recommendations must be evaluated with the specific application contexts.

TpSI1	***Tinted*** *Tinted glazing have generally different coloration (grey, green, bronzed or blue are the most common) obtained directly within the vitreous paste; their solar control properties and their chromatic tone vary according to pane's thickness while their reflective ability is slightly low than those of clear float glass.* Thermal control | Quite low if relying only on the ability of the single glass pane; the tinted mass indeed, can block more light than heat thus means that they can reduce only minimally cooling load (significant in temperate climate conditions). Instead, if employed in IGU their insulation ability increase. In these solutions, the tinted glass should face the outside so as it can dissipate more easily the absorbed radiation. Further, adding to glass panes low emissivity properties (such as, for instance, through a low-emissivity coating or film) could help in reducing energy consumption for cooling. Visual performance | They reduce glare, lowering at the same time VLT, this means they are particularly suitable for highly glare-sensitive conditions even if they can diminish views and create gloomy interiors under some weather conditions. For this reason, their adoption in SI buildings must be carefully evaluated according to the activities conducted within confined spaces. A good approach for daylighting and glare control could be separate view and light windows (i.e. use high-transmission clear glazing from one side, and lower transmission glazing windows, to control glare, from the other). Acoustic comfort | The acoustic comfort ensured by the single pane is fair and comparable to those of a common clear single glass; to obtain significant improvement, IGU system or assembly of more than one panes with PVB could help in increasing their acoustic performance, as well as recurring to particular sealing and frame technologies (with increased insulation properties) or, again, coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. However, it must be observed that the energy savings coming from their adoption is greater than the energy needed for their production. Interaction and users' control | Tinted glazing does not allow forms of interaction and users control as they are passive, static window technologies. Limited interactions can be obtained by their integration with other devices (such as movable shading devices), suitable to be adjusted according to users' preferences or particular behaviour's scenarios. Maintenance and operation | Advantages in adopt such technology are related to their great availability and affordability. In general terms it can be said that to improve the specific technologies' performance designers can: alternate system selection opportunities with various glazing and shading options; fine-tune window sizing, window location and shading strategy for a more efficient system; curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI2	***Reflective*** *Reflective glasses present the ability to reflect infrared radiations, reducing transmission through them without shading the infrared waves; their reflectivity increases according to the thickness of the surficial treatment (film or coating).* Thermal control | Quite low if relying only on the ability of the single glass pane. If employed in IGU their insulation ability increase. In these solutions, the reflective glass should face the outside to perform their ability to reflect infrared radiation. Visual performance | They allow only a one-side view, lowering light transmittance. The more reflective they are the low light transmission they allow, bringing with it all the interior disadvantages that may be associated with that characteristic. However, their high lighting reflection values in the visible range (RL about 35/40%) and low in the infrared range, combined with their SHGC, recommend their use in climate contexts in which solar gains' reduction is fundamental (such as temperate climate). Moreover, it must be observed, speaking about SI buildings, that their application, as one-side view systems, allows privacy of the indoor spaces. Acoustic comfort | The acoustic comfort ensured by the single pane is fair and comparable to those of a common clear single glass; to obtain significant improvement, IGU system or assembly of more than one panes with PVB could help in increasing their acoustic performance, as well as recurring to particular sealing and frame technologies (with increased insulation properties) or, again, coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. Interaction and users' control | Reflective glazing does not allow forms of interaction and users control as they are passive, static window technologies. Limited interactions can be obtained by their integration with other devices (such as movable shading devices), suitable to be adjusted according to users' preferences or particular behaviour's scenarios. Maintenance and operation | Advantages in adopt such technology are related to their great availability and affordability. In general terms it can be said that to improve the specific technologies' performance designers can: alternate system selection opportunities with various glazing and shading options; fine-tune window sizing, window location and shading strategy for a more efficient system; curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI6	***<u>TIM</u>*** *Systems that incorporate transparent or translucent insulating material; their main advantage is that they combine diffused lighting features with limited thermal losses that usually characterize glazing surfaces.* Thermal control | Good heat-insulation capacity thanks to the presence of TIM in the interspace; moreover, the good protection from the sun increase their thermal performance. On the contrary, the high transmittance in the infrared spectrum could lead to an increase in cooling loads during summer; for this reason, their integration with shading devices could be useful. Visual performance | They present high and uniform light transmittance into confined spaces, even if coupled with a reduced vision quality, due to the light scattering; being translucent in fact (SHGC is equal to that of a common IGU), they allow the diffusion of natural daylight, preventing glare phenomena. However, they avoid complete transparency towards the outside. Acoustic comfort | Their acoustic abilities are pretty good due to the presence of the TIM within the air-gap; it has to be noticed indeed, that they imply their arrangement in an IGU, thus means that their sound insulation capacity does not decrease under predetermined values. Acoustic improvement could be obtained recurring to particular sealing and frame technologies (with increased insulation properties) or coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. Interaction and users' control | TIM glasses do not allow forms of interaction and users control as they are passive, static window technologies. Limited interactions can be obtained by their integration with other devices, suitable to be adjusted according to users' preferences or particular behaviour's scenarios. Maintenance and operation | They do not require particular precaution, even if their duration is connected to the performance maintenance of the Transparent Insulation Material employed within the air-gap. However, it has to be highlighted the fact that they present a quite high cost if compared to current glazing technologies. In general terms it can be said that to improve the specific technologies' performance designers can: fine-tune window sizing, window location and shading strategy for a more efficient system; adopt frames and devices with improved performance, curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI7	***Self-Cleaning*** *Windows technology able to reduce maintenance needs, particularly suitable for situations where glazed surfaces are difficulty reachable.* Thermal control | Quite low if relying only on the ability of the single glass pane. If employed in IGU, their insulation ability increase. Further, adding to glass panes low emissivity properties (such as, for instance, through a low-emissivity coating or film) could help in reducing energy consumption for cooling. Visual performance | Thanks to the reduction of dirt on their surfaces, self-cleaning systems improve light transmission through them, reducing energy costs for lighting accordingly. However, it has to be said that they effectively act on maintenance needs but they are not able to operate a control on solar and visual transmittance, for which shading devices or secondary glazing treatments are needed. Acoustic comfort | The acoustic comfort ensured by the single pane is fair and comparable to those of a common clear single glass; to obtain significant improvement, IGU system or assembly of more than one panes with PVB could help in increasing their acoustic performance, as well as recurring to particular sealing and frame technologies (with increased insulation properties) or coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. Interaction and users' control | SC glasses do not allow forms of interaction and users control as they are passive, static window technologies. Limited interactions can be obtained by their integration with other devices (such as shading devices), suitable to be adjusted according to users' preferences or particular behaviour's scenarios. Maintenance and operation | They do not require particular precaution even if their duration is limited over time; moreover, it has to be said that their effectiveness is connected with the possibility to activate the phenomenon that permits their functioning. The reason to adopt them is generally connected with the need to reduce maintenance needs of out-of-reach glazed surfaces. In general terms it can be said that to improve the specific technologies' performance designers can: alternate system selection opportunities with various glazing and shading options; fine-tune window sizing, window location and shading strategy for a more efficient system; consider the possibility to couple this technology with secondary glazing treatments (such as windows' tints and films); curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI10	<u>*PCM*</u> *Glazing systems that integrate the insulating and the overheating-control function in a single functional unit thanks to the presence of a PCM mixture within the air-gap of an IGU.* **Thermal control |** Good heat-insulation capacity thanks to the presence of PCM in the interspace that increase also passive solar heat gain. Advantage of such systems is that in addition to the contribution given by the PCM, they generally are employed in multiple glass units, increasing evermore their thermal control ability. Further, to improve passive solar control, prismatic pane or shading systems can be integrated within one of the air-gap of the system. **Visual performance |** They allow diffused natural lighting of spaces (about 28% at the solid-state while over 40% in the liquid state), exploiting natural daylighting even during summer season without excessive overheating. However, it has to be said that although translucent PCMs are available, light quality transmittance of these technologies is still a weak point. **Acoustic comfort |** Their acoustic abilities are pretty good due to the presence of the PCM within the air-gap; it has to be noticed indeed, that they imply their arrangement in an IGU, thus means that their sound insulation capacity does not decrease under predetermined values. Acoustic improvement could be obtained recurring to particular sealing and frame technologies (with increased insulation properties) or coupling them with specific acoustic devices. **Energy generation |** They do not possess energy generation abilities; however, it has to be said that the presence of the PCM confers the system the storage ability. **Interaction and users' control |** PCM glasses do not allow forms of interaction and users control despite they're considered as active, dynamic window technologies. Their operation mode indeed is completely intrinsic, being only activated through external temperature variation. Limited forms of interaction can be obtained by their integration with other devices, suitable to be adjusted according to users' preferences or particular behaviour's scenarios. **Maintenance and operation |** They do not require particular precaution even if their duration is connected to the performance maintenance of the Phase Change Material employed within the air-gap. It has to be highlighted the fact that they present a quite high cost if compared to current glazing technologies as well as those limitations are existing regarding their large-scale applications. In general terms it can be said that to improve the specific technologies' performance designers can: fine-tune window sizing and window location; adopt frames and devices with improved performance, curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI15	***Thermotropic*** *Thermotropic glazing dynamically alters their solar and visible light transmittance and reflectance, according to windows' temperature changes by switching between a transparent and an opaque state.* Thermal control | Quite low if relying only on the ability of the single glass pane even if they're application as IGU increase their insulation abilities. Their particular functioning protects against overheating and for use as a blind; indeed, the dynamic adjustment to the fluctuating amount of light and heat, allowing the efficient use of daylight during winter and preventing the excessive heat during summer, thus reducing heating and cooling costs. Dynamic systems can be effectively employed to achieve significant benefits in terms of energy efficiency especially for climate contexts in which the temperature experiences high differences such as temperate climate. Visual performance | By switching between a transparent and an opaque state, they offer self-regulating solar protection. Even if the degree of light scattering can be varied, they do not retain visibility in the opaque mode, so as they are suitable for all the application in which a direct view is not significant. Acoustic comfort | The acoustic comfort ensured by the system is fair and comparable to those of a common IGU, which means that their sound insulation capacity does not decrease under predetermined values. Acoustic improvement could be obtained recurring to particular sealing and frame technologies (with increased insulation properties) or coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. Interaction and users' control | They do not allow forms of interaction and users control despite they're considered as active, dynamic window technologies. Their operation mode indeed is completely intrinsic, being only activated through external temperature variation; indeed, they do not require electrical power source nor electrical control device are needed. Limited forms of interaction can be obtained by their integration with other devices, suitable to be adjusted according to users' preferences or particular behaviour's scenarios. Combination with an individual switching behaviour is possible. Maintenance and operation | They do not require particular precaution as they are very durable and compatible with existing conventional glazing systems since no sealing frames are required. It has to be highlighted the fact that they present a quite high cost with respect of current glazing technologies; for this reason, their application is suggested only for particular, great applications or in regions with high energy costs. In general terms it can be said that to improve the specific technologies' performance, designers can: fine-tune window sizing and window location; adopt frames and devices with improved performance, curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI16	***Photochromic*** *Glazing systems that gradually vary their optical properties due to external light intensity variations; they modify their transmission capacity based on the intensity, duration and nature of the incident solar radiation.* Thermal control | Quite low if relying only on the ability of the single glass pane even if they're application as IGU increase their insulation abilities. Their particular functioning protects against overheating and for use as a blind; indeed, the dynamic adjustment to the fluctuating amount of light and heat, allowing the efficient use of daylight during winter and preventing the excessive heat during summer, thus reducing heating and cooling costs. Dynamic systems can be effectively employed to achieve significant benefits in terms of energy efficiency especially for climate contexts in which the temperature experiences high differences such as temperate climate. Visual performance | Their light transmission ability depends on the amount of light on glass surface; however, since they darken gradually when heated from direct sunlight, they cannot control heat gain (e.g. they could darken more in winter than in summer). In general, when they decrease light transmission, even SHG in the internal environment decreases. Acoustic comfort | The acoustic comfort ensured by the system is fair and comparable to those of a common IGU, which means that their sound insulation capacity does not decrease under predetermined values. Acoustic improvement could be obtained recurring to particular sealing and frame technologies (with increased insulation properties) or coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. Interaction and users' control | They do not allow forms of interaction and users control despite they're considered as active, dynamic window technologies as their operation mode is completely intrinsic, being only activated through external temperature variation. Limited forms of interaction can be obtained by their integration with other devices, suitable to be adjusted according to users' preferences or particular behaviour's scenarios. Maintenance and operation | They do not require particular precaution even if their use in buildings is still poor due to the fact that they are ambient-temperature sensitive. Additionally, it has to be highlighted the fact that they present a quite high cost if compared to current glazing technologies; for this reason, their application is suggested only for particular applications. In general terms it can be said that to improve the specific technologies' performance designers can: fine-tune window sizing and window location; adopt frames and devices with improved performance, curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices).

TpSI17	***<u>Gasochromic</u>*** *Systems obtained through the incorporation of a gasochromic layer between two panes of an IGU which, when exposed to diluted hydrogen gas, colors and change system's transparency according to the volume of hydrogen to which the layer has been exposed.* Thermal control | Quite low if relying only on the ability of the single glass pane even if they're application as IGU (generally double or triple), often coupled with low-emissive coating, significantly increase their insulation abilities. Their particular functioning protects against overheating and for use as a blind; indeed, the dynamic adjustment to the fluctuating amount of light and heat, allowing the efficient use of daylight during winter and preventing the excessive heat during summer, thus reducing heating and cooling costs. Dynamic systems can be effectively employed to achieve significant benefits in terms of energy efficiency especially for climate contexts in which the temperature experiences high differences such as temperate climate. Visual performance | Their light transmission ability depends on the volume of hydrogen to which the layer has been exposed. Contrarily than other dynamic technologies, gasochromics retain clear visibility from inside to outside in all the switching states. Lower SHG values can be obtained by adding solar control coatings. Acoustic comfort | The acoustic comfort ensured by the system is fair and comparable to those of a common IGU, which means that their sound insulation capacity does not decrease under predetermined values. Acoustic improvement could be obtained recurring to particular sealing and frame technologies (with increased insulation properties) or coupling them with specific acoustic devices. Energy generation | They do not possess energy generation ability. Interaction and users' control | The control unit requested by the system permits both manual as automatic control; further, the integration into a bus system allow the glazing to be switched to optimize lighting conditions, thermal comfort and building energy consumption. Maintenance and operation | They do not require particular precaution even if their use in buildings is still poor since they are pretty expensive and that they need quite complex control equipment. In general terms it can be said that to improve the specific technologies' performance, designers can: fine-tune window sizing and window location; adopt frames and devices with improved performance, curate the installing phase to ensure the performance maintenance within the interface according to the specific wall support as well the windows' technical features (frames, fastening systems, added mechanical equipment and other devices). Additionally, installing daylight-activated (automated) controls can have cost-saving applications and benefits by dimming or turning off windows with them.

RESULTS ACHIEVED AND ONGOING CHALLENGES
Conclusions

The present dissertation was motivated by the worrying realization that often, architects and, more in general, professionals in the field of building technology, overlook some important aspects, passing very late in the design process the responsibility of building envelope performance and demanding it to mechanical and building envelope engineers.
Frequently, the performance response expected during the design phase does not match with what obtained during construction phases.

Fig. 01 – "Funny" and curious resolution of the interface criticalities in an existing window.

Detailed design decisions are essential from the very beginning of the process to ensure the correspondence among initial concept and its realization, especially when dealing with advanced technologies for building envelope or with specific building components that need of particular attention during design and installation phase, as – for instance – fenestration.
Understanding their nature and behaviour within the whole system allows conceiving a new generation of architectural solutions, able to provide an operational response balanced among performance to be guaranteed and regulations to be respected, here defined with the term "**smart buildings**".

Indeed, **the very first milestone** of the present dissertation has been **the definition of the concept of "smart" in architecture**, for which many interpretations are existing but a precise definition of its meaning appears surprisingly difficult. So, even if today the smart feature in the architecture's domain is generally associated to materials and technologies highly-engineered, this concept has not to be intended only as of the integration of different or unconventional features in a given material, component or system, but it can also be attributed to the intelligent application of something within building system in its whole or, again, to the intelligent management of a complex organism such as the building one.
Accordingly, such idea led to the definition of smart buildings as systems able to adapt – in a responsive way – not only to the variability of boundary conditions but even to the continuously evolving needs of their end-users.
Thus, a smart building is not only an edifice that makes use of building automation technologies – definition which sounds as rather reductive – but it is a building equipped with technological solutions able to provide high performance in terms of comfort, energy efficiency and

environmental sustainability, capable of dynamically interact with the surrounding and to acquire data and information useful for optimize its functioning, thus correct possible inefficiencies.
Thus, **a deliverable** has been the **development of a supporting database** – in the form of a catalogue – **providing a systematic characterization of smart buildings for future trends in design, mapping strategies adopted in such systems, recognizing common patterns and identifying unexplored concepts to help further development of high-potential, innovative smart building components**.
Besides, this recognition has been necessary to acquire knowledge about the functioning of smart buildings and to respond to another research question, that is the one related to how the smart advanced technologies analyzed within the present work have changed architectural features over time, becoming, in some cases, the innovation of specific traditional elements. Indeed, the establishment of architectures with responsive and adaptive capabilities, previously unthinkable, to face the modern need of change, has rapidly triggered a revolution in the creation of the architectural work as a whole, giving to technology for architecture an active role: no longer as 'engineering' of a project but rather an element of synthesis – centralizer of multiple instances – on which leverage to foster interactions among buildings, surrounding environment and user-needs.
It has been evident that the application of the innovations here investigated has produced a modification of project practices, enriching architectural language through the adoption of heterogeneous components, sometimes known but endowed with new technological values, while sometimes resulting from technological transfer processes from other sectors or the most recent scientific and technical discoveries.
The evolution of the demanding framework that modified the use of materials and products according to a functional approach towards matter (Sinopoli and Tatano, 2012), generated architectures with complex shapes, able to overcome the simplification of traditional architectural solutions, often determined by the assembly of regular elements, in favor of more evolved shapes, assisted by ICT for the building process, thus making building materials functional elements that could perform an adaptive behavior.
So, smart building envelopes, whose technological components acquire new aesthetic-formal value, become the driving force for the development of unconventional architectural ideas and forms, being "the next big milestone" of the technology for architecture (Gallo and Romano, 2017) thanks to their ability in giving to buildings the desired resilience capacity, becoming, at the same time, iconographic supports able to evolve with the use they made of innovative materials and components (Romano, 2013).
Therefore, even the use of materials has been separated from their application, according to conventional forms and meanings dictated by cultural traditions, availability of resources or precise formal and aesthetic features, to become 'linguistic' means for communicating the project, with precise functional intentions, expression of a new 'glocal' language, able to adapt itself to the ever-changing needs of a 'hybrid' contemporary society while finding at the same time a relationship with local traditions, even if innovated in form and vocation.

Finally, this first part of the work **has allowed choosing which kind technologies consider in further work**. According to the case-studies analysis indeed, **the present research narrows the field to transparent building components** because it has been evident that fenestration design issues still constitute a gap in this broad scenario due to the significant role they play in building energy efficiency and internal environmental comfort as well.
Although nowadays market offers different types of high-performance glazing systems, ever more frequently enhanced with added functions to increase their whole performance response as building envelope components, smart windows and, more in general, windows technologies

with outside-the-box performance are still in the early stage of development.
So far, transparent building components – even if equipped with quite high-performance – are still the weakest point of building envelopes, especially in terms of thermal resistance.
For this reason, fenestrations' design optimization challenge is more complex than for many other building components and systems and smart windows technologies are still often neglected in architecture and buildings, even though some functions would already be technically feasible.
Research is now focusing on strategies to improve windows' performance, reducing costs and favoring sensors and control-systems installation to increase their operation efficiency, making them monitorable and reactive to various stimuli on the basis on predetermined inputs, quantifying at the same time benefits thus obtained. Developing windows with reduced weight, cost and thermal features, able to control and harvest energy, is of paramount importance such they will have a high impact in the window industry.

Fig. 02 – World map of barriers declared by experts for widespread integration in building envelope of smart windows technologies.

However, at the same time, there is the need to provide designers with the appropriate tools to manage such complexity, according to a holistic and integrated approach which consider building systems in their whole.
Therefore, after **collecting and presenting the state-of-the-art** about available **smart windows' technologies**, providing a systematic methodology to assess their building integration potential, the **final result** of the present work consists of **the development of a toolbox to support decision making** towards the **conscious and effective integration of transparent building components within smart building envelope systems**. It gathered results and considerations coming from the preliminary literature and technical research to further re-elaborate and systematize them, helping designers and professional in the fields in developing new high-performance solutions, thus solving the problem of design and construct sustainable smart buildings.
The toolbox is composed by a 1) **balanced scorecard**, which helps in defining the set of actions to be undertaken to increase performance features of products evaluated about predetermined requirements; an 2) **assessment matrix**, which systematizes measure depicted within the balanced scorecard with research objective and a 3) **smart windows' configurator**, an open matrix for compiling and validating different technical solutions, supporting the design of transparent building components towards the improvement of building envelope performance.
By using elements coming from the previous analysis, such tool focuses on suggesting a variety

of near-optimal possibilities based on the optimization of single building envelope requirements. It has been proved, indeed, that suggesting multiple and diverse good initial alternatives is more beneficial for the early design stages, when designers are still exploring various design routes and numeric detailed properties of any building elements systems are irrelevant.
The general approach used by the tool foresees the introduction of some input data, related to the climatic condition of the application surroundings and to the type of building under investigation, to further select the type of windows technologies for which advice are needed. Interpreting such data, already known at the initial design stages general design consideration related to building requirements implementation are provided.
In the present dissertation, final concepts are stated only for the combinations among input data recognized as the most frequents by the case-studies analysis, pointing the attention towards technologies that obtained the lower score within the assessment matrix. The structure of the configurator is suitable to further implementation according to the various possible combinations of the variables involved. At the moment indeed, it is designed as a standalone tool, suitable to be translated into a software for an easier consultation, able to provides design directions and assist architects in the early design stages of a smart building envelope or, again, to supports researchers and producers in deciding on the most pertinent research and development activities concerning windows technologies.
Through this work, it has been shown that smart building envelope can only be the result of an informed design process that requires very careful attention since its very first stages. Yet, some differences distinguish itself from the "traditional" design activity. Smart architectural design decision at the whole building level must be considered as well as passive design strategies, aimed at achieving and ensuring the occupants' comfort; the choice of the most suitable elements coupled with their proper integration within the main building envelope interfaces allow to make buildings adaptable to the environmental challenges we are facing.
Moreover, it is important to clarify that not all the buildings' elements and materials chose must have an outstanding performance – as it sometimes adds unwanted complexity to the strategies put in place – but rather they must be based on conscious design decisions, being considered in their whole and in relationship with the other components installed. It has to be considered that even the examples chose within the present dissertation as case-studies cannot be provided with just a collection of "smart" elements placed together, then somehow expected to perform adequately; also components with the highest degree of smartness require a proper integration, programming and control to face the different challenges they are going to meet.
This makes essential to adopt strategical addresses for building applications of the wide variety of material and components available for smart building envelope such as advanced integrated façades, adaptive glazing, thermal massive components, dynamic insulation systems and so on. Only their strategic and well-studied combination can enrich the design, providing a real implementation of building envelope performance in their whole.
Furthermore, nowadays, the design of a smart building envelope can benefit from modern design tools that have taken advantage of computer development of the fourth industrial revolution. This has expanded the range of available possibilities, informing new design options and allowing to perform corrective operation also before construction, even if it has to be said that software and digital tools currently available generally evaluate finished alternatives rather than suggest design directions.
On the contrary, the toolbox developed within the present dissertation aimed at encouraging the arising of relevant questions ("what if" scenarios) and suggest a series of solutions or possible promising design directions according to the specific need that concern the design of transparent building components. It will also trigger further development of advanced tools that can enable the exploration of different novel solutions through a smart approach.
Indeed, it can be expected that smart building envelopes in general will have a much wider

implementation in the near future due to the acceptance – within the construction industry – of technological innovations of last years. Any forthcoming directions for the development of high-performance smart building envelopes must include an improved cognition of perception elements, as well as building industry need to handle more detailed information beyond what is available today.

Certainly, further research has to be done so that smart building components can be expected to become equipped with devices based on wireless data transmission – such as, for instance, intelligent sensors capable of detecting real-time data about environmental parameters, consumption, user behavior and operation of technical plants – which allow to concretely suppose the development of a new generation of products, even smarter than before, capable of autonomous and efficient management. Additionally, obtaining feedbacks and real-time information on them will lead to more informed decision-makers and to the definition of more effective management strategies that will be reflected on a real implementation of the systems thus obtained, making them real UGCs (User-Generated Contents) thus guaranteeing their functionality over time and, above all, their compliance with the ever-changing needs of their occupants, making them (inter)active and interoperable structures thanks to the introduction of the aforementioned technological innovations, as an element of mediation among multiple instances, sometimes juxtaposed but essentially interconnected.

Further studies are then required to provide new operation modes to well-known actuators such as blinds, shading elements, lighting controls, etc. Other directions for research include new additional explorations in the fields of smart materials, accomplishing a series of functions that currently cannot be carried efficiently with traditional materials and components.

Moreover, ongoing challenges are those related to the proper design of building envelope's interfaces, especially when dealing with such advanced technologies, for their nature equipped with high performance, to guaranteeing their performance maintenance over time. Indeed, detailed design of heterogeneous components as a whole constitutes the contact points among the conceptual design phase and the implementation, actualizing one, means to avoid the performance decay over time.

APPENDIX I
Related research programs

A Novel BIPV – PCM Heat and Power Cogeneration System for Buildings

CREDITS

Project ID	298093
Country	United Kingdom
Coordinator	University of Hull, UK
Funded under	FP7 - PEOPLE
Started in	2012-12-07
Ended in	2014-12-06
Contact information	Xudong Zhao

[Relation to the current research]
Development of an innovative building materials employable in façade able to obtain a benefit in cutting carbon emission by means of its high-energy potential.

[Project description] The project BIPV-PCM-COGEN aims at develop a novel BIPV (Building-Integrated PhotoVoltaic) façade module that can be used to replace conventional building materials in several parts of the building envelope.
The specific objectives of the project are: **1)** to design a conceptual BIPV module and the associated heat and power co-generation system, using a PCM slurry[1]; **2)** to develop a computer model to optimize the configuration of the BIPV/PCM system and to predict its energy generating performance; **3)** to construct and test a prototype of a BIPV/PCM system and to validate the above-mentioned computer model using the experimental data; **4)** to carry out economic, environmental and regional acceptance analyses.
Project achievements are: **1)** a new BIPV structure and a dedicated PCM slurry (able to overcome the difficulties associated with existing BIPV systems); **2)** a design for a conceptual PCM-slurry adapted to the BIPV module; **3)** a computer model to optimize the configuration between the PCM-slurry and the BIPV module and predict its operational performance; **4)** the construction of a prototype of a BIPV – PCM – slurry energy system and its validation.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	■
Control systems	

[Notes]
1 The slurry is a mixture of micro-encapsulated PCM particles and water, with variable concentration determined through the experimental tests, that transfers heat away from the back of the PV modules to increase their efficiency. Dedicated heat exchangers transfer heat energy from the PCM slurry to a refrigerant used to ventilated the building and provide heat and hot water for domestic uses; any excess is stored and returned to the system on demand.

The developed BIPV module is constituted by a multi-layer structure incorporating a glazing cover, a PV layer, a serpentine tube that allows PCM slurry to pass through and an insulation layer and frame set. The dimension of each module is fixed in 1600 mm x 800 mm and has a predicted heat output of 0,66 kW with an electrical output of 35 W, slurry flow rate of 40 kg/h and flow resistance of 125 Pa, per module.
The experimental prototype was constructed and tested under laboratory conditions with the aim of examining its operational performance; testing conditions are: solar radiation range within 525-825 W/m^2; ambient temperature of 29,5°C, heat-pump evaporation and condensation temperature of 15° and 70°C, refrigerant flow rate of 0,012 kg/s, water inlet temperature of 24,75°C and water flow rate of 0,0042 kg/s.
Under these conditions, the system could provide 585-895 WW of heat in form of hot water at 60°C and 97-150 W of electricity. The average COP of the overall system is 8,14 while the solar efficiency of the BIPV – PVM – slurry module is the 83,8%.
Therefore, the testing results indicated that module's electrical and thermal efficiency decrease while system's COP increase when solar radiation is increasing from 525 W/m^2 to 825 W/m^2. Also the verification of other parameters showed that the model could achieve the acceptable accuracy in predicting system's operational performances.
Tests showed as well that the developed system is more suitable for Southern-Europe regions due to the fact its energy output is higher mainly owing to the higher solar radiation and ambient temperature.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/result/rcn/170414_en.html*

CLEAR-UP B-c 02

Clean buildings along with resource efficiency enhancement using appropriate materials and technology

CREDITS

Project ID	211948
Country	Germany
Coordinator	University of Tuebingen
Funded under	FP7-NMP
Started in	2008-11-01
Ended in	2012-10-31
Contact information	Prof. Dr. Udo Weimar, University of Tübingen coordination@clear-up.eu

[Relation to the current research] Development and test of advanced technologies to improve building envelope's performance in a holistic system working on windows as buildings' key components.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	■
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

[Project description] Clear-up project's aim is to reduce energy use in new and existing buildings, using environmentally-sound components thus creating sustainable solutions.
The challenges they deal with regard mainly the development of new technological solutions and the integration of new components and building control strategies in a holistic system, using large scale tests in real buildings for simulate their energy savings.
Clear-up project worked on four key components of buildings:
1) sensors and intelligent control development for smart windows, demand controlled ventilation and air purification to provide and energy-optimize the indoor environment;
2) air conditioning systems for the intelligent combination of natural and artificial ventilation;
3) walls, using photo-catalytic materials for air purification and nano-porous vacuum insulation, combined with PCMs to passively control temperature;
4) windows, using shutters and electro-chromic window to reduce building cooling loads and needs for artificial lighting.
To reach its objectives, Clear-up selected several

test buildings (with different features) to integrate various solutions and understood how to make them easily work together through a BMS system that controlled different actuators: the self-opening of windows, the activation of energy efficient ventilation systems and the EC-windows. In addition to these advanced technologies, some passive components for retrofitting have been installed on such building(for instance PCM and VIP panels for insulation).

[Partners' list] Acciona Real Estate, Spain – Siemens Building Technology, Switzerland – Italcementi (CTG), Italy – Applied Sensor, Germany – Porextherm-Daemmstoffe, Germany – Fraunhofer Institute for Solar Energy Systems, Germany - Fraunhofer Institute for Surface Engineering and Thin Films, Germany – Technical University of Denmark, Denmark - Uppsala University, Sweden – Foundation for Research and Technology – Hellas, Greece - European Commission, DG Joint Research Centre, Institute for Health and Consumer Protection, Italy / EU – Steinbeis Transfer Centre AO Action, Germany – Centre Scientifique et Technique du Bâtiment, France – Bouygues Construction, France - Belgian Building Research Institute, Belgium – Siemens Corporate Technology, Germany - Budapest University of Technology and Economics, Hungary – Czech Technical University, Czech Republic – Saint-Gobain Weber GmbH, Germany – Saint-Gobain Weber Terranova a.s., Czech Republic.

References

1) **Clear-up project website**, *https://www.clear-up.eu*

2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/88889_en.html*

CLIMAWIN B-c 03

An intelligent window for optimal ventilation and minimum thermal loss

CREDITS

Project ID	262262
Country	Denmark
Coordinator	Aalborg Universitet
Funded under	FP7-SME
Started in	2010-10-01
Ended in	2012-09-30
Contact information	Climawin Europe, 63 Pleasants Pl., D08N6DN, Dublin, Ireland.

[Relation to the current research] Set-up of a window prototype that uses "traditional" material and components to develop a smart fenestration system able to results in consistent energy savings over years.

[Project description] The project aimed at develop an energy efficient fenestration system for the renovation of residential and commercial buildings in the form of a novel high performance window with electronic operation of an auto-regulated natural ventilation system and electronic insulating night blind powered by solar power.
Through in-site smart sensors, the system will optimize in real time indoor climate on the basis of parameters such as temperature, CO2 and humidity thereby reducing thermal losses.
The system thus obtained, that integrates ventilation in a fenestration system (optionally equipped with blinds and an inbuilt photovoltaic power system), uses the heat normally lost through a window to bring it in, preheating the entering air (raising or lowering its temperature) to increase comfort. Air is drawn through an electronically regulated valve at the bottom of the glass' frames, through the cavity between them where it is pre-warmed by the heat which is escaping through the glass.
The air flow is modulated in response to room and outside conditions detected by Climawin's sensors (inside, centre and outside of the window) and ceilings that monitor CO2, RH and interior

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	■

temperature. A bypass valve that allows air entering during hot months complete the system for cool and temperate climates.
The intelligent window has been tested in 7 pilot installations across Europe (in different climatic conditions); achieved results indicate that the system is well-performing and able to rise the temperature of the incoming ventilation-air up to 10 degrees thus generate 20% and more energy benefits over the year.

[Partners' list] Universidade Do Minho, Portugal - Designit A/S, Denmark - Fraunhofer Gesellschaft zur Foerderung der Angewandten Forschung E.V., Germany - Irene Karoline Christensen Horn, Denmark - Rauh SR Fensterbau Gmbh, Germany - Solearth Ecological Architecture, Dublin.

References

1) **Climawin project website**, *http://climawin.eu*

2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/96091_en.html*

3) (2014), ***Climawin, la finestra intelligente lanciata da tre Pmi europee***, Casaeclima.com, *http://www.casaeclima.com/ar_16974__TECH-Innovazioni-finestra-intelligente-recupero-di-calore-Climawin-la-finestra-intelligente-lanciata-da-tre-Pmi-europee.html*

EELICON B-c 04

Enhanced Energy Efficiency and Comfort by Smart Light Transmittance Control

CREDITS

Project ID	604204
Country	Germany
Coordinator	Fraunhofer Institute
Funded under	FP7-NMP
Started in	2014-01-01
Ended in	2017-06-30
Contact information	Walter Krause, (EU Projects Officer), Tel. +49 89 1205 2713

[Relation to the current research] Development of an advanced solution (switch-able light transmittance EC technology) to retrofitting existing glazed components with an electrically dimmable plastic film.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	■
Energy generating	
Control systems	

[Project description] The EELICON project concerned an innovative switch-able light transmittance technology based on electro-chromic materials; the core of this development were mechanically flexible and light-weight EC-film devices based on a conductive polymer-nanocomposite coating, with outstanding electro-optical properties that can change their optical absorption, opening the possibility to retrofit existing windows with an electrically dimmable plastic film.

As opposed to state-of-the-art liquid crystal films, EC-films maintain their transparency throughout the whole switching process; this unique property has been recently considered a breakthrough in overcoming common limitations of state-of-the-art smart window technology which means that such devices can be used in a multitude of applications where the control of visible light transmittance is required for reasons of safety, comfort and energy saving.

The project has comprised a pilot-line, a validation, and a prototyping phase: application testing revealed promising results in terms of cycle life (10 k cycles proven for unsealed sample tested under laboratory conditions), energy transmittance properties (g-values from about 34 % in a clear state to 18 % in a dark state), self-bleaching (>55 h for a 10% bleaching) and regarding response times (20-30 s for A3 window size).

[Partners' list] COATEMA COATING MACHINERY GMBH, Germany - YD YNVISIBLE SA, Portugal - TEKS SARL, France - MICROELETRONICA MASER SL, Spain - LCS LIFE CYCLE SIMULATION GMBH, Germany - CONSORZIO INTERUNIVERSITARIO NAZIONALE PER LA SCIENZA E TECNOLOGIA DEI MATERIALI, Italy - HYDRO-QUEBEC, Canada - CENTRUM ORGANICKE CHEMIE SRO, Czech Republic - GORENJE GOSPODINJSKI APARATI D.D., Slovenia - ACREO SWEDISH ICT AB, Sweden - UNIVERSITAET STUTTGART, Germany - ECONTROL-GLAS GMBH & CO. KG, Germany.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/110859_en.html*

2) **Eelicon project website**, *http://www.eelicon.eu*

EENSULATE C-o 05

Development of innovative lightweight and highly insulating energy efficient components and associated enabling materials for cost-effective retrofitting and new construction of curtain wall facades

CREDITS

Project ID	723868
Country	Italy
Coordinator	D'Appolonia SPA
Funded under	H2020-EEB-2016
Started in	2016-08-01
Ended in	ongoing (2020-01-31)
Contact information	General contact: info@eensulate.eu

[Relation to the current research] Development of a technology to implement performance of (transparent) building components - acting on their insulation - according to different levels of performance achievable.

[Project description] The goal of the project is to develop an affordable and lightweight solution for building envelope insulation through two commercial products: an highly insulated mono-component foam – for the insulation of the opaque components and the reduction of thermal bridges during installation phases – and a lightweight and thin double pane vacuum glass for the insulation of transparent components, through an innovative low temperature process, using polymeric flexible adhesives and distributed getter technology, thus allowing to use both annealed and tempered glass as well as low emissivity coatings.
The product will enable insulating solutions with two different levels of performance: the basic solution foresees a curtain wall module to implement thermal and acoustic insulation by the use of EENSULATE glass and EENSULATE foam in the spandrels, combined with state-of-the-art low-e coated glass; while the premium module integrates the thermo-chromic coated glass with additional self-cleaning and anti-fogging functionalities.

[Partners' list] AGC GLASS EUROPE SA, Belgium - SAES GETTERS S.P.A., Italy -

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

SELENA LABS SPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA, Poland - UNIVERSITY COLLEGE LONDON, United Kingdom - EVONIK NUTRITION & CARE GMBH, Germany - UNIVERSITY OF ULSTER, United Kingdom - TECNICAS DE VIDRIO TRANSFORMADO, SL, Spain - FOCCHI SPA, Italy - Van Berkel & Bos U.N. Studio B.V., Netherlands - FENIX TNT SRO, Czech Republic - BERGAMO TECNOLOGIE SPZOO, Poland - UNIVERSITA POLITECNICA DELLE MARCHE, Italy - GMINA MIEJSKA DZIERZONIOW, Poland.

References

1) **Eensulate project website,** *http://www.eensulate.eu*

2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/205458_en.html*

FLUIDGLASS B-c 06

Solar Thermal Glass Facades with Adjustable Transparency

CREDITS

Project ID	608509
Country	Liechtenstein
Coordinator	Univ. Liechtenstein
Funded under	FP7-ENERGY
Started in	2013-09-01
Ended in	2017-08-31
Contact information	Project Coordinator: Anne-Sophie Zapf, anne-sophie.zapf@uni.li

[Relation to the current research] Development of a window prototype which integrates different functionalities in one integrated system to increase the performance of the whole building envelope.

[Project description] The FLUIDGLASS project developed a new and innovative concept for multifunctional solar thermal glass façades systems, turning passive glass façades into active transparent solar collectors, controlling at the same time the energy flow through the building envelope.

The collector panel is a combination of fluid and glass layers and a thermal barrier; layers can be differently assembled according with various applications and sections of building envelope.

In the proposed prototype, two fluid-filled layers are implemented in the glass façade and regulate the whole energy flow within it; the internal fluid layer keeps the inside surface temperature just below or above room temperature for heating and cooling, while the external liquid layer controls the energy transmission by absorption of the solar irradiation.

The main project's objectives were:

- to design and develop an easy-to-install modular frame system;
- to develop a fully automatic device to control the transmittance of energy-absorbing fluid;
- to integrate the FLUIDGLASS system into the HVAC system, increasing the use of

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

renewable energy at building level;
- to deploy and demonstrate the whole system under real conditions in different geographical locations;
- to assess the implications of such a system from an economical point of view, demonstrating its economic benefits.

First assessments showed that FLUIDGLASS prototype, which unites four key functionalities in one integrated system (a transparent solar thermal façade system combining solar thermal collector; an insulation glazing; a shading device and a heating/cooling panel in one element), can increase the thermal performance of the whole building, resulting in energy savings potential of 50%-70% for retrofitting and 20%-30% for new low energy buildings.

[Partners' list] MGT - MAYER GLASTECHNIK GESELLSCHAFT MBH, Austria - INTERSTAATLICHE HOCHSCHULE FUR TECHNIK BUCHS NTB, Switzerland - TECHNISCHE UNIVERSITAET MUENCHEN, Germany - GLASSX AG, Switzerland - Hoval Aktiengesellschaft, Liechtenstein - COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, France - UNIVERSITAET STUTTGART, Germany - CY.R.I.C CYPRUS RESEARCH AND INNOVATION CENTER LTD, Cyprus - ALCOA EUROPE COMMERCIAL SAS, France - AMIRES SRO, Czech Republic.

References

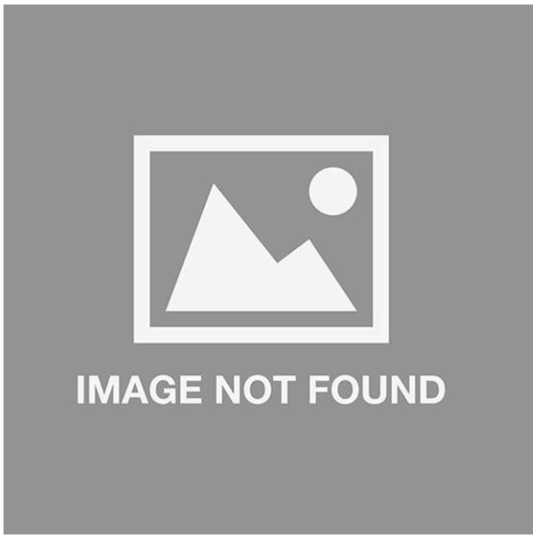
1) **Fluidglass project website,** *http://www.fluidglass.eu*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/110009_en.html*

GRINDOOR B-c 07

Green Nanotechnology for the Indoor Environment

CREDITS

Project ID	267234
Country	Sweden
Coordinator	Uppsala Universitet
Funded under	FP7-IDEAS-ERC
Started in	2011-06-01
Ended in	2016-05-31
Contact information	Mikael Jonsson, Tel.: +46 18 4713072



[Relation to the current research]
Development of thermal control, solar energy and visible light control solutions for windows and glass façades.

[Project description] The GRINDOOR Project developed new materials and technologies (based on nanotechnology) for healthy energy efficient indoor environments in buildings.
Within this main topic, two of the four developed sub-projects were about thermal control and transmission of solar energy and visible light in windows and glass façades whose main results are stated as follows:

- development of materials for electro-chromic windows and glass facades and of useful information for further implementation of energy efficient EC smart windows;
- development of materials for thermo-chromic windows and glass facades to permit the solar energy throughout them to be lowered automatically as the temperature rises above a comfort temperature;
- exploration of several metallic and semi-conducting nano-materials for the recording of gaseous pollutants characteristic for indoor air;
- investigation of solar-energy-powered purification techniques. A fundamental understanding was about the fact that tuned

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	■
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	■
Energy generating	
Control systems	

coating technology could yield thin films whose surface structures were dominated by crystalline facets are the most efficient for photo-catalysis. This opens ways towards the use of fenestration technology to accomplish efficient purification of indoor air.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/99257_en.html*

2) (2015), ***GRINDOOR, nanomateriali per ambienti interni più sani***, Casaeclima.com, *http://www.casaeclima.com/ar_25370__GRINDOOR-nanomateriali-ambienti-interni-sani.html*

HarWin B-c 08

Harvesting solar energy with multifunctional glass-polymer windows

CREDITS

Project ID	314653
Country	Germany
Coordinator	Univ. Bayreuth
Funded under	FP7-NMP
Started in	2012-09-01
Ended in	2015-08-31
Contact information	Prof. Dr. Monika Willert-Porada, monika.willert-porada@uni-bayreuth.de

[Relation to the current research] Will to develop new generation windows with reduced weight, reduced thermal conductivity and low environmental impact.

[Project description] The aim of the HarWin project was to develop new materials for constructing next generation windows, able to significantly improve energy efficiency in buildings. Improvements are based on reduced weight, reduced thermal conductivity and energy consumption, reduced material usage and life cycle environmental performances control of the windows.
The main goal was about such optimizations and the further development of laminated glass panes made of glass particles in ball form, able to decrease thermal conduction, facilitate sound insulation, regulate humidity and increase the mechanical properties of the windows. The challenge is to combine these functional characteristics into a new window pane with enough transparency.
The project began by examining the effectiveness of various innovative materials with low embodied energy. The mechanical performance of these materials was then improved through the use of advanced strengthening methods for both glazing and frame construction.
The final result was a thin glass laminated panes, reinforced with new polymer-glass composite materials, comparable or even superior to existing

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

triple glazing in terms of performance (U-value of about 0.4 $W/m^2/K$ and VLT of about the 75%) but at 50 % less weight; also the new extremely stiff thermally insulated frame, based on polymer foam core-glass fibre reinforced polymer skin materials, offers additional embodied energy savings due to weight reduction by a factor of 5-10 as compared to existing polymer/metal or metal frame.
Energy harvesting feature is based on the use of Phase Change Materials (PCM) of organic nature in glazing in glazing, to guarantee high light transmission, as additional thermal mass and new glass with Luminescent Down Conversion (LDC) properties to increase the Visible Light Transmission (VLT) through the conversion of UV radiation into visible range of wavelengths, with almost 30% photonic efficiency.

[Partners' list] INGLAS PRODUKTIONS GMBH, Germany - ECKART PIGMENTS KY, Finland - GLASSX AG, Switzerland - CENTROSOLAR GLAS GMBH & CO KG, Germany - ISOMATEX SA, Belgium - INTEGRATED ENVIRONMENTAL SOLUTIONS LIMITED, United Kingdom - JRC -JOINT RESEARCH CENTRE- EUROPEAN COMMISSION, Belgium - FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V., Germany - ZACHODNIOPOMORSKI UNIWERSYTET TECHNOLOGICZNY W SZCZECINIE, Poland - BAYERISCHE FORSCHUNGSALLIANZ BAVARIAN RESEARCH ALLIANCE GMBH, Germany - DIETRICH SCHWARZ ARCHITEKTEN AG, Switzerland.

References
1) **HarWin project website,** *www.harwin-fp7.eu*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/104545_en.htm*

LaWIN C-c 09

Large Area Fluidic Window

CREDITS

Project ID	637108
Country	Germany
Coordinator	Universitat Jena
Funded under	H2020-EeB-2014
Started in	2015-01-01
Ended in	2017-12-31
Contact information	n.f.

[Relation to the current research]
Development of an active window component (thorough the incorporation within it of micro fluid devices) to reduce heating cost by means of the adjustment of the incidence of light through the facade.

[Project description] LaWin targets an innovative material solution for efficient solar energy and ambient heat harvesting through an active building envelope component. This project indeed, uses large-area micro-fluid devices implemented into windows and façades with the aim of reduce heating costs and, in general, at least the 10% of the whole energy spent during the whole life cycle of a building.
Large-area fluidic windows use a fluid contained in micro-channels – embossed in structured glass further laminated – that makes possible to automatically adjust the incidence of light, thus managing heat exchanges through the surface – or to harvest exterior heat to be transported to a heat pump
First prototype uses aqueous solutions but any fluid with high heat exchange properties and, eventually, added further functionality, such as polychromatism (where the fluid's optical absorption properties depend on the magnitude of incident irradiation, or may be tuned electrically), could be used.
The prototype developed within the project has been installed in model buildings across 2017 to validate and optimise its design parameters.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	■
Energy generating	■
Control systems	

From testing and simulations resulted that such a window will cost 2,5 times more than common triple glazed windows but that energy savings that it produced during building's life cycle can will partly cut down such higher costs.

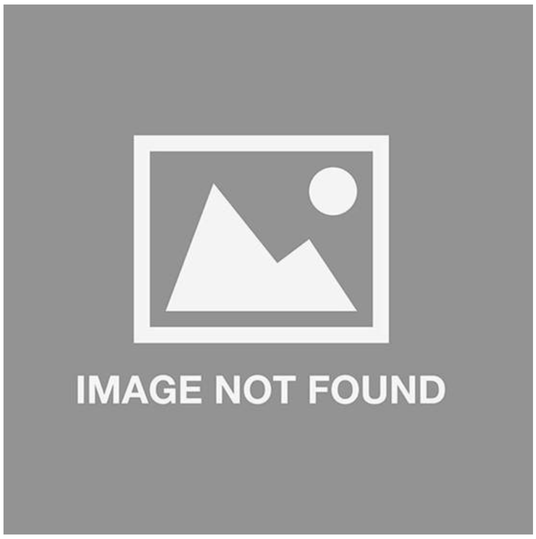
[Partners' list] SCHOTT TECHNICAL GLASS SOLUTIONS GMBH, Germany - BAUHAUS-UNIVERSITAET WEIMAR, Germany - Ducatt NV, Belgium - EURA INNOVATION GMBH, Germany - GLASS SERVICE AS, Czech Republic - FLACHGLAS SACHSEN GMBH, Germany - EILENBURGER FENSTERTECHNIK GMBH & CO. KG, Germany - A. + E. UNGRICHT GMBH + CO KG, Germany - FICKERT & WINTERLING MASCHINENBAU GMBH, Germany - BEUTH-HOCHSCHULE FUER TECHNIK BERLIN, Germany - FOLIENWERK WOLFEN GMBH, Germany - Clariant Produkte (Deutschland) GmbH, Germany - LISEC AUSTRIA GMBH, Austria.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/193466_en.html*

LCDAYLIGHT A-c 10

Liquid crystal techniques and daylight systems



CREDITS	
Project ID	ENK6-CT-2002-30023
Country	France
Coordinator	Rosenheimer Germany
Funded under	FP5-EESD
Started in	2003-01-01
Ended in	2004-12-31
Contact information	Administrative contact: Johannes RIEDIGER - Tel.: +49-80-319414831

[Relation to the current research] Development of a multifunctional system capable of controlling light and climate through the transparent building envelope to optimize energy savings.

[Project description] The LCDAYLIGHT project focused on realizing a new multifunctional daylight system capable of controlling simultaneously light and climate (i.e. transmission, reflection and scattering of daylight and sunlight) by exploiting suitable liquid crystal techniques with the goal of optimizing energy savings during all seasons.
Polymage, a member of the consortium, developed within project's activities a viable solution based on a switchable lamella that employs liquid crystal technology. The lamella modifies its chromatic properties in order to regulate the transmission of light and heat between the building and its environment. When integrated into full-scale fenestration systems, such system allows to obtain substantial advances in energy savings.
The work done during project's implementation was about the incorporation of the lamellas into glazed building components.
Other applications of the technology have also been investigated.

[Partners' list] BARTENBACH LICHTLABOR GMBH, Austria - CATALYSE SARL, France - POLYMAGE SARL, France - RUDOLF BRAUNS GMBH AND CO. KG, Germany -

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	■
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

SHERPA ENGINEERING SARL, France.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/67326_en.html*

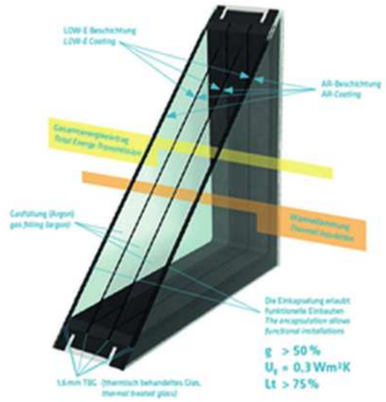
MEM4WIN B-c 11

Ultra thin glass membranes for advanced, adjustable and affordable quadruple glazing windows for zero-energy buildings

CREDITS

Project ID	314578
Country	Austria
Coordinator	Lisec Austria GMBH
Funded under	FP7-NMP
Started in	2012-10-01
Ended in	2016-03-31
Contact information	Mr. Leopold Mader, leopold.mader@lisec.com

MEM4WIN ADVANCED TECHNOLOGIES FOR SMART WINDOWS



[Relation to the current research] Development of an innovative IGU with reduced weight and almost frame-less able to control and harvest energy at the same time by means of printed organic photovoltaic, solar thermal collectors and switch-able micro mirrors for energy control.

[Project description] MEM4WIN aims at introduce a novel IG-Unit for quadruple glazing containing ultra-thin glass membranes and frame-less operable windows for direct application in façades.

Project main goals were: **1)** reducing weight of almost 50%; **2)** controlling and harvesting energy through a façade component that employs implemented printed organic photovoltaic (in line OPVs) and solar thermal collectors as well as switchable micro mirrors for energy control; **3)** introduce more sustainable processes and materials and reduce production costs (if compared to a conventional window with the same functionalities) using advanced fabrication technologies and less cost intensive materials;

So the technologies explored within the project, at the end integrated into a prototype, has been:

- tempered ultra-thin glass membranes;
- anti-Reflective coating;
- quadruple insulated glass unit (Ug-value: 0,3 W/m^{2}K);
- frame-less operable window for façades' applications;
- CVD and LPE graphenes for transparent contacts;

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	■
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

- OPV ink for direct printed organic PV cells;
- new lamination techniques for fabrication of OPV glass-glass modules lamination of OLED glass-glass modules;
- micro mirror arrays for control of solar radiation and light guidance;
- solar-thermal collector (fully integrated in the IGU).

[Partners' list] INOVA LISEC TECHNOLOGIEZENTRUM GMBH, Austria - PROFACTOR GMBH, Austria - BELECTRIC OPV GMBH, Germany - ENERGY GLAS GMBH, Germany - DURST PHOTOTECHNIK SPA, Italy - TIGER Coatings, Austria - CONSIGLIO NAZIONALE DELLE RICERCHE, Italy - UNIVERSITAT LINZ, Austria - THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE, United Kingdom - EV GROUP E. THALLNER GMBH, Austria - AIXTRON SE, Germany - AIXTRON LIMITED, United Kingdom - UNIVERSITAET KASSEL, Germany - KOREA UNIVERSITY RESEARCH AND BUSINESS FOUNDATION, South Korea.

References
1) **MEM4WIN project website,** *http://mem4win.eu/index.php?id=1*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/104757_en.html*

ML System C-c 12

Heatable, integrated photovoltaics with insulated glass units

CREDITS

Project ID	673917
Country	Poland
Coordinator	ML System Spolka Z
Funded under	H2020-SMEINST-1-2014
Started in	2015-05-01
Ended in	2015-10-31
Contact information	n.f.

[Relation to the current research] Development of a multi-functional window system for ultra-low energy buildings.

[Project description] Main objective of this project was to launch a semi-transparent multifunctional (heating, insulation, energy generation via photovoltaics) window/facade system for new ultra-low energy buildings.

The subject matter of the project was about the invention of a multiple glazed unit as part of window fixtures and building's front wall façades, containing rigid flat glass plates. One of such plate is covered with a thin electrically conductive layer, furnished with electrodes and supplied by voltage and active photovoltaic system, with a face sealed around its entire circumference, and a compound resistant to water, moisture and temperature variations.

The objective of the research was to optimize material and electrical parameters for heating rather than using other conductive components for developing a simple and compact design of universal multiple glazed unit.

The project has been resulted in a novel multifunctional window: a façade glass unit for building integration that **1)** provides semi-transparent heating of the interior of the building, **2)** uses semi-transparent photovoltaic to generate electricity and **3)** delivers superior thermal

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	■
Control systems	

insulation properties of the whole system.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/196662_en.html*

NECSO B-c 13

Nanoscale Enhanced Characterization of Solar selective coatings

CREDITS

Project ID	310344
Country	Spain
Coordinator	Fundacion Tekniker
Funded under	FP7-NMP
Started in	2013-03-01
Ended in	2016-02-29
Contact information	Javier Barriga, javier.barriga@tekniker.es

[Relation to the current research]
Development of protocols as a tool useful for developers, producers and end users to increase the efficiency (under many point of view) of selective coating for solar plants.

Purpose	
EE / Consumption reduction	
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

[Project description] The main idea behind NECSO project is to provide tools to solar plants builders, to guarantee that their selective coating will work properly during 20 to 25 years.
Infact, if optical parameters of coatings (absorbency and emissivity) are relatively easy to measure on specimens after the deposition process, it is more complicate to characterize the evolution of these values in a relatively short period of time, to ensure the proper performance of the coating during 25 years; nowadays indeed, these components are normally guaranteed only for 2 years.
Therefore, the main objective of NESCO was to correlate nano-structure and nano-mechanical properties of these coatings, and related requirements (Nano-roughness, Nano-hardness, crystallography, composition, vibrational spectra...) with performance requirements (optical and, more important, life expectancy) to develop characterization and degradation protocols to serve as a powerful tool for coating developers, producers and end users for life prediction to push the collector parameters (temperatures and environments) to higher efficiency parameters.
Thus, during the project testing equipment,

protocols and models for lifetime assessment have been developed in order to assess the expected lifetime of the solar selective coatings for high temperature parabolic through Concentrated Solar Power applications.

[Partners' list] ARIES INGENIERIA Y SISTEMAS S.A, Spain - CSM INSTRUMENTS, Switzerland - KEMIJSKI INSTITUT, Slovenia - TECNOLOGIA DE VACIO SLU, Spain - KATHOLIEKE UNIVERSITEIT LEUVEN, Belgium - CENTRALE RECHERCHE SA, France.

References

1) **Necso project website,** *www.necso.eu*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/result/rcn/187006_en.html*

SmartBlind B-c 14

Development of an active film for smart windows with inkjet method. Application to a building envelope component: autonomous smart device

CREDITS	
Project ID	314454
Country	France
Coordinator	Polymage SARL
Funded under	FP7-NMP
Started in	2012-09-01
Ended in	2015-08-31
Contact information	Pierre Sixou, (Technical Director), mob. +33493881725

[Relation to the current research]
Development of an energy efficient smart window to guarantee a low-cost industrial solution.

[Project description] The SmartBlind project aimed at develop an energy efficient smart window that will include a hybrid film composed of an electro-chromic film and a photovoltaic film, printed on a long-lasting flexible substrate.
Project's main objective were:
1) to reduce by 50% the weight of the system (if compared with normal windows), offering at the same time transparency and flexibility;
2) to improve the optical response-time of windows, while enabling the switching to larger panes;
3) to integrate an electronic control system with an embedded power source;
4) to guarantee a low-cost industrial solution adaptable to large and shaped surfaces.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	■
Energy generating	
Control systems	

[Partners' list] POL FR SME POLYMAGE SARL, France – FFCT PT Research Center FUNDACAODAFACULDADEDECIENCIAS E TECNOLOGIA DA UNIVERSIDADE NOVA DE LISBOA, Portugal – ARDEJE FR SME ARDEJE SARL, France – DITF DE Research Center DEUTSCHE INSTITUTE FUR TEXTIL - UND FASERFORSCHUNG DENKENDORF, Germany – LOD PL Research

Center POLITECHNIKA LODZKA – VUB BE Research Center VRIJE UNIVERSITEIT BRUSSEL, Belgium – IASO ES SME IASO SA, Spain – ACAT PT SME A CATEDRAL - CARPINTERIA MARCENARIA LDA - CEA-INES FR Research Center COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, France – TERM RO SME TERMOGLASS CIV SRL*TERMO – LEITAT ES Research Center ACONDICIONAMIENTO TARRASENSE ASSOCIACION, FCCCO ES Other FCC CONSTRUCCION SA - KS FR Other KURT SALMON FRANCE SAS.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/result/rcn/150225_en.html*

SolarGain B-c 15

Low cost switchable reflective polymeric solar heat gain control films for energy efficient smart window applications

CREDITS

Project ID	285952
Country	United Kingdom
Coordinator	Eurofilms Extrusion
Funded under	FP7-SME
Started in	2011-10-01
Ended in	2014-03-31
Contact information	Nick Smith, Eurofilms Extrusion Limited - nicks@eurofilms.com

[Relation to the current research]
Development of a low-cost switch-able window film suitable for bot retro-fit solution or in new window assemblies.

[Project description] SolarGain aim was to develop a low cost switch-able and fully adjustable polymer window film that allows energy savings by controlling heat and gain losses, thus resulting in an energy saving of up to 70%.
The SolarGain film consists of Giant Birefringent Optical elements, assembled from multi-layer polymers' films, designed to reflect light of one polarization direction while being transparent for the other polarization direction; the liquid crystals in-between the two GBO reflective polarisers realize a switch-able polymeric window film for solar heat gain control.
It enables the regulation of solar infrared radiation penetration into buildings meaning that in summer it shields from excessive sun radiation – by absorbing specific wavelengths of light – (saving in this way air-conditioning costs) while in winter it maximises sun heat radiation penetration, saving heating costs as well. It is transparent, colourless, dynamic and could be used either as a retro-fit solution or in new window assemblies, as a part of the window-unit, to control heat/energy loss in winter months and solar heat gain (overheating) during summer months.
To work, it requires a small voltage to allow the

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	■
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

film to switch.
Incorporated in a brand new sealed-window unit with state-of-the-art photovoltaic and sensor technology, SolarGain film allows to achieve an U-value lower than 1,2 Wm^2/K, a light transmittance higher than 0,45 in the off state, a solar heat gain coefficient lower than 0,05 in the on state, a 15 years and over acceptable performance lifetime and a manufacturing cost below than 60€ per square meters.

[Partners' list] WELLS PLASTICS LTD, United Kingdom - HANITA COATINGS RCA LTD, Israel - ALUMINIOS J.P. DEL PINO SL, Spain - JOANNEUM RESEARCH FORSCHUNGSGESELLSCHAFT MBH, Austria - THE UK MATERIALS TECHNOLOGY RESEARCH INSTITUTE LIMITED, United Kingdom - HERMANOS DEL PINO ESPINOSA SL, Spain.

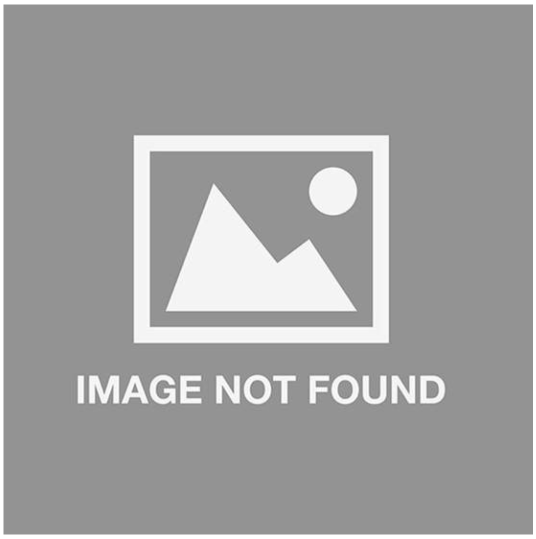
References
1) **SolarGain project website,** *http://www.solargain.eu/project.html*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/100404_en.html*

SOLPCM B-c 16

Solar Collector and PCM Thermal Façade for Low Carbon Buildings

CREDITS

Project ID	622117
Country	United Kingdom
Coordinator	Univ. of Nottingham
Funded under	FP7-PEOPLE
Started in	2014-08-15
Ended in	2016-08-14
Contact information	Paul Cartledge Tel.: +44 115 9515679



[Relation to the current research]
Studies aimed at develop a novel facade for increase building performance, integrating solar energy technology and novel materials, such as PCM.

[Project description] The aim of SOLPCM project was to develop green buildings technology integrated with solar energy and novel materials to better utilize renewable energies for low carbon buildings.
Project works started reasoning on the study of Trombe wall integrated with novel materials (as, for instance, solar selective absorbing coating, transparent insulation material and phase change material).
Within project's activities, it has been produced a novel PCM usable as renewable energy storage material in buildings, suitable for contexts with a great amount of solar radiation and a great daily outdoor air temperature range.
According to the first demo case simulation, when the latent heat is 250 kJ/kg, with a phase change temperature of 40±5 °C, the energy saving (reductions of building load) can reach the 32.5% compared with non-SSPCM board.
After project conclusion, the research results have been applied in a real scale building to storage thermal energy.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

References
1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/185764_it.html*

Smart, lightweight, cost-effective and energy efficient windows based on novel material combinations

CREDITS

Project ID	314407
Country	Denmark
Coordinator	Teknologisk Institut
Funded under	FP7-NMP
Started in	2012-10-01
Ended in	2016-09-30
Contact information	Niels Morsing, Danish Technological Institute, nmo@dti.dk

WIN SMART
SETS NEW STANDARDS FOR WINDOWS!

[Relation to the current research] Will to overcome shortcoming of technology already used - such as VIG - with the development of new smart, lightweight, cost effective and energy efficient windows, based on novel material combination.

[Project description] The goal of WINSMART project was to develop a smart, lightweight, cost-effective and energy efficient window based on novel material combinations in order to reduce:
1) the U-value from 0,8 to 0,3;
2) the weight of the window by 50%;
3) the window's overall energy consumption (embodied energy) during the manufacturing process and disposal/recycling by 50 %.
The WINSMART concept combines vacuum insulation glazing (VIG) with optical transmission control schemes to lower U-value by up to 60 %. The adopted strategy overcomes common issues of traditional VIG[1] that are not able to reach these low values due to technical limitations, by using a flexible edge seal that consists of laser-welded metallic ribbons. The result is a VIG-unit with a flexible edge seal and without a pump-out hole.
Another topic that WINSMART dealt with was about discovering how optical transmission control technologies, incorporated into the VIG, can facilitate colour change (shading) in response to the intensity of incident light (photochromic) or to a small applied voltage (electro-chromic).
Within the WINSMART project, different technologies of optically switch-able windows have

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

[Notes]
1 VIG currently has critical aspects connected to the edge seal. Typically, the edge between the panes is sealed with a $PbO\text{-}SiO_2$ based solder glass, before being evacuated and sealed. The result is a rigid edge seal and a visible pump-out hole in one of the corners of the glazing which impose limitations on the performance of the VIG unit: for large sizes, high temperature differences between the inner and outer pane result in differential expansion of the panes, which may bend and break the VIG.

been developed as well as the current state-of-the-art electro-chromic window with oxide electro-chromic and oxide counter electrode, separated by an ion conductor, will be further improved. As alternative, electro-chromic windows with redox electrolyte are being developed.

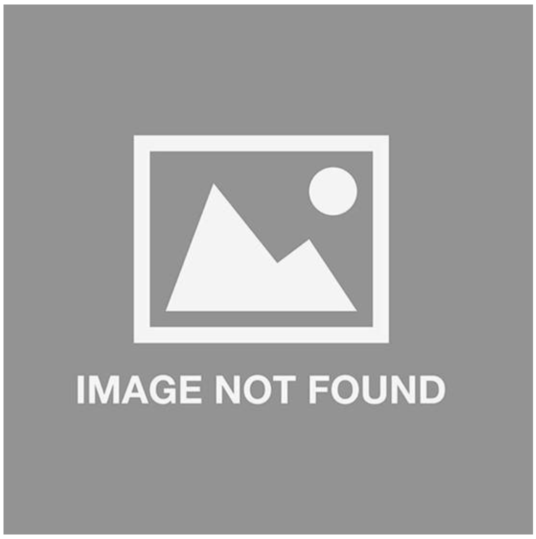
[Partners' list] EIDGENOSSISCHE MATERIALPRUFUNGS- UND FORSCHUNGSANSTALT, Switzerland - FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V., Germany - UNIVERZA V LJUBLJANI, Slovenia - AGC GLASS EUROPE SA, Belgium - PHOTOSOLAR AS, Denmark - ECONTROL-GLAS GMBH & CO. KG, Germany - IDEALCOMBI AS, Denmark.

References
1) **WinSmart project website,** *http://winsmart.eu*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/104742_en.html*

WISER C-c 18

The energy saving and burglar proof window that breathes for enhanced indoor comfort

CREDITS	
Project ID	710440
Country	Poland
Coordinator	Bergamo Tecnologie
Funded under	H2020-SMEINST-1-2015
Started in	2015-12-01
Ended in	2016-05-31
Contact information	n.f.



[Relation to the current research] Development of a window prototype able to increase its performance response by using a simply traditional technology,

[Project description] WISER project developed a reversible window enabled by innovative hydraulic gaskets and burglar-proof electro-magnetic locking mechanisms, fully integrated in the structure of the frame, operated via a simple-to-use control system, which can be integrated to a central building automation.
Its advantage is the ability to reduce the thermal radiation from the outside during summer season while reducing thermal losses from the interior in winter, thanks to the double positioning of the Low-E glass.
Enhanced ventilation is permitted through an innovative use of the active gaskets, which allow air flowing while keeping the window locked.
WISER window can be easily adapted to different climates and seasons along the year, as well as material combinations and building types.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	■
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/199308_en.html*

BRESAER C-o 19

BREakthrough Solutions for Adaptable Envelopes in building Refurbishment

CREDITS	
Project ID	637186
Country	Spain
Coordinator	Acciona
Funded under	H2020-EeB-2014
Started in	2015-02-01
Ended in	ongoing (2019-07-31)
Contact information	Ms. Isabel Lacave Azpeitia, isabel.lacave.azpeitia.EXT@acciona.com

[Relation to the current research] Development of a building envelope system which comprises dynamic and automatically controlled window.

[Project description] The objective of BRESAER project is to design, develop and demonstrate an innovative, cost-effective, adaptable and industrialized envelope system for buildings refurbishment, made of active and passive pre-fabricated solutions.

It comprises: **1)** dynamic window with automatic and controlled air-tightness and insulated solar blinds (automatically adjustable according to sun's position and occupant's comfort), equipped with energy saving and visual comfort strategies, such as light redirection and response to solar radiation; **2)** multifunctional and multilayer insulation panels; **3)** combined solar thermal air and PV envelope component for indoor space heating and ventilation, thermal insulation and electricity generation; **4)** multifunctional lightweight ventilated façade module; **5)** BIPV and combined thermo-reflexive (improving fire resistance) self-cleaning coating (through photo-catalytic nano-particles).

The whole building envelope system, as well as the energy use of the building, will be governed by a BEMS, specifically developed to measure and control both the envelope and the building's energy consumption trough integrated

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

simulation-based control techniques for the automated establishment of optimal operational plans. Thanks to the improvement in building envelope's performance it has been expected an energy demand reduction, for space heating and cooling, of about the 30%, contributions for space conditioning and electricity of, respectively, about 37% and 12%, a total primary energy consumption reduction of at least the 60%, and, in any case, with a consumption of less than 60 kWh/m², along with an improved indoor environmental quality with a pay-back time below than 7 years.

[Partners' list] ASOCIACION ESPANOLA DE NORMALIZACION, Spain - FUNDACIO PRIVADA ASCAMM, Spain - FUNDACIO EURECAT, Spain - FUNDACION CARTIF, Spain - EKODENGE MUHENDISLIK MIMARLIK DANISMANLIK TICARET ANONIM SIRKETI, Turkey - EPITESUGYI MINOSEGELLENORZO INNOVACIOS KOEHASZNU TARSASAG, Hungary - MONDRAGON CORPORACION COOPERATIVA SCOOP, Spain - NANOPHOS ANONIMI EMPORIKI ETAIRIA ANAPTIXIS KAI YPIRESION - NANOPHOS COMMERCIAL SOCIETE ANONYME OF SERVICES AND DEVELOPMENT, Greece - NATIONAL MINISTRY OF EDUCATION, Turkey - NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO, Netherlands - SOLARWALL EFFICIENT ENERGY SL, Spain - STAMTECH SRL, Italy - TECHNION - ISRAEL INSTITUTE OF TECHNOLOGY, Israel – TECHNOFI, France - FUNDACION TECNALIA RESEARCH & INNOVATION, Spain - YOURIS.COM, Belgium - STAM SRL, Italy - VEOLIA SERVICIOS LECAM SOCIEDAD ANONIMA UNIPERSONAL, Spain

References
1) **Bresaer project website,** *www.bresaer.eu*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/193471_en.html*

P2Endure C-o 20

Plug-and-Play product and process innovation for Energy-efficient building deep renovation.

CREDITS

Project ID	723391
Country	Netherlands
Coordinator	DEMO Consultants
Funded under	H2020-EE-2016-PPP
Started in	2016-09-01
Ended in	ongoing (2020-08-31)
Contact information	Coordinator: Dr. Rizal Sebastian, rizal@demobv.nl

[Relation to the current research] Fostering of innovative solutions for buildings' renovation based on prefabricated systems and technology; among them, significant is the prototype of smart reversible window.

[Project description] The project promotes the development of innovative solutions for buildings' deep renovation based on prefabricated Plug-and-Play systems, in combination with on-site robotic 3D-printing and Building Information Modelling (BIM), to be applied and monitored in 10 real projects in 4 geo-clusters within EU.

One of the objective is to increase the scale and level of adoption of such solutions through innovative combinations and processes and supporting ICT tools, with the aim of create the supply-chain infrastructure for large-scale commercial implementation and up-scaling of prefabricated deep renovation solutions.

Among the proposed solutions, it has been developed even a smart energy-efficient window, reversible in the sense that it can be rotated by 180° to reduce the thermal radiation from the outside during summer season, thus reducing the thermal dispersion from the interior during winter, thanks to the double positioning of the low-E glass.

Such smart window provides natural ventilation, rotating and locking mechanisms which enhance anti-burglary features, as well as integration with state-of-the-art domotics solutions. It satisfies the

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

needs for high energy-efficiency, better indoor climate, and top class security features.
The reversible window technology is enabled by innovative hydraulic gaskets and burglar-proof electro-magnetic locking mechanisms, fully integrated within the frame.

[Partners' list] Huygen Installatie Adviseurs, Netherlands - BECQUEREL ELECTRIC SRL, Italy - LENZE-LUIG 3-L-PLAN GBR, Germany – INVELA, Denmark - BERGAMO TECNOLOGIE SPZOO, Poland - "PRZEDSIEBIORSTWO ROBOT ELEWACYJNYCH ""FASADA"" SPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA", Poland - FERMACELL GMBH, Germany - SGR SERVIZI SPA, Italy - RINA CONSULTING SPA, Italy - MOSTOSTAL WARSZAWA SA, Poland - UNIVERSITA POLITECNICA DELLE MARCHE, Italy - TECHNISCHE UNIVERSITAET BERLIN, Germany - MIASTO STOLECZNE WARSZAWA, Poland - PANPLUS ARCHITEKTUUR, Netherlands - CAMELOT VASTGOED NEDERLAND BV, Netherlands.

References

1) **P2Endure project website,** *https://www.p2endure-project.eu/en*
2) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *https://cordis.europa.eu/project/rcn/205666_it.html*

HEARTC-o 21

Holistic Energy and Architectural Retrofit Toolkit

CREDITS	
Project ID	768921
Country	Italy
Coordinator	POLIMI
Funded under	H2020-EEB-2017
Started in	2017-10-01
Ended in	ongoing (2021-09-30)
Contact information	n.f.

[Relation to the current research]
Development of a retrofit tool-kit with different technologies to transform an existing building into a smart building. Among them, significant is the operational guidance to assemble existing windows frames to increase their performance.

[Project description] HEART project aims at develop a multifunctional retrofit tool-kit within which different subcomponents – ICT, BEMS, HVAC, BIPV and Envelope Technologies – cooperate in synergy to transform an existing building into a Smart Building.
Based on a whole-building performance approach, the tool-kit is conceived to achieve extremely high levels of energy efficiency in the existing residential building stock.
The system's central core consists of a cloud-based computing platform which concentrates managing and operational logics to support decision-making in planning and construction, as well as energy performance enhancement and monitoring during operation.
The tool-kit provide energy saving, energy fluxes optimization, data exchange, stakeholders' active involvement and Smart Grid interactivity.
Interoperable building technologies and installations are also integrated in the tool-kit: envelope solutions (thermal insulation and windows) to ensure a reduction of thermal loads, as well as technical systems (BEMS, BIPV, heat pump, fan-coils, power controller, storage systems) to ensure energy efficiency and RES

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

exploitation.
An interesting solution promoted within project's activities about energy efficient envelope technologies, regards the development of an operational guidance to assemble the existing windows frame, in the event that they can be maintained, with a specific set of innovative cost-effective and easy-to-apply technologies such as low-thickness insulated glass units, new frame elements, shading systems or advanced coatings/films.

[Partners' list] ECOLE NATIONALE DES TRAVAUX PUBLICS DE L'ETAT, France - UNIVERZA V LJUBLJANI, Slovenia - ACCADEMIA EUROPEA DI BOLZANO, Italy - TURBO POWER SYSTEMS LTD, United Kingdom - HELIOTHERM WARMEPUMPENTECHNIK GES MBH, Austria - ZH SRL, Italy - VYZVOICE SA, Luxembourg - STILLE EKO DRUSTVO S OGRANICENOM ODGOVORNOSCU ZA TRGOVINU I USLUGE, Croatia - REVOLVE WATER, Belgium – QUANTIS, Switzerland -CONSTRUCCIONES GARCIA RAMA SL, Spain - COMITE EUROPEEN DE COORDINATION DE L'HABITAT SOCIAL AISBL, Belgium - AZIENDA CASA EMILIA ROMAGNA DELLA PROVINCIA DI REGGIO EMILIA, Italy - EST METROPOLE HABITAT, France - FUNDACION CTIC CENTRO TECNOLOGICO PARA EL DESARROLLO EN ASTURIAS DE LAS TECNOLOGIAS DE LA INFORMACION, Spain

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/211645_en.html*
2) **HEART project website,** *http://www.heartproject.eu*

InDeWaG C-c 22

Industrial Development of Water Flow Glazing Systems

CREDITS

Project ID	680441
Country	Germany
Coordinator	Univ. Bayreuth
Funded under	H2020-EE-2015-1-PPP
Started in	2015-08-01
Ended in	2019-01-31
Contact information	Prof. Dr. Dieter Brüggemann, coordinator@indewag.eu

[Relation to the current research]
Set-up of new solutions for building envelope through the maximization of daylight thanks to an innovative transparent glass facade.

[Project description] InDeWaG project proposes new solutions for building envelope with the aim to reduce at least the 15% of building cost through:

- the production of standardized components, which can be used for multiple building types in different climatic zones;
- the development of a simulation tool for precise early stage planning of buildings, that makes use of innovative glazing building envelope and interior elements, such as those developed within the project (i.e. Fluid Flow Glazing façades - FFG and Radiant Interior Walls - RIW)

The proposed approach is based on the maximization of the use of daylight by a transparent glass façade within which the active fluid flow glazing will combine water, as heat transfer media, with compressed air and solar-thermal energy conversion with BIPV (Building Integrated Photovoltaic).
Project's final goal is to bring to industrial ripeness the façade and the interior wall system developed, based on radiant heating and cooling glass surfaces made from water and/or air flow glazing, which harvests solar energy for various use at large scale.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	■
Energy generating	
Control systems	

Indeed, even if the benefits of fluid flow glazing facade technologies were already proven over years (thanks to few demonstrator projects) there are still many difficulties for their right practical implementation; InDeWaG would try to extend state-of-art in such technologies through the integration of a series of transparent, translucent or opaque solar thermal absorbers which operate at different nominal temperatures (namely 30ºC for heating and seasonal energy storage, 60ºC for sanitary hot water supply and 90ºC for cooling through absorption chillers).
In this way, a complete glass curtain wall façade will be able to deliver all the levels of thermal energy required by a building while retaining its architectural aesthetics.

[Partners' list] BOLLINGER + GROHMANN CONSULTING GMBH, Germany - ETEM BULGARIA AD, Bulgaria - HTCO GmbH, Germany – GMAE TRANSFORMA SL, Spain - FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V., Germany - UNIVERSIDAD POLITECNICA DE MADRID, Spain - CERVIGLAS S.L., Spain - ARCHITEKTONIKA STUDIO DRUZHESTVO SOGRANICHENA OTGOVORNOST, Bulgaria - CENTRAL LABORATORY OF SOLAR ENERGY& NEW ENERGY SOURCES OF THE BULGARIAN ACADEMY OF SCIENCES, Bulgaria.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/198361_en.html*
2) **InDeWaG project website,** *http://www.indewag.eu*

ENergy harVesting by Invisible Solar IntegratiON in building skins

CREDITS

Project ID	767180
Country	Netherlands
Coordinator	Org. Voor Toegepast
Funded under	H2020-EEB-2017
Started in	2017-10-01
Ended in	ongoing (2022-03-31)
Contact information	n.f.

[Relation to the current research] Will to enhance building façades as energy harvesting surface by implementing performance (and transparency) of PV solutions.

[Project description] Envision project focuses on the possibility to exploit facade as energy harvesting surfaces (both opaque and transparent surfaces) owing to the great availability of building surface within 2028 (estimated approximately around 120 billion m^2).

The proposed hybrid solutions will harvest energy either thermal and electric from the whole envelope, using standard PV solutions for roof and developing new invisible aesthetic solutions for the façade that will gather maximum amount of solar energy, while simultaneously retain their aesthetic and functional properties. To maximise efficient usage of the harvested energy, such solutions are coupled with novel heat systems and district heat networks.

To sum up, ENVISION harvesting of solar energy is achieved via:

1) heat collecting non-transparent aesthetically pleasing façade elements that capture the NIR solar radiation;

2) heat harvesting ventilated glass to gather the NIR solar radiation;

3) electricity harvesting photovoltaic glazing solutions.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	■
Control systems	

[Partners' list] Akzo Nobel Decorative Coatings bv, Netherlands - IMPERIAL CHEMICAL INDUSTRIES LIMITED, United Kingdom - BAM TECHNIEK BV, Netherlands - BAM WONINGBOUW BV, Netherlands - ELECTRICITE DE FRANCE, France - PILKINGTON NEDERLAND BV, Netherlands - PILKINGTON DEUTSCHLAND AG, Germany - RINA CONSULTING SPA, Italy - BERGAMO TECNOLOGIE SPZOO, Poland - UNIVERSITA DEGLI STUDI DI GENOVA, Italy - STICHTING VESTIA, Netherlands - EMERGO HOUT & BOUW BV.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/211446_en.html*

Large area transparent thin film thermoelectric devices for smart window and flexible applications

CREDITS

Project ID	645241
Country	Portugal
Coordinator	Uninova
Funded under	H2020-ICT-2014-1
Started in	2015-01-01
Ended in	2018-12-31
Contact information	n.f.

[Relation to the current research] Development of a smart window technology equipped with distributed sensor network to measure air quality and environmental parameters, suitable to further control indoor climate conditions.

[Project description] The main objective of the TransFlexTeg project is to demonstrate the functionalities of a smart window able to measure air quality and environmental parameters - such as temperature, sun radiation and humidity - through the development of an innovative large area distributed sensor network, integrating transparent thin film thermoelectric devices and sensors to save more than 25% of the electrical usage of residential homes and office buildings.
For the development of such devices, different concepts have been proposed:
1) large area high performance transparent thermoelectric thin films, deposited on flexible substrates for thermal energy harvesting;
2) low cost high throughput thin film thermal sensors, for thermal mapping and gesture sensing;
3) flexible smart windows and walls with energy harvesting, environmental sensing and wireless communication functionalities.
Operational data have been automatically collected and can be utilized for controlling heating, cooling and ventilation systems of indoors.
The proposed concept of smart windows replaces several conventional sensors with a distributed

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	■
Other	

Classification	
High-performance	
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	■

sensor network that is invisibly integrated into windows. In addition to the power generated from the thermal energy harvesting, the thermoelectric elements (TE) are also used as temperature sensors that, while being distributed over large area, enable thermal mapping of the area instead of just one or few values measured from particular points.

Even if this smart window can be produced on glass, project's final goal will be the fabrication on transparent flexible organic substrates using Roll to Roll Atomic Layer Deposition (R2R ALD), that can be fixed or retrofitted on existing windows or walls, which will significantly broaden the field of applications and improve business opportunities.

[Partners' list] SCIENCE TECHNOLOGY RESEARCH PARTNERS LIMITED, Ireland – Teknologian tutkimuskeskus VTT Oy, Finland - TEKNOLOGIAN TUTKIMUSKESKUS VTT, Finland - PICOSUN OY, Finland - AGFA-GEVAERT N.V., Belgium - AALTO-KORKEAKOULUSAATIO, Finland - CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, France - SOLEARTH LIMITED, Ireland - GRINP SRL, Italy.

References

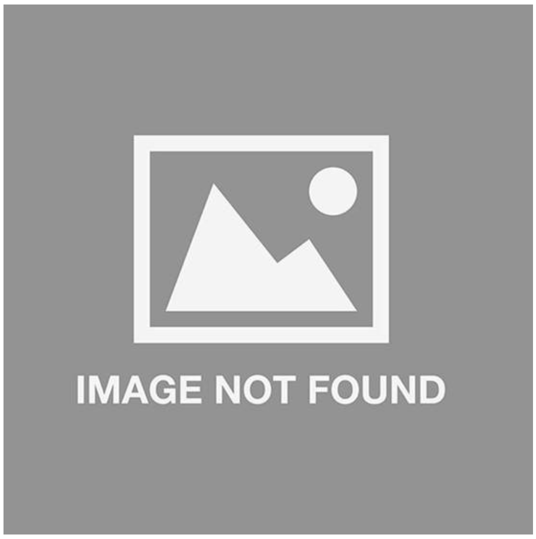
1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/194300_en.html*

2) **TransFlexTeg project website,** *http://www.transflexteg.eu*

IntelGlazing C-o 25

Intelligent functional glazing with self-cleaning properties to improve the energy efficiency of the built environment

CREDITS	
Project ID	679891
Country	United Kingdom
Coordinator	UCL
Funded under	ERC-2015-STG
Started in	2016-03-01
Ended in	ongoing (2021-02-28)
Contact information	n.f.



[Relation to the current research]

Development of intelligent window insulation technologies to reduce thermal losses through them.

[Project description] The objective of this proposal is to develop intelligent window insulation technologies from sustainable materials, with the aim of reduce the amount of heat escaping or entering a window depending upon the ambient environmental conditions and obtain, in this way, significant reductions in terms of energy needed for regulating buildings' temperatures.

Recognising the distinct requirements between newly built and existing infrastructure, two parallel concepts will be developed:

1) a new class of intelligent glazing for new window installations;

2) a flexible, intelligent, polymer film to retrofit existing window installations.

Both solutions will be enhanced with unique self-cleaning properties, bringing about additional economic benefits through a substantial reduction in maintenance costs.

Overall, the project's aim is to develop intelligent glazing technologies that combine:

1) power savings of > 250 W/m^2 of glazing capable of delivering more than the 25% of energy savings and efficiency improvements, the 50% plus if compared with existing static solutions;

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

2) visible transparency of more than 60% to comply with the EU standards for windows;
3) self-cleaning properties that introduce a cost balance.

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/199577_en.html*

FIBGLOW C-c 26

High insulating fiberglass window and curtain wall profiles

CREDITS

Project ID	673878
Country	Italy
Coordinator	Gualini SPA
Funded under	H2020-SMEINST-1-2014
Started in	2015-05-01
Ended in	2015-08-31
Contact information	n.f.

[Relation to the current research]
Design of a fiber glass based window with enhanced properties.

[Project description] FIBGLOW project consisted in the design, industrialization and commercialization of fiberglass-based window and curtain wall profiles, with enhanced thermal insulation, mechanical and fire resistance properties.
Based on fiberglass "threads" embedded into a unique inorganic aqueous-based resin, the FIBGLOW profiles present the following outstanding properties:

- U-value of 0,26;
- Outstanding fire resistance (Euroclass A1);
- High mechanical properties (Young Modulus of 21,3 GPa);
- Great durabiltity (38% longer than PVC).

It has been established that the adoption of FIBGLOW solutions in buildings has led to efficiency resulted in energy savings of up to 2,06% per year.

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	■
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

References

1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/result/rcn/185482_en.html*

Sustainable Prefabricated Glass Façade with Performance Exceeding State-of-the-art Glass Façades

CREDITS	
Project ID	737757
Country	Slovenia
Coordinator	Trimo d.o.o.
Funded under	H2020-FTIPilot-2016-1
Started in	2017-01-01
Ended in	2018-12-31
Contact information	n.f.

[Relation to the current research] Development of innovative solution in glass faced to obtain a superior thermal insulation glass curtain wall system.

[Project description] The Q-Air project is about the development of an innovative solution in glass façade design for more sustainable architecture and construction.
Project's final development was a glass curtain wall system in which a unique single skin glass facade, thanks to is multi-chamber insulating core, offers all the performance and benefits of an active double skin façade, such as a superior thermal insulation and an U value ≥ 0.3 kWh/m²K.
To assure a complete building envelope solution for any building type or application, Q-Air is available in transparent, translucent and opaque unit options, supported by either polymer or aluminium extrusion profiles.
Q-Air can be used either for new constructions or refurbishments, for all-glass buildings or for buildings incorporating other materials.
Other performance values of Q-Air system are: a g value comprises between 0,09 and 0,34 and a LT between 0,10 and 0,56.
Q-Air glass facade manages solar heat gain (g value), thermal transmittance (U value) and light transmittance (LT value) in a very good manner so that a full transparent glazed area (panoramic

Purpose	
EE / Consumption reduction	■
Sustainability in buildings	
Other	

Classification	
High-performance	■
Selective	
Adaptive glazing / Dynamic facade	
Energy generating	
Control systems	

glazing) is achievable whilst fulfilling buildings' regulations for thermal insulation and total energy consumption of the building.
Indeed, Q-Air provides a superior thermal insulation level with a U value major to 0.30 W/m^2K for fully transparent glass façade.

[Partners' list] Trimo, architectural solutions, d.o.o. - Kohlbecker Gesamtplan GmbH - ZAG, Slovenian national building and civil engineering institute - Cantori s.r.l. - Skandinaviska Glassystem AB

References
1) **European Commission, CORDIS portal, Projects and Results,** project's result in brief, available at: *http://cordis.europa.eu/project/rcn/207683_en.html*
2) **Q-Air project H2020,** TRIMO website, *https://trimo-group.com/en/trimo/products/facades-and-walls/q-air/q-air-project-h2020/#tab-1038*

APPENDIX II
Smart materials for Smart applications

Despite multiple definitions that can be given about what a smart material is, the five fundamental features that distinguish it (from a traditional material) can be resumed as follow (Abeer 2017, Addington and Schodek, 2005, Iranmanesh et al., 2013):

- **immediacy**, defined as the ability to respond to real-time solicitations;
- **transiency**, defined as the ability to respond to more than one environmental state;
- **self-actuation**, defined as the intrinsic ability to respond to external stimuli;
- **selectivity**, intended as the ability to respond in a discrete and predictable way;
- **directness**, because generally the response is local and consequent to an activating event.

Therefore, available smart materials can be distinguished according to different classifications; most common are those that divide them based on:

- their **intrinsic properties**, such as nature, appearance, chemical composition, mechanical and physical properties, etc.
- the **performance they are able to guarantee**; distinguishing among materials with **fixed performance** (materials' properties that remain constant under normal conditions) and materials with **variable performance**. Fixed-performance materials could be structural advanced materials, thermo-structural materials or surface-properties materials while variable-performance materials can be in turn divided between property-changing or energy-exchanging materials;
- their **modes of operation**:
  - **passive,** if activated in response to temperature or lighting variations;
  - **active**, if electrically regulated, through artificial stimulus;
  - **intelligent** (or self-regulating), if able to autonomously adapt to the surrounding environment, coupling both the above-mentioned manners.

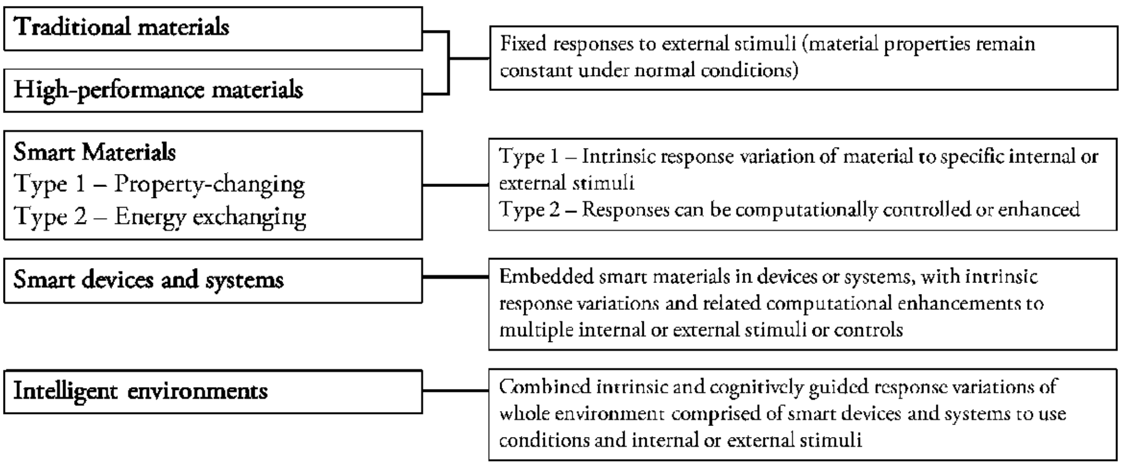


Fig. 01 – Comparison between smart materials and traditional materials.

Another classification – that descends from previous ones – distinguishes smart materials according to two categories: from one side materials that vary one or more of their features (chemical, thermal, mechanical, magnetic, optical or electrical) depending on the changes of the external conditions or through direct stimuli; while from the other, materials that – following various inputs – change energy into another form (Abeer, 2017; Addington and Schodek, 2005; Aggour and Soliman, 2013; Iranmanesh et al., 2013; Malekizadeh et al., 2014; Ritter, 2017; et al.)

First-class materials are called **property-changing materials** and include: thermochromics[1], electrochromic[2] and related technologies, mechanochromics[3], chemochromics[4], phototrophics[5], magnetorheological and electrorheological[6], thermotropic[7], shape-memory[8], phase-changing materials[9] and adhesion-changing materials[10].

Second-class materials instead, even defined as **energy-exchanging materials**, include: light-emitting materials[11], photovoltaics, electrostrictives and magnetostrictives[12], Light Emitting Diodes, thermoelectric[13] and piezoelectric[14] materials, piezoresistive[15] and thermo-responsive materials[16].

If in both cases, changes are direct and reversible, first-class materials are those altered in their molecular structure while seconds remain the same since it's only energy that will be converted into another form.

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[1] Materials that change their color after thermal energy inputs.

[2] Materials that change color when a voltage is applied. Related technologies include liquid crystals and suspended particle devices that change color or transparencies when electrically activated.

[3] Materials that change color due to imposed stresses and/or deformations.

[4] Materials that change color when exposed to specific chemical environments

[5] Materials that change their color when exposed to light.

[6] Materials – generally fluids – in which the application of a magnetic field (or, for electro-rheological, of an electrical field) causes a change in micro-structural orientation, resulting in a change of the viscosity of the fluid.

[7] Materials in which an input of thermal energy (or radiation for a phototropic, electricity for electrotrophic and so on) alters their microstructure through a phase change. In a different phase, most materials demonstrate different properties, including conductivity, transmissivity, volumetric expansion, and solubility.

[8] Materials in which an input of thermal energy (that can also be produced through resistance to an electrical current) alters the microstructure through a crystalline phase change. This change enables multiple shapes in relationship to the environmental stimulus.

[9] Materials that use chemical bonds to store and release heat.

[10] Materials that change the attraction forces among their atoms or molecules when exposed to lights or to an electrical field.

[11] Materials that convert energy into an output of radiation energy, in the visible spectrum; they include: photoluminescents, where input is radiation energy from the ultraviolet spectrum; electroluminescent, where input is electrical energy, and chemoluminescent, where input is a chemical reaction.

[12] Materials in which the application of a (respectively) electrical or magnetic field produces elastic energy in the form of a strain that deforms material's shape.

[13] Materials in which an input of electrical current produces a temperature differential on the opposite sides of the material itself.

[14] Materials in which an input of elastic energy generates an electrical current. This technology is most of time bi-directional which means that input can be switched thus an electrical stimulation will induce a mechanical deformation.

[15] Materials in which the application of a mechanical stress will induce an electrical resistance variation.

[16] Materials that change their shape according to a temperature variation (such as Shape Memory Alloys).

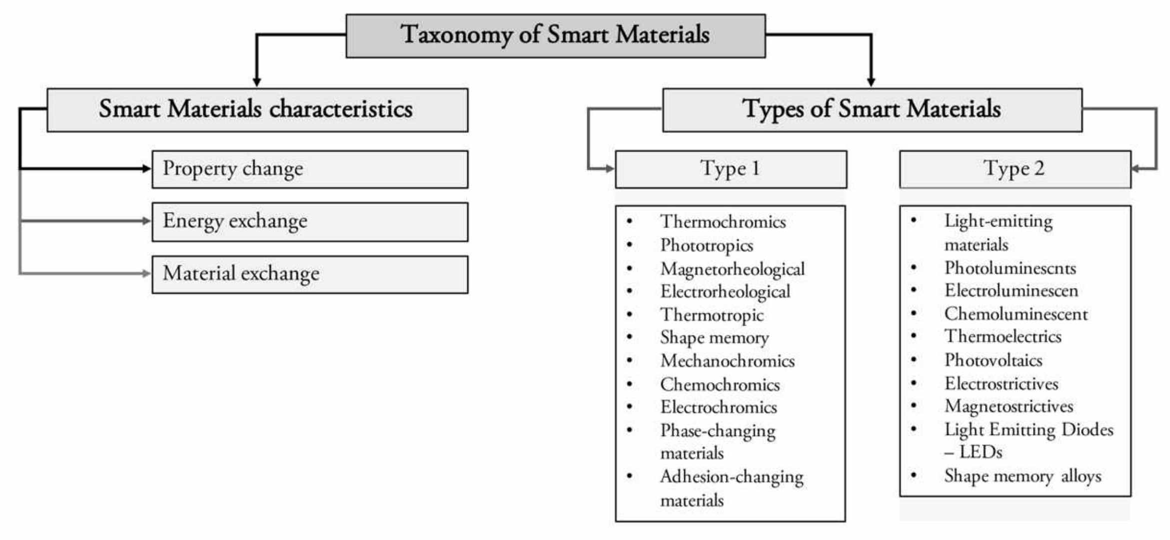

Fig. 02 – Smart materials' taxonomy.

Due to their outside-the-box performance, smart materials' application in construction field implies a wide range of benefit, thanks to the possibilities offered by the use of such more capable, effective and resistant materials (Malekizadeh B. et al., 2014). They indeed, offer increased resistance, formability, durability and other unconventional features (Golabchi et al., 2011) also from an aesthetic point of view, because of their appearance sometimes very attractive.

So, smart materials' application potential in architecture is surely wide, since they can perform different and sometimes juxtaposed roles thanks to the almost uncountable possible combinations among them, suitable for a high-number of purpose.

In the context of technologies for architecture, and especially concerning building envelope's performance, it is clear that smart materials with variable performance are those equipped with the greatest potential since they seem able to face variations of boundary conditions that can affect building performance.

In this domain fit chromogenic, technologies that find fertile ground especially if related to glazed systems, due to the opportunities they offer to control incident solar radiation; phase change materials, able to storage latent heat and to release it further exploiting phase transition phenomena; and nanotechnologies, technologies of an interdisciplinary scope defined as the design, characterization, production and application of structures, services and systems through shape and dimensional control at nanometre scale (The Royal Society & The Royal Academy of Engineering, 2004:5). Functions of nanomaterials include improved chemical and mechanical properties; new electronic, magnetic and optical functions; enhanced thermal properties; biological properties.

Frequently, advanced materials employed in buildings derived from technology transfer processes among industry areas characterized by strong innovation forces (such as aerospace, automotive and biomedical). Materials of such a kind indeed, seem able to perform differently and alternative roles, thanks to smaller sizes, lower assembly time and larger life cycles, by means of their enhanced properties.

However, it has to be said that not all materials and technologies that can be defined as smart materials are useful for implementing building performance because barriers facing their adoption are still present and range from cost's issues, liability to market cycles and a lack of established reliability for some products, as well as a lack of coherence and consistency in the measurement of their success is existing (Abeer, 2017).

BUILDING SYSTEM NEEDS	RELEVANT MATERIAL OR SYSTEM CHARACTERISTICS	REPRESENTATIVE APPLICABLE SMART MATERIALS
Control of solar radiation transmitted through the building envelope	Spectral absorptivity/transmission of envelope material	Suspended particle panels Liquid crystal panels Photochromics Electrochromics
	Relative position of envelope material	Louver or panel systems - Exterior and exterior radiation sensors > Photovoltaics, photoelectrics - Control/actuators > Shape memory alloys, electro and magnetorestrictive
Control of conductive heat-transfer through the building envelope	Thermal conductivity of envelope materials	Thermotropics, phase-change materials
Control of interior heat generation	Heat capacity of interior material	Phase-change materials
	Relative location of heat source	Thermoelectrics
	Lumen/watt energy conversion	Photoluminescents, electroluminescents, light-emitting diodes
Energy delivery	Conversion of ambient energy to electrical energy	Photovoltaics
Optimization of lighting systems	Daylight sensing Illuminance measurements Occupancy sensing	Photovoltaics, photoelectrics, pyroelectrics
	Relative size, location and colour of source	Light-emitting diodes (LEDs), electroluminescents
Optimization of HVAC systems	Temperature sensing Humidity sensing Occupancy sensing CO2 and chemical detection	Thermoelectrics, pyroelectrics, biosensors, chemical sensors, optical MEMS
	Relative location of source and/or sink	Thermoelectrics, phase-change materials, heat pipes
Control of structural systems	Stress and deformation monitoring Crack monitoring Stress and deformation control Vibration monitoring and control	Fiber-optics, piezoelectrics, electrorheologicals, magnetorheologicals, shape memory alloys

Fig. 03 – Mapping of typical building system design needs in relation to potentially applicable smart materials.

Since innovative building materials and, more in general, components and systems currently on-the-market available that can be inserted within this category constitute a very heterogeneous sample, it was decided to report only a sample of promising technologies, considered significant for the present dissertation by virtue of the contribution they offer in implementing building envelope performance.
The selected products have been described according to material properties as it is generally done for building materials, whether traditional or not, distinguishing between wood-based, ceramic, metallic and polymeric products.

Timber-based products

Although timber products with unconventional features are not so spread in architecture – mainly because wood is generally employed by the particular characteristics that signify it – materials treated with surficial coatings able to improve their cleaning abilities and resistance towards atmospheric agents, as well as towards biological and chemical attacks, are possible (Zacchei, 2011).
A product that is worth considering as well, is the translucent wood[17] – developed within the KTH Royal Institute of Technology, in Stockholm, by a team of researchers led by Prof. L. Berglund – apparently comparable to a common polycarbonate-sheet but equipped with the original properties of timber-based support. Thanks to a particular chemical process indeed, researchers managed to remove lignin from it, making it almost colorless; the product obtained was then impregnated with a transparent polymer that allowed uniform optical properties, making it suitable for window fixtures or for increasing the efficiency of solar cells in photovoltaic components.

Fig. 04 – Translucent wood developed within the KTH Royal Institute of Technology in Stockholm.

[17] https://www.kth.se/en/forskning/artiklar/kth-forskare-har-uppfunnit-genomskinligt-tra-1.638511

Ceramic products

The ceramic materials' sector, thanks to the great variety of products it groups (such as ceramics properly said, bricks, glass, concrete, etc.) is the one that, over years, has concentrated the largest number of experiments and investments in research.
Besides, to well-known self-cleaning products (hydrophobic or photocatalytic)[18], innovations in the ceramic field (in the widening sense of that term) are generally aimed at coupling positive aspects that distinguish ceramics with original features.

Fig. 05 – Jubilee Church, R. Meier & Partners, Rome (1998-2003). The photocatalytic concrete cladding, with Carrara's marble aggregates and titanium dioxide, allows the activation - in presence of natural lighting – of an oxidative process able to decompose organic compound, further removed thanks to the washing away of rainwater.

Interesting products are, for instance, tiles able to regulate moisture degree within confined spaces, such as the Japanese Ecocarat[19], made of a particular clay with microporous surface able to absorb the exceeding water-vapor within rooms to further release it when the air-moisture level changes.
In bricks, an interesting innovation is the development of sensors, signal processors and wireless communication links able to detect stresses of damage in case of catastrophic events such as earthquakes[20]. Other additional functions could be those to investigate moisture, humidity, and many other parameters.

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[18] Hydrophobic or photocatalytic, both based on different techniques that modify, at the nanometre scale, the adhesion angle among the surface and the water droplets on it.

[19] For further information, see producer's company website: http://ecocarat.ph

[20] Riferimento a paper su smart materials dove si parla dei mattoni con sensori.

Speaking about smart ceramic materials, you cannot mention concretes with improved performances, that goes from well-known HPCs[21] and photocatalytic concrete to fibre-reinforced concretes[22], photocatalytic concrete[23] or, again, to recent technologies, such as:

- smart concrete, with carbon or optical fibres that allow the monitoring of the structure integrity thanks to an electricity transfer (Abeer, 2017; Chen and Chung, 1993);
- translucent concrete with a low-density mixture – even if with a high quantity of reinforcing fibres – that allows seeing through them;
- fluorescent concrete[24], able to re-emits light after its absorption thanks to a micro-structural modification aimed at rendering the compound jellified, thus suitable for lighting public spaces without recurring to electricity;
- bio-receptive concrete[25], with magnesium phosphate that allows the bio-colonization and growth of photosynthetic micro-organism, able to produce oxygen and absorb CO_2 and pollution;
- water-reactive concrete, which suffers moisture thanks to a special ink which in actual environmental humidity condition it's not visible while if dampened shows its texture, according to a thermo-chromic reaction.
- self-repairing concrete[26], in which the presence of biochemical additives with dormant bacteria and other organic compounds – packed in particles of porous-expanded clay – allows the triggering of self-repairing mechanisms able to seal cracks smaller than mm. This concrete, durable and sustainable, is suitable for applications in all humid contexts where corrosion tends to compromise the durability of traditional products.

Fig. 06 – Fluorescent concrete.

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[21] High Performance Concrete (Y. Malier and R. Lacroix, 1980), defined as «concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices». American Concrete Institute Terminology, available at:

https://www.concrete.org/topicsinconcrete/topicdetail/high%20performance%20concrete (Accessed: the 20th of June, 2018)

[22] That embeds polymeric fibers to increase their bend resistance.

[23] One of the first materials on which has been tested the photocatalytic reaction indeed, is actually concrete, in which the titanium dioxide coating, if activated by incident solar radiation, allow to decompose organic dirt and pollutant agents.

[24] Developed by Dr. J. C. Rubio Avalos within UMSNH, University Michoacan of San Nicolas Hidalgo, Spain.

[25] Created within the Biotechnology & Architecture Lab, at The Bartlett School of Architecture, University College of London.

[26] Developed by a team of the Delft University of Technology (https://www.tudelft.nl/en/2015/tu-delft/tu-delft-self-healing-bio-concrete-nominated-for-european-inventor-award/)

Fig. 07 – Bio-receptive concrete.

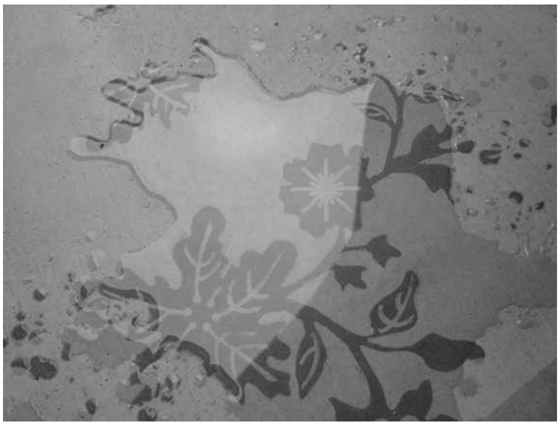

Fig. 08 – Water-reactive concrete.

In the field of glass-based products, several experiments are currently underway as well. They started with those aimed at conferring glasses self-cleaning abilities, making their surface able to repel dirt thus reduce maintenance issues, and have later oriented towards the development of systems able to selectively control the amount of solar radiation within confined environments, to avoid undesired overheating during hot seasons exploiting it, at the same time, during cold seasons.

Technological developments in this field, have ranged from products with static properties – such as low-emissive, reflective and selective glasses – to dynamic products equipped with variable performance, the so-called "smart windows", that generally exploit chromogenic technologies to modify glass' optical and thermal features according to solar variations, electrical inputs or other solicitations that occur in the surrounding environment

Other interesting experiments are those aimed at integrating transparent photovoltaic systems or high-performance materials (such as phase change materials) in glazed components, or, again, those designed to improve the lightness of such systems, such as the composite material developed by Nippon Electric[27], which combines the advantages of glass with resin resistance.

Despite systems' evolution, thanks to the advancement in technological progress, their application in current situations are still rare mainly due to high costs that justify their application only in interventions of a particular size.

[27] Source and other information on Material ConneXion library, LAMION™, Nippon Electric Glass Co., Ltd., MC 7737-02, https://www.materialconnexion.com/database_italy/773702.html [Accessed: the 22nd of March, 2018].

Metallic products

Within metallic field ongoing experimentations are mainly oriented towards the development of alloys with increased resistance and handling capacity, suitable for high-precision processes; last generation products indeed, are corrosion resistant, ductile, of easy processing and with great adherence towards surficial treatments. Most wide-spread are light alloys, metallic foams, composite steels, shape memory alloys and metallic wires or tissues.
Among them, a special mention deserves the boing micro lattice[28], an extremely light metallic foam (even lighter than aerogel, with a density of 0.9 mg/cm^3) originally developed to realize aerospace components; it has a three-dimensional open-cell structure, made of hollow metal nano-tubes with a polymer matrix and a reticule composed of about 99.9% of air, such as to provide it with characteristics that are completely unusual for a metal. Thanks to its extraordinary lightness and high capacity of absorbing mechanical energy indeed, it could be used in architecture as an insulating material, suitable for applications in floating floors, panelling or in particular components subject to impact, for which particular mechanical resistance is required.

Polymeric products

Polymers are quite diffuse in architecture, employed in different forms and for various purposes due to their lightness and aesthetic value above all.
Recent developments in this field are directed to increase polymers' performance in terms of resistance, insulations, durability and maintenance terms.
Products that seem most promising for architectural purposes are membranes or tissues, resins soaked to confer them greatly improved resistance.
Generally, textile materials suitable for building applications are distinguishable according to the number of polymers employed for their realizations and are multicomponent products (such as polyester tissues, PVC, PTFE) or mono-component products (expanded PTFE or ETFE plastic films).
Other interesting products are those equipped with unique aesthetic features, such as reflecting, fluorescent and shimmering polymers, sometimes with light-filtering abilities, or those reinforced with fibres that confer them extreme resistance and flexibility.
In the field of polymer-based products, it is worth mentioning the fabric produced by SEFAR[29], highly-transparent conductive tissue made by weaving micrometre-size conductive metal wires and transparent polymer fibres, usable as transparent conductive electrodes in electronic applications for OLEDs, solar cells, electroluminescent devices and electrochromic glasses.
Another component equipped with interesting ability is PNIPAN[30], a special polymer developed at ETH-Zürich, used for the creation of a breathable mat designed for cool-roofs. In case of an atmospheric event, the mat will absorb the water and then release it once the temperatures rise again, extracting heat from the inside of the building, thus reducing the energy consumption of about 60% during summer months.

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[28] Artificial structured material with electromagnetic properties, whose features depend not only to its molecular structure but also to the geometry in which it is shaped and employed.

[29] Source and other information on Material ConneXion library, SEFAR ® TCF, Sefar AG, MC 6408-12, https://www.materialconnexion.com/database_italy/640812.html. [Accessed: the 22nd of March, 2018].

[30] http://www.ethlife.ethz.ch/archive_articles/120102_schwitzende_daecher_fb/index_EN.html

APPENDIX III

Critical interactions: the case of window-wall interface

As demonstrated in the previous parts of the present research, the building envelope is a complex system aimed to guarantee precise performance requirements and ensure the indoor environmental comfort of the space it surrounds.

According to current ever strictly regulations, it has to meet several requirements, gatherable under three main categories, divided as follow: 1) **structural requirements**, to perform its support function in resisting and transferring structural and dynamic loads to the bearing structure and, from it to the ground; 2) **performance requirements**, to perform its exchange-control functions, in terms of flows' control; 3) **aesthetic features**, to make buildings attractive.

Since building envelope is composed by layers and other heterogeneous elements such as membranes, blocks, frames and preassembled components with different characteristics, their assembly is the key to appropriately respond to the conditions dictated by in-force regulations. Indeed, it is exactly through the correct relationship between them that the envelope can face boundary conditions and to maintain precise comfort conditions within limited spaces, avoiding thermal bridges or other accident that can determine performance decays over time.

Therefore, all building envelope's parts have to be designed as a whole to contribute to the functional effectiveness of the entire building system; moreover, considering that each of them has functional, performance and construction relationships with others, this means that their physical connections and integrations are of paramount importance to meet established requirements.

The on-site behavior of systems as complex as building envelopes correspond only partially to design prescriptions; recent studies indeed, showed that around the 75% of existing buildings do not meet pre-set energy goals[1] and that, most of them, make use of 2 to 5 times more energy than what estimated[2].

The main causes of these issues have to be sought from one side in the lack of rigorous protocols aimed at guarantee the "*rule of the art*[3]" in its most complete sense, while, from another side, in building management habits, often demanded to uninformed users.

Components with high performance indeed, not always allow to obtain constructive interfaces equipped with the expected performance values: an exemplary case is the one of the **window-wall interface**, in which performance-control needs, sometimes juxtaposed, are gathered together, and for which the absence of a mandatory norm that regulates its set-up within the whole system demands to the discretion of installers and producers the actions to be done.

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[1] *Closing the gap. Lesson learned on realizing the potential of low carbon building design*, July 2011, Queen's Printer and Controller of HMSO, UK (cited in reference section).

[2] Anna Carolina Menezes et al., "Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap", *Applied Energy,* n. 97, 2012, pp. 355-364.

[3] Literally, from an Italian common speaking, the compliance of something with the perfect execution, that is, indeed, the so-called "rule of the art". In this case, such expression refers to the way of laying down and installing building components in a proper way under many point of view.

1. The window-wall interface

Even if there is a quite common awareness about the fact that energy efficiency of fenestration system is highly influenced by the correct interface between the window and the wall, a specific (mandatory) norm which describes the precise rules to be followed during installation phases still does not exist. The only available documents are handbooks or manuals, drafted by single producers or installers, that concern different and various reference norms.

89/106/CEE	Directive of the 21st December 1988 about building products.
DPR n.246/1993	Standards for the implementation of the Directive n. 89/106/CEE.
L n. 10/1991	Standards for the implementation of the National Energetic Plan in terms of energy use, energy-saving and development of renewable energy sources.
DL n. 192/2005	Standards for the implementation of the European Directive 2002/91/CE about buildings' energy performance.
DL n. 311/2006	Integrations to the DL 192/2005
L n. 447/1995	Framework laws about noise pollution
DPCM 05/12/1997	Definition of buildings' passive acoustic requirements
UNI NORM 10818: 1999	Windows, doors and shutters. General guidelines for installing operations.
UNI EN ISO NORM 13659:2004	Shading enclosures. Performance requirements (including safety)
UNI EN ISO NORM 11173:2005	Windows, doors and curtain walls. Selection criteria based on air permeability, watertight, wind resistance, thermal transmittance and acoustic insulation.
UNI EN ISO NORM 14352:2006	Windows and doors – General product norm and performance features.
UNI NORM 11673:2017	Laying operation of fenestration.

2. Functional surfaces of the fenestration system

The most recent regulation on the subject investigated is the UNI Norm 11673-1:2017 – Laying operation of fenestration – Part 1: Design requirements and assessment criteria, which introduces suggestions about the design of the specific interface among window and wall. In particular, it points the attention on the importance to properly design the installation joints of the fenestration system, considering mutual behaviors and relationships among them.
To ensure the performance of the interface it highlights the importance of three critical joints:

- the **primary joint**, that is the connection between the window's counter-frame and the wall. It is of paramount importance because it must allow the dimensional variations of the frame's outlines caused by temperature fluctuations, while absorbing the stresses induced by wall movements, avoiding their transfer to the fenestration.
  The primary joint has to resist loads' solicitations[4], acting as a barrier between inside and outside to prevent thermal bridges and condensation formation within it. If well-executed, the primary joint has a thickness of about 10-20 mm.
- the **secondary joint**, that is represented by the interface between the window's frame and the counter-frame. It requests more elasticity than the primary joint and, this additional feature must be constant overtime to compensate for the behavioral difference between the glazing and the counter-frame/wall systems.
- the **third joint**, between the windows' units and the frame.

In general, the first two interfaces – that are the only joints whose design is in charge of the architect (the third is solved by windows' producers) – must ensure insulation towards air, water, vapor, temperature and noise, guaranteeing this features at three functional levels:

1) **internal level** (air-permeability level) – between the external environment and internal climate; it must guarantee air- and water-tight. The seal must be done uninterruptedly along the whole perimeter to avoid, at this level, a higher temperature than the environmental one, favorable for molds' insurgency (air humidity equal to 80%).
2) **medium level** (thermo-acoustic insulation level) – that has to be acoustically and thermally insulated so as functional to fastening operations;
3) **external level** (atmospheric agents-seal level) – that must be waterproof to resist to weather agents while permitting the discharge of steam towards the outside, to avoid condensation and molds' formation in the joint, allowing at the same time mutual movements within the connection.

[4] Stresses that act on the joint are different (compression, traction and shear stress) and depend on various kind of loads such as windows units' movements, thermal pressure/depression or caused by wind or building structure.

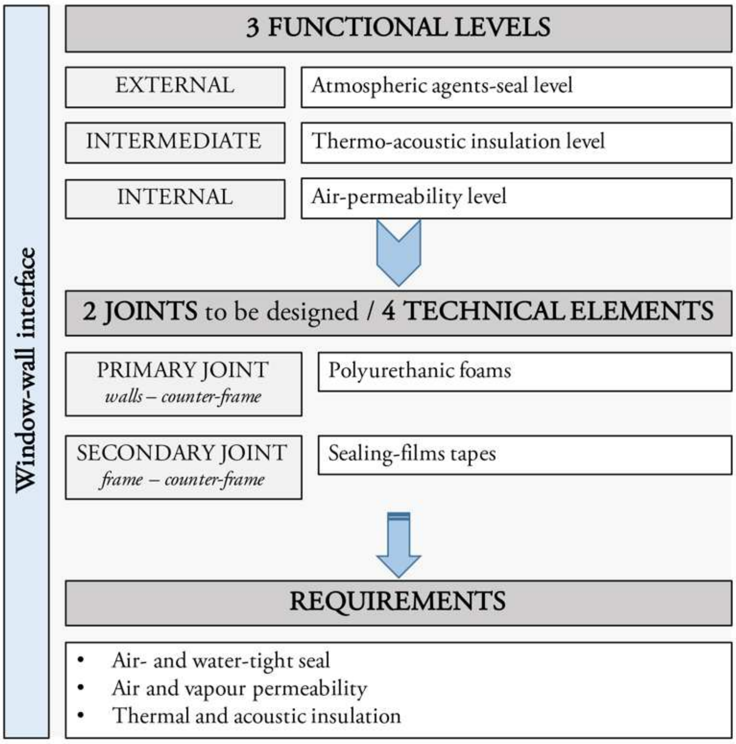

Fig. 01 – A synoptic scheme which resumes key points on which act to properly design the window-wall interface to fulfill the expected requirements.

In the Italian language, talking about "a job well done"[5] means referring to the whole set of techniques considered correct for the execution of certain manufacturing, typically artisanal, for the realization of artifacts. There is no a precise technical definition of such concept even if single specific descriptions are given by professional associations or groups; however, it has to be said that nowadays the compliance with this rule is still on a voluntary basis.
For fenestration, in particular, the reference framework is quite murky due to the absence of a binding norm that regulates installation and setup operation aimed at overcoming the difference between the design phase and real on-site performance of the components in the whole interface.
As stated before, criticalities in the examined interface are several. Mains are connected to the position of the window system within the wall, to the compatibility of materials and components employed for its installation, to the type of selected fastening and the water- and air-seal of the interface.
Some of them are conditioned by the correct design of the interface while some others don't; obviously, all of the abovementioned factors are affected by windows' characteristics as well as by walls' features.

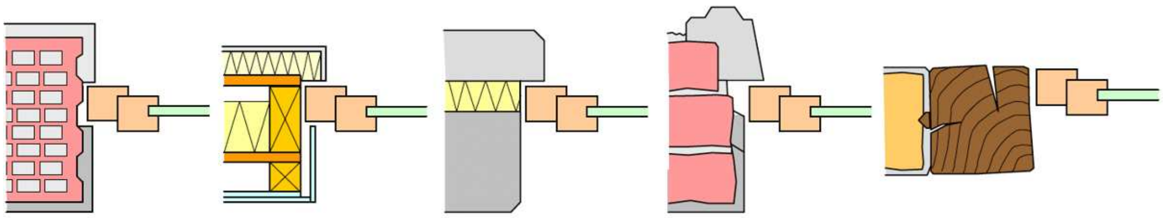

Fig. 02 – Different walls' features and relationship with window system in the specific interface.

Fenestration systems are extremely complex and subjected to numerous stresses due to the repeated and very frequent mechanical handling of their units, in addition to external and internal solicitations of other kinds.
A key role to ensure the yield of the system is performed by primary joint, to which is entrusted the connection between the wall and the window's counter-frame, allowing appropriate mutual dilatations of structures, maintaining seal and insulation levels as requested for the interface, and avoiding, at the same time, condensation formation.
The technical elements that compose windows' joints are basically:

- the **counter-frame**, employed for the on-site assembly of the frame and generally made of galvanized steel. In its traditional version, it can be made also of wood while in most recent and innovative solution it is generally replaced by the so-called mono-blocks, already equipped with useful devices to ensure correct installation.
  The counter-frame is always connected to the masonry support through mechanical fastenings to delimit the opening and its shape in a univocal and precise way;
- the **window's frame**, composed by a fixed and mobile part and made of different materials according to window's characteristics;
- **assembly materials** and components employed for seal and insulation of joints.

[5] Or, in other words, to comply with the so-called "*rule of the art*".

Fig. 03 – Mono-block window's counter-frame.

Mutual relationships among the above-mentioned elements are responsible for most of the interface's criticalities, essentially gatherable in four categories:

1) **performance criticalities**, essentially determined by materials and components employed for insulating and seal the joints;
2) **geometric criticalities**, function of dimension and geometry of the elements employed as well as of the dimension and position of the fenestration system within the wall;
3) **mechanical criticalities**, determined by fastening typology, and of wall supports as well;
4) **chemical-physical criticalities**, function of the mutual compatibility among materials used for sealing the joints and supports.

So, it can be said that critical situations are generally determined by:

- window's position within the wall;
- fastening typology;
- primary and secondary joints' insulation and materials employed for joints' sealing.

1. Window's position within the interface

How window's frame connects itself to building envelope vertical enclosure determines mostly of the performance of the whole system.
Despite specific performance issues concerning this interface, that will be further analyzed, the optimal position of the fenestration within the wall has to be determined to avoid critical performance decays, mainly caused by the discontinuity of the insulation layer between the frame and the wall that results in thermal bridges and possible condensation formation.
Three geometrical positions of the fenestration system within the wall are possible: flush with the internal surface, flush with the external surface or in the median strip.
The first case, we can say, constitutes the optimal situation since the insulation layer, generally located on the outer surface of the building envelope, can be flipped over the window's frame, avoiding thermal bridges; also positioning the window in the median strip of the wall could be an acceptable solution while its installation flushing with the external surface is generally not recommended because a thermal bridge will be almost certainly be created.

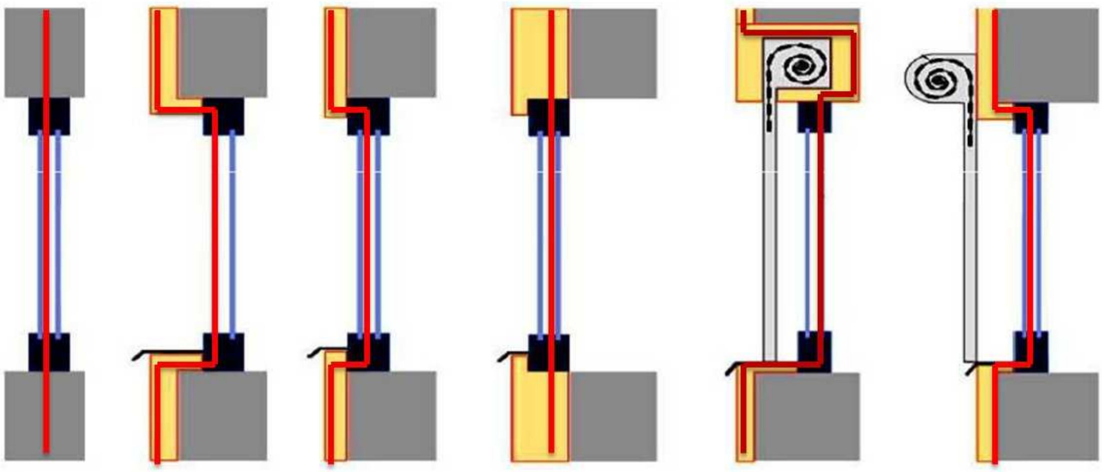

Fig. 04 – Window positioning within the wall and related criticalities

2. Fastening typology

Selection criteria

The fastening typology's selection must derive from type, dimension and weight of windows; it depends on the frame's geometry and wall's stratigraphy, responsible for specific stresses' response.
In general, parameters that influence the choice of fastening typology are:

- involved loads (including external forces or atmospheric events);
- position of fenestration within the wall (internal, central or external);
- wall's stratigraphy;
- window's frame (in terms of both shape and material);

Materials available

Several fastening typologies are available; most common are:

- screw and metallic screw anchor;
- nylon dowel;
- high-loads' bracket;
- bracket or square;

General guidelines

Presuming that fastening must be done through mechanical anchorages and that the use of expanded materials (such as foams or glues) is not allowed, to appropriately proceed with fastening operations it has to be taken in consideration: **1)** the center-to-center distance between fastening points, that must be not greater than 700 mm and **2)** the distance between fastening points and internal angle of window's frame (or strut/beam), which must be at most 150 mm.

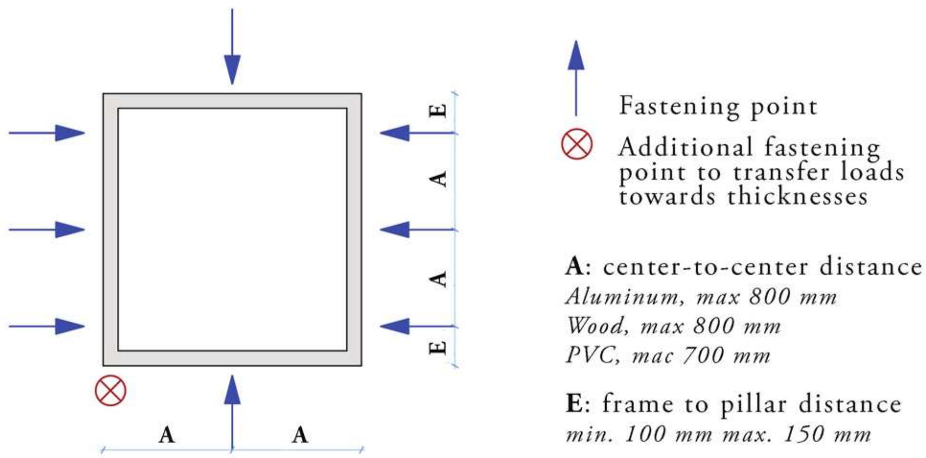

Fig. 05 – Proper distance among fastening points, guidelines from UNI NORM 11673:2017.

Main criticalities

Main criticalities concerning fastening typologies derive from the chemical-physical compatibility between fastenings and supports (due to possible corrosion phenomena caused by contact with concrete mortar, metallic surfaces that can suffer galvanic corrosion or mortars' alkalinity) or from a scarce distance from the edges, the poor profundity of the hole or insufficient center-to-center distance/thickness to be drilled.
Based on fastening typologies and supports as well, also different kind of drilling can be employed; most common are:

- **rotary drill**, used in case of hollow bricks or materials with poor resistance to avoid hollows with a too high dimension or destruction of bearing structures;
- **rotary-percussive drill**, employed for compact blocks or solid structure supports, such as concrete or natural stone;
- **pneumatic drill**, suitable for concrete and other compact materials with high resistance.

3. Primary and secondary joints' insulation

Primary and secondary joints must be protected towards water and humidity, caused by:

- widespread leakages;
- dissemination for infiltration;
- driving rain and wind pressure (due to air-pressure difference between inside and outside);
- air transfer between a higher-temperature ambient to a lower-temperature one, with condensation formation in the spacing.

Selection criteria

Factors of influence in selecting caulk materials are movements and loads, appropriate execution of joints, tolerances, geometry and employed materials. Therefore, suitable materials are those compatible with common building materials that can provide air- and water-tight seal, even if expanded, over time.

Materials available

Generally, materials employed to seal the joints are *polyurethane foams* or innovative caulk products such as *auto-expanding tapes, sealing films* or *fluid sealants* based on MS polymer.
Nowadays, air and water-proof films are most employed technologies to seal the primary joint, due to their easy application. They are made of tissues of various nature, resin-impregnated, aimed at preventing air, water and vapor transfer.
These technologies present an adhesive side to fix the strip on the counter-frame, while the other side will be fixed with a specific glue on the wall. When the sealant is dry, the film can be plastered. Films must absorb the joint's movements without damages.

Fig. 06 – Application of sealing films on a window specimen.

Based on their permeability, three types of sealing films can be identified:

- films to be employed on the internal side,
- films to be employed on the external side,
- multifunctional films.

The firsts must seal in a waterproof way the primary joint presenting at the same time low vapor-diffusion value (μ=80000); the seconds, must be air- and waterproof but steam-permeable, to let vapor out thus avoiding humidity collection within the joint (μ=70); while the thirds must gather both functions, with variable vapor-diffusion value, making their steam-permeability adaptable in an inverse way towards relative humidity conditions. This means that they become waterproof when the vapor-concentration increase, remaining permeable when it is low. The more humid is the ambient, the more the film become waterproof.

Sealing films: main features	
Composition	PES – PP – PES
Waterproof to heavy rain	> 600 Pa
S_d Value	~ 0,05 m ÷ ~ 39 m
Application temperature	+ 5°C ÷ + 40°C
Exercise temperature	- 40°C ÷ + 80°C

A running alternative to sealing films are auto-expanding tapes; suitable for every atmospheric condition, they are long-lasting and able to seal joints with variable dimensions, such as those between window's frame and counter-frame.

Generally, auto-expanding tapes are made with expanded polyurethane, resin-soaked to confer it high durability even towards the fire.

They work as contact sealants, which means that they react if subjected to a flatten pressure. The weather-strip return speed, from the pressed thickness to the nominal dimension, is influenced by temperature, so it conditions tapes' use.

Auto-expanding tapes are classified by a DIN norm, according to their performance feature: BG1 are tapes suitable even for external applications, BG2 are tapes suitable for external applications, but in a protected position, while BGR are tapes extremely airproof, that means suitable for internal applications.

Fig. 07 – Application of auto-expanding tape on a window frame

The three numbers that mark out each kind of tape represent, respectively: the width of the tape, the minimum tape's seal-thickness at a pressure of 600 Pa and the maximum tape's seal-

thickness to ensure the expected performance. Tape's choice indeed, is determined by joint's dimension; if under-dimensioned in fact, it wouldn't allow the expected performance since influenced by its compression grade.
It can be said that a tape of 15 mm wide could ensure a good frame's watertight with a sufficient safety margin.
Multifunctional auto-expanding tapes can be employed both in the primary as in secondary joints, since they couple the advantages of the tapes with positive features of sealing-films; they are indeed defined 3E because they satisfy the whole three functional level.

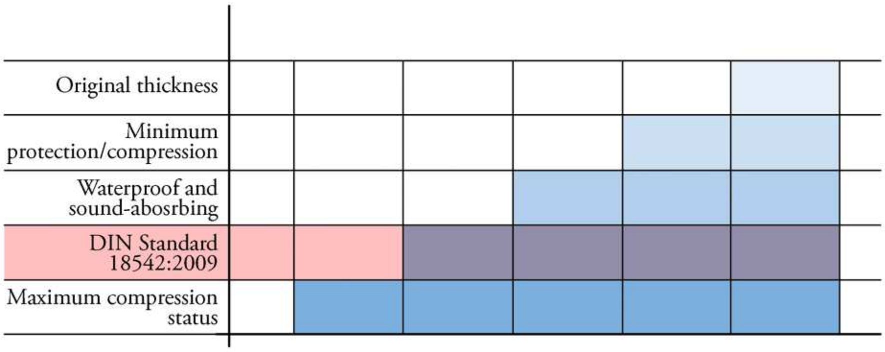

Fig. 08 – Waterproofing action – compression relationship in auto-expanding tapes

Finally, the most traditional sealing solution provides for the use of polyurethane foams, commonly chosen considering their elasticity and expansion-speed, parameters influenced by the application context temperature as well as by chemical nature of the base polymer and by its compatibility with the support.
In general, it is always suggested to use low-expansion foams that harden by means of the atmospheric humidity; the high is the moisture level, the faster is the hardening process. For this reason, it is recommended to damp the surfaces, favoring in this way foam's surficial adhesion.
It is of paramount importance to remember that the use of polyurethane foams or other sealants does not substitute in any way mechanical fastenings of fenestration in the interface.

General guidelines

General directions can be given considering the type of joint on which intervene. For the *primary joint*, it has to be employed a sealing and resistant material, with thermo-acoustic insulation capacity as well as air- and water-proof.
Sometimes, mortar it's inappropriately used, determining cracks due to its high rigidity and volumetric retirement, even because of its lower adhesion to support; besides, mortar is a very bad insulation material; for these reasons, its application is highly advised against.
Recommended materials are mono-component polyurethane foams, which expand their volume filling up the whole spaces; they are highly adhesive and elastic and, putting in pressure the counter-frame, contribute to the mechanical performance of the system, absorbing eventual movements thus avoiding fissures' formation.
To reach for a perfect watertight seal its recommended to adopt sealing films over the joint, between the counter-frame and the wall, and to insert in the lower part of the spacing a joint-bottom made of expanded polyurethane with closed cells, to limit the adhesion of the sealant to the only side surfaces. If this happens in fact, there is a high probability that the joint will be broken after shear stresses. Furthermore, the joint-bottom limits the thickness of the employed sealant, allowing a higher compression within the spacing.
Requirements for *secondary joint* are pretty the same; advice concerns the employ of a material able to adapt itself to eventual mutual structural movements (such as auto-expanding tapes), sealing at the same time the spacing.

For the lower part of the frame, in correspondence of the standing of the frame on the window's ledge, it is recommended to use a silicone or an MS polymer, to ensure the watertight of the system because its adhesion is excellent for each kind of support.

Main criticalities

As stated before, main critical issues are determined by the situations above analyzed, and by their incorrect resolution during installation and setup operations, which, in other words, means by poor installation techniques. The lack of an adequate level of insulation and air- and water-tight of the joints can determine condensation and mold formation because of the humidity that seeps through window and wall; moreover, the correct permeability of the primary joint allows the discharge of eventual steam residuals.
Other criticalities may be determined by the relationship of the window's ledge with the frame as well as by the materials employed to seal the primary joint such as silicone, that sometimes does not adhere correctly and which, over years, can be detached by the support.

To sum up, correct operations for a job well done, after determining exactly the position of the window within the wall, can be resumed as follow:

1) fastening of the counter-frame to the wall with adequate anchorages, in relationship to counter-frame materials and of the kind of wall supports;
2) insulation of the primary joint between the counter-frame and the wall (in a vapor-permeable way from the inside and air- and water-proof way from the outside, paying attention to the watertight of the lower part);
3) fastening of the window's frame to the wall support, through the counter-frame;
4) completion of the sealing alongside the whole perimeter of the secondary joint.

Fig. 09, 10, 11, 12 (pag. 424) – Blower-door test to verify windows proper installation.

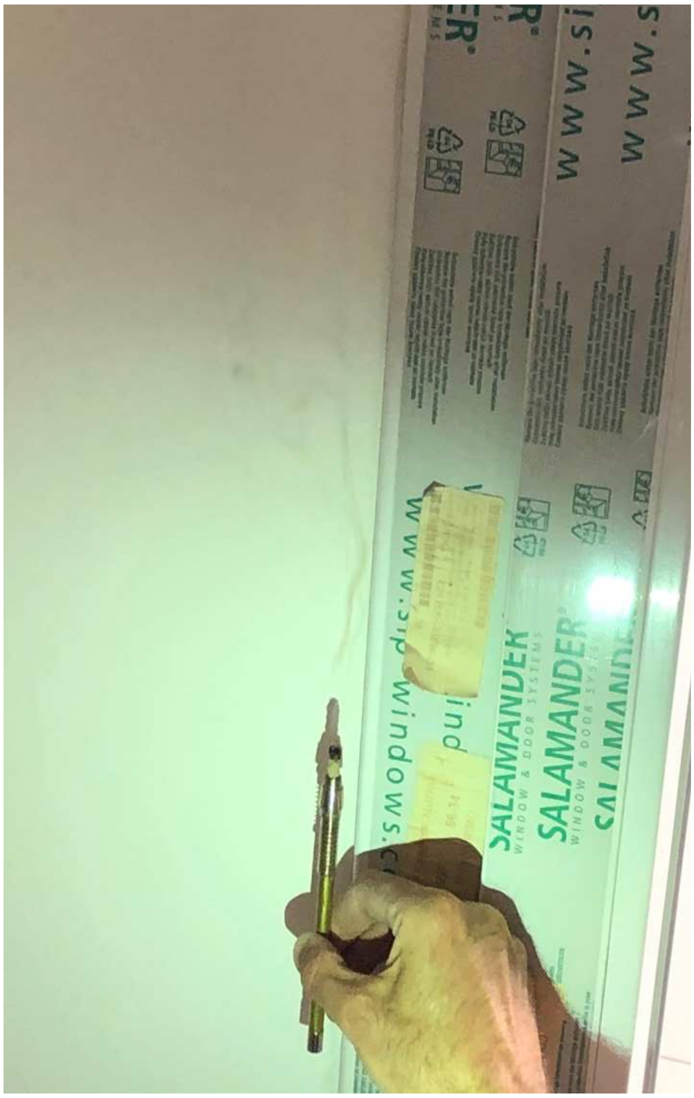
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Fig. 50 – Source: Hufton + Crow, available at: https://www.archdaily.com/791741/siemens-headquarters-henning-larsen-architects
Fig. 51 – Source: Mattew Carbone, available at: https://divisare.com/projects/368942-morphosis-architects-thom-mayne-matthew-carbone-bloomberg-center-at-cornell-tech-campus-on-roosevelt-island
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Fig. 54 – Source: Luc Boegly, available at: https://divisare.com/projects/370209-jacques-ferrier-architecture-luc-boegly-metropole-rouen-normandy
Fig. 55 – Source: Sergio Grazia, available at: https://divisare.com/projects/346955-brenac-gonzalez-sergio-grazia-offices-quai-ouest
Fig. 56 – Source: Richard Bryant, available at: https://www.dezeen.com/2017/12/18/kieran-timberlake-us-embassy-london-nine-elms-american-architecture-uk/

4.4 Lessons learned

Fig. 01 to 14 – Author's elaboration

x x x

5. Why windows matter?

Fig. 01 – Author's editing on Building Technologies Program of the U.S. Department of Energy data, Environmental Energy Technologies Division.
Fig. 02 – Author's photo.
Fig. 03 – Author's editing on Building Science Consortium data.
Fig. 04 – Author's editing on the basis of Technology Roadmap-Energy efficient building
Fig. 05 – Source: Pilkington, The float process, available at: https://www.pilkington.com/-/media/Pilkington/Site%20Content/UK/Reference/FloatPlant.jpg
Fig. 06 – Source: AGC Glass
Tab. 01 – Source: UNI EN 572-1 Vetro per edilizia – Prodotti di base di vetro di silicato sodo-calcio – Parte 1: Definizioni e proprietà generali fisiche e meccaniche.
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Fig. 08 – Source: Van Den Bergh, S. et al (2013), *Energy and Buildings*, 58, pp. 263-280; p. 264-265
Fig. 09 – Source: Finstral
Fig. 10 – Source: Finstral

Fig. 11 – Source: Van Den Bergh, S. et al (2013), *Energy and Buildings*, 58, pp. 263-280; p. 271
Fig. 12 – Source: Alpac, available at: https://alpac.it/prodotti/monoblocchi-presystem/monoblocco-finestra-per-frangisole/
Fig. 13 – On the left: Lai-Sys, windows' stiles; Source: Dosteba, available at: https://www.dosteba.eu/p/3456/elemento-di-riempimento-lai-sys - On the right: Sillpack, insulating system for windows' ledges; Source: Re-Pack.it, available at: https://www.re-pack.it/it/isolanti/eliminazione-dei-ponti-termici/sillpack-sistema-di-isolamento-per-davanzali
Fig. 14 – Source: AGC Glass
Fig. 15 – *Ibidem*
Fig. 16 – Author's elaboration
Fig. 17 – Author's image
Tab. 02 – Author's editing on Appendix B, Tab. 4 data within the Decree 26th of June 2015.
Tab. 03 – Author's editing on Appendix B, Tab. 4 data within the Decree 26th of June 2015.
Fig. 18 – Source: AGC Glass
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DEVELOPMENT AND IMPLEMENTATION | Results and sources

6. Glazing for Smart Architecture

Fig. 01 – Source: View Dynamic Glass website
Fig. 02 – Source: Okna perfect, available at: https://perfect-okna.com.ua/accessories/glass/sklo/
Tab. 01 – Author's editing on Rezaei, S.D. et al. (2017), *Solar Energy Materials & Solar Cells*, 159, pp. 26-51
Fig. 03 – Author's image
Fig. 04 – Source: AGC Glass Europe
Fig. 05 – Author's image
Fig. 06 – Author's photo
Fig. 07 – Author's reworked version; original image available at: https://www.architetturaecosostenibile.it/materiali/vetro/vetri-controllo-solare-307
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Fig. 10 – Source: PilkingtonSpacia, available at: http://www.pilkington.com/en-GB/uk
Fig. 11 – Source: Kapilux Okapane, available at: http://www.ecoedility.it/e3news/?p=270
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Fig. 14 – Source: www.wikipedia.com; www.buyaerogel.com; www.jiosaerogel.com
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Fig. 25 – Source: Yimu Zhao, available at: http://www.sunwindenergy.com/photovoltaics/transparent-solar-windows
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Fig. 31 – Source: VIEW Dynamic Glass
Fig. 32 – Author's editing on n-tech Research data (2016)
Tab. 05 – Author's elaboration on Rezaei, S.D. et al. (2017), *Solar Energy Materials & Solar Cells*, 159, pp. 26-51
Fig. 33 – Source: SAGE Glass
Fig. 34 – Source: Sunintuitive ®
Fig. 35 – n.a.
Tab. 06 – Author's elaboration on Rezaei, S.D. et al. (2017), *Solar Energy Materials & Solar Cells*, 159, pp. 26-51

Fig. 36 – Suntuitive® Glass windows installed at an educational facility in Keller, Texas, USA. Photo courtesy of Pleotint, LLC, available at: https://www.commercialwindows.org/thermochromic.php
Fig. 37 – Source: https://designbuildexpo.com.au/sustainability/eliminating-need-blinds-thermochromic-technology/
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ASSESMENT AND DISCUSSION | Findings

7. The Smart Window Configurator

Fig. 01 to 05 – Author's elaboration
Tab. 01 – Author's elaboration
Fig. 06 to 10 – Author's elaboration

RESULTS ACHIEVED AND ONGOING CHALLENGES | Conclusions

Fig. 01 – Author's photo
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APPENDIX I | Related research projects

Where relevant, images included within each best-practice sheet are respectively indexed in project's reference.

APPENDIX II | Smart materials for Smart applications

Fig. 01 – Author's editing on Addington, M. and Schodek, D. (2005), *Smart Materials and New Technologies. For architecture and design professions*, Oxford (UK): Architectural Press, Elsevier.
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Fig. 08 – Source: https://www.stylepark.com/en/studio-frederik-molenschot/solid-poetry

APPENDIX III

Critical interactions: the case of window-wall interface

Fig. 01 – Author's elaboration

x x x

Installation and setup operations for a job well done (La regola dell'arte)

Fig. 02 – n.a.
Fig. 03 – Source: Monoblocco INQUADRA FRANGISOLE DeFaveri, available: https://www.infobuild.it/prodotti/monoblocco-inquadra-frangisole-de-faveri/
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Fig. 05 – Author's editing on the basis of UNI NORM 11673:2017 guidelines
Fig. 06 – Author's photo
Fig. 07 – Author's photo
Fig. 08 – Author's elaboration
Fig. 09 to 12 – Author's photo

ACKNOWLEDGEMENTS

Pare che sia giunto, anche questa volta, il momento dei ringraziamenti; forse più sintetici e maturi di quelli della tesi di laurea ma sempre scritti di getto e con il cuore.

Questa volta, prima di tutto, voglio ringraziare la mia famiglia, sempre disposta a credere in me e ad assecondarmi nella scelta di intraprendere questo percorso didattico e di ricerca. Grazie perché posso sempre contare su di voi.
Grazie Clo, perché mi supporti e sopporti ora come allora, perché insieme abbiamo costruito la nostra famiglia e perché, allo stesso tempo, mi hai sempre permesso di dedicare tempo e passione a quello che spero possa diventare il mio lavoro, mettendomi nelle condizioni di poterlo fare con la massima serenità. Sei unico, e anche se non te lo dico mai, non so come farei senza di te!
Grazie papà, perché se anche non ti racconto mai niente di quello che sto facendo spero di renderti orgoglioso, da te ho imparato cosa vuol dire dedicarsi con serietà e impegno al proprio lavoro.
Grazie mamma, che quotidianamente ti prendi cura del nostro Sofino (e di me), senza di te non avrei mai potuto portare a termine questo percorso.

In seconda battuta, ma non certo per ordine di importanza, va un doveroso ringraziamento a chi mi ha accompagnato in questi anni.
Prima di tutto Fabio, mentore e punto di riferimento da oramai diversi anni; forse lo scrissi già in occasione della tesi di laura ma, anche adesso, senza di te non sarei arrivata fino a qui. Grazie di cuore per avere creduto in me, per avermi sempre supportato ed insegnato, con passione e tenacia, a non mollare mai.
Grazie al Prof. Giovanni Zannoni, fondamentale punto di riferimento per lo sviluppo di questo lavoro e non solo, al quale con sincera gratitudine ed affetto, va il mio più sentito ringraziamento per i consigli, la sempre presente disponibilità ed il tempo dedicatomi.
Grazie inoltre a tutte le persone incontrate in questi anni, che attraverso il loro coinvolgimento, impegno e dedizione mi hanno permesso di mettermi in gioco e continuare il mio percorso di formazione e ricerca. Il Prof. Roberto Di Giulio, il Prof. Theo Zaffagnini, il Prof. Pietro Davoli, Emanuele, Silvia, Marta e tutti i colleghi e amici che hanno incrociato il mio cammino. Grazie ad ognuno di voi per aver reso indimenticabile questo viaggio.

Un grazie infine al Prof. Fabrizio Tucci e al Prof. Jacopo Gaspari per aver dedicato parte del loro tempo alla revisione del mio lavoro.

International Doctorate in Architecture and Urban Planning (IDAUP)
International Consortium Agreement between University of Ferrara
Department of Architecture (DA) and Polis University of Tirana (Albania)
and with Associate members 2014 (teaching agreement)
University of Malta / Faculty for the Built Environment;
Slovak University of Technology (STU) / Institute of Management and
University of Pécs / Pollack Mihály Faculty of Engineering and
Information Technology.