Chapter 2
History and State of the Art

2.1 Early Developments and Postulates

Technological developments leading to the current state of the art for intelligent building envelopes have a long history. The design and building activities move at a particular pace, and the efficacy of new technologies can only be proven with particular examples. The following account is not exhaustive and pretends to highlight only some representative works of the many examples available.

The first dwellings crafted and used by human beings had the obvious intention of creating spaces that would provide protection and comfort from the external environment. But changing conditions during the day and the year would have required some type of internal environment regulation to avoid extremes during day or night, winter or summer.

Even though concrete evidence of building envelope regulation in prehistoric times is scarce, some early tribes had dwellings made out of organic materials such as the wigwam. In it both structure and envelope can be moved to allow ventilation and privacy as needed (Canadian Encyclopaedia 2016), constituting a primal example of an adaptable cover.

Early examples of ancestral Native American pueblos in New Mexico, Arizona and Colorado, show adaptation to changing conditions during seasons and hours of the day, making intelligent use of the geometry and orientation of the overhanging cliffs where the buildings were located, and the correct use of the heavy thermal mass of the stone.

In traditional or historic construction, internal regulation depends largely on the thermal properties of static materials composing the opaque area of the enclosing walls. This is experienced in well-made ancient buildings made of stone, mud, wood or even those insulated with cellulose or straw (Bozsaky 2010), of which abundant examples exist such as ancient indigenous adobe buildings in the Americas (Keoke and Porterfield 2003). Nevertheless, the fragility of such materials requires constant and dedicated preservation measures (Technical Preservation Services 2016).

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Historically there are also many surviving examples of adaptable openings, which would become the inspiration behind contemporary devices. These include old “box-type” windows, commonly found in Eastern Europe, that have double windows to protect against cold weather. They do work as a small-scale double facades (Fig. 2.1). Also to be mentioned as historical examples, are the well-known movable wooden shutters, which provide privacy, night insulation when needed, protect against excessive heat and light penetration in Mediterranean and tropical climates (Fig. 2.2). However, operation of these traditional elements still depends on manual actions by the user.

At the turn of the 20th century, many building types had already become more complex than their traditional precedents, new usages were required, and novel engineering technologies were becoming available. Architects understood that the design of building components such as the external envelope could not strictly follow traditional design methods due to the requirements of modern buildings. Facades and roofs required an organized planning process directed to the accomplishment of formal and functional objectives that could have a more tangible evaluation.

One early example of modern detailed envelope design corresponds to the Paimio sanatorium, planned by Alvar Aalto in 1932. The envelope layout was produced after incorporating relevant medical professionals in the design team, which for the time was a revolutionary way of working.

Fig. 2.1 Traditional double windows in Warsaw, Poland. *Photo credit* Carlos E. Ochoa

Fig. 2.2 Traditional wooden shutters in Rome, Italy. *Photo credit* Carlos E. Ochoa

Careful detailing was placed on the window as a generator of health. Its components had enough parts to manually regulate air intake and shading as desired by the patients, therefore giving the possibility of changing the micro climate inside the room. Architectural elements such as sun-bathing terraces were also placed according to their most suitable orientation (Anderson 2010; National Board of Antiquities 2005).

Le Corbusier, on the other hand, also introduced the concept of *brise soleil* and detailed facade sub-division. Such concepts were based on observations he made of traditional window latticework during his travels to Mediterranean countries. He also tried to include climatic principles in the façade designs, with views of some sort of adaptability to local climates.

Although now we can evaluate his work in retrospective, the execution of his climatic principles was not always successful. For example, some of the methodologies he used tended towards the empirical, and throughout his *ouvre* there were few exceptions to his generalized utilization of materials such as concrete and glass despite the location.

However, it was notable that, based on earlier industrial achievements for mass production, the architect had among his many propositions that buildings would be used as "machines" for living inside them. Such machines were to be covered with "breathing skins" (Curtis 1994).

2.2 Historical Points of View for Intelligent Building Envelopes

2.2.1 The Highly Mechanized Envelope

Such view of a self-regulating, highly mechanized building, would have its first truly operational interpretations during the last decades of the 20th century. This period also coincides with breakthroughs in the development and generalization of sensing capabilities and electronic technologies, such as the personal computer and the microprocessor, which before had been very expensive and unpractical products. The introduction of these elements to a wider audience, and for a larger variety of applications, allowed the beginning of a significant size reduction process for electronic elements. As a result, portability and applicability of computers and microprocessors in new situations, such as building components and controls was considered.

In 1980, the nine-story *Occidental Chemical Center* in Niagara Falls, New York, was completed. The building featured many technological advances for the time: Thermal insulation was provided by a double façade with outer insulating floor-to-ceiling glazing, ventilation was controlled by electronic dampers, and daylight was regulated by inner automated aluminum louvers. Quite advanced for its time, it was hailed as the future of building and of low energy consumption.

However, over-dependence on mechanical elements, and lack of control of users over their working environment, made it sadly become an example of what can go wrong with automated buildings. The systems were too complex for that period, and never received adequate maintenance, leading to their malfunction. System design was made according to a usage model that was supposed to be stable during the years, and which proved otherwise. In addition, external and unforeseen factors occurred, such as changes in occupancy and ownership. Even the decision of the new owners to change the landscaping to a parking lot, and the construction of neighboring buildings, meant that the systems could not work as intended. Eventually the components were replaced by extremely cheap substitutes. Nowadays the building is almost empty, in need of repairs and its space is destined to other uses different than the original ones (Fortmeyer and Linn 2013).

In 1983, *City Place I* in Hartford, Connecticut opened to the public. The building comprises 38 stories and was designed by Skidmore, Owings and Merrill (SOM). Although today it would be defined as a "highly wired building", it was planned to coordinate HVAC, lighting, security, communications and other systems through a central computer network with the stated aim of making energy consumption more efficient. Its data was gathered from sensors rather than following a program, and also included different user scenarios (New York Times 1983).

This made it one of the first buildings of its kind that incorporated computer systems and interactive internal climate control. Although it used a more conservative approach and depended on mechanical systems (a well-known strategy available during the 80s), the building is still in use today.

Some years later, in 1987, Jean Nouvel's *Arab World Institute in Paris* was finalized. One of its distinguishing features is the use of 240 photo-sensitive modules with 30,000 motorized diaphragm apertures placed on different facades behind glazed surfaces of the main building (Figs. 2.3 and 2.4). Fabricated in metal, the diaphragms open and close according to conditions determined by light sensors.

The intention by the designers was to ornament the façade and reduce the amount of light entering the space, using a modernized version of the *mashrabiyas*, a window lattice from Arab countries (Hanser 2006) that allows achieving privacy as well as shading and ventilation passively, making good use of the geometrical proportion of its components. Although the devices create a special aesthetic quality, the diaphragms depending exclusively on complex mechanical systems encountered technical problems, and their maintenance proved complex and expensive for the building owner (Fortmeyer and Linn idem).

The *GSW headquarters* in Berlin, was designed by Sauerbruch Hutton and completed in 1999. One of its particular characteristics is a series of colorful shades, in red and pink hues placed on the West façade of the new tower (Fig. 2.5). The shades slide sideways, regulating solar radiation, while being located inside a double façade with a cross-ventilation system (Fig. 2.6).

Climate strategies (such as spray cooling) are managed by a central system which gathers information through sensors. However, in contrast to the fully automated approach, a range of aspects such as ventilation, shading and lighting can be regulated by users. This creates a changing pattern in the distribution of openings in the canvases. The tower was intended as a generator for reconstruction in the reunited city. It also provides it with a noticeable visual urban reference, through the particular coloring scheme of its dynamic canvases (Wigginton and Harris 2002).

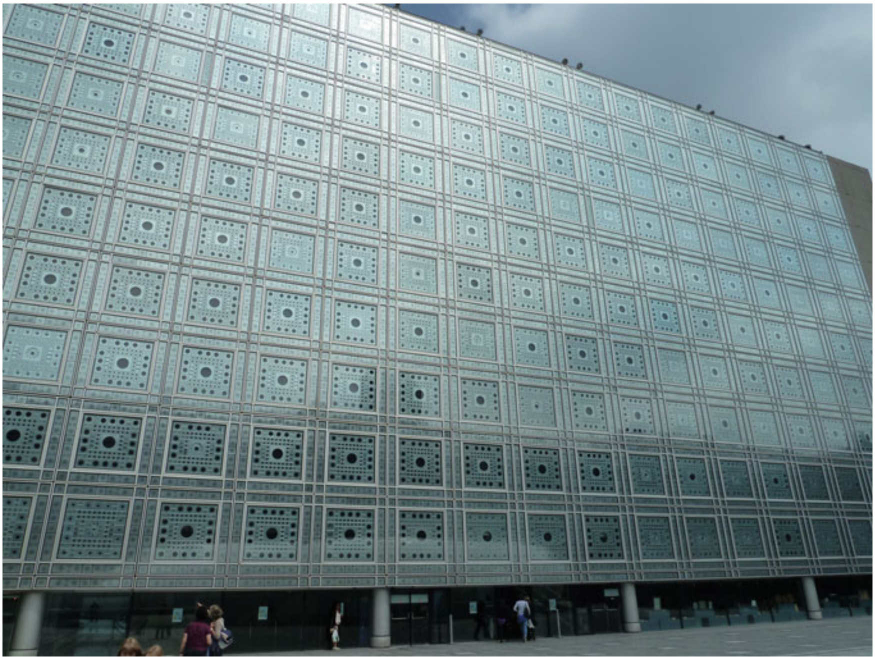

Fig. 2.3 Façade of the Arab World Institute Paris with the operable diaphragms. *Photo credit* Carlos E. Ochoa

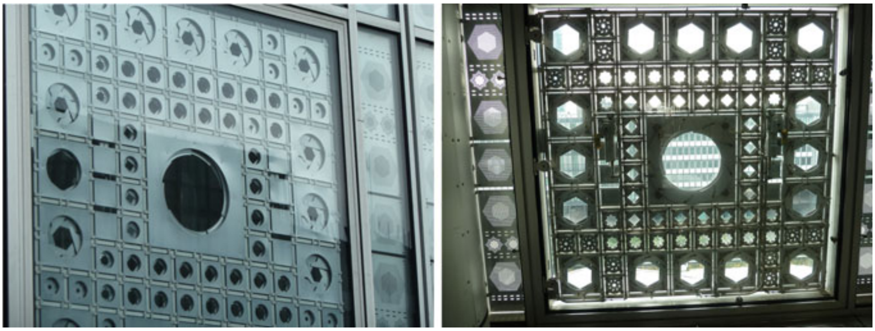

Fig. 2.4 External (*left*) and internal (*right*) details of the operable diaphragms of the Arab World Institute Paris. *Photo credit* Carlos E. Ochoa

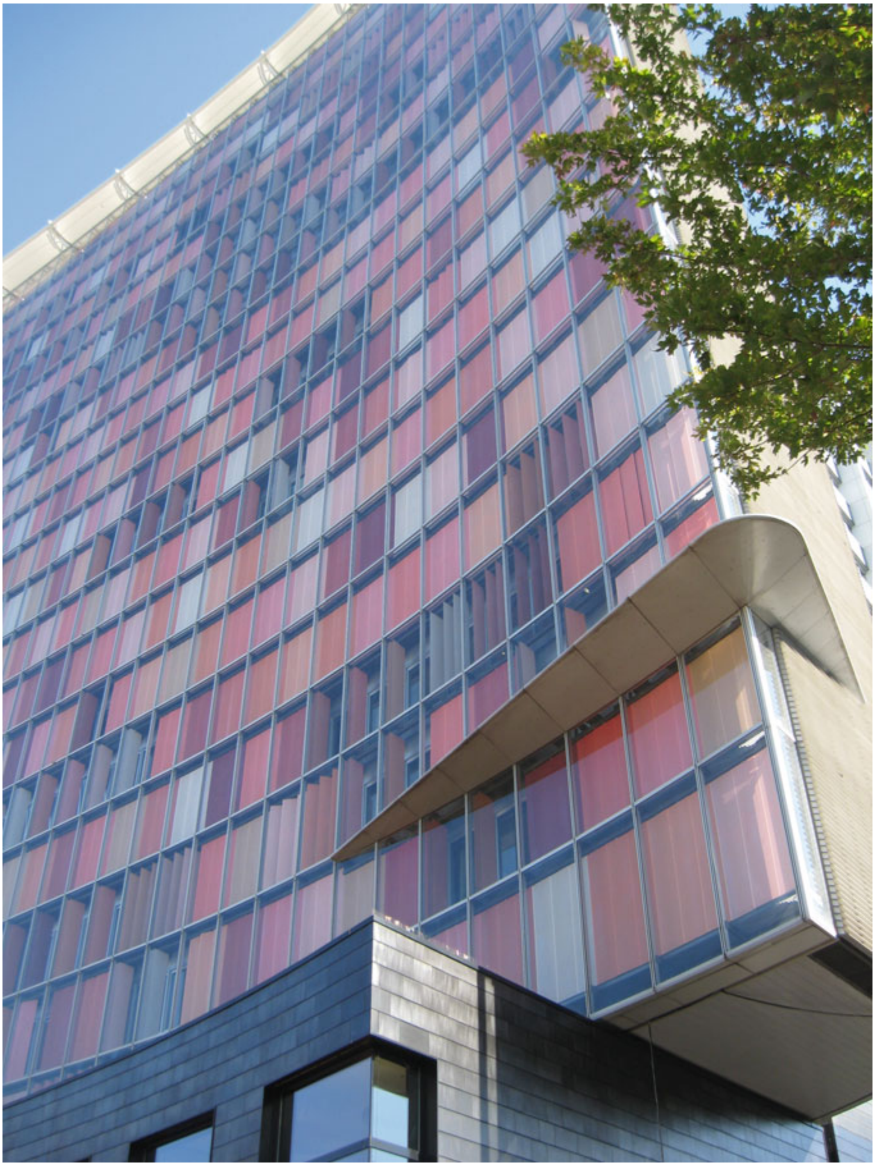

Fig. 2.5 West façade GSW building, Berlin. *Photo credit* Guedi Capeluto

Fig. 2.6 Detail GSW building shades. *Photo credit* Guedi Capeluto

2.2.2 The Naturalistic Envelope

The decade of the 1990s saw a more widespread manifestation of ecological and energy saving ideals as design generators in architecture as part of a new mainstream school of thought, where nature is an important factor to be considered. Climatic design principles had reached maturity, and started to be taught as part of an increased number of architectural education curriculums.

A post-modernism point of view was introduced to architecture in a more widespread fashion. Elements used in traditional architecture were re-evaluated for their contributions to comfort. They were perceived as intelligent solutions executed in a time when the only choice was the lowest or no energy use. Traditional construction technologies that use thermally comfortable materials, such as adobe, were reevaluated through a more scientific scope towards their use.

New construction technologies, developed with the specific objective of minimizing energy consumption, were developed and brought into practice. It was also acknowledged that mechanical systems could not become the only source for occupant comfort. Many of these ideas were implemented into architectural designs around the world as these ideas found wide acceptance.

In contrast to the highly mechanized approach under this view, building envelope systems were envisioned not as separate entities that are solved later on by mechanical engineers, but as integral components that have received detailed thought from the start of the design process. In addition, calculation methods for energy and performance prediction became more accessible through newly developed computer programs. They allowed parametric exploration of different design options and more accurate prediction of the expected performance.

An outstanding example of this new vision for intelligent building envelopes is found in 1993s *Consorcio Vida building* in Santiago, Chile, designed by Enrique Browne and Borja Huidobro. One of the main distinguishing features of the project is the use of dynamic shading provided by deciduous vines that grow to almost the full size of the West façade. They were conceived as a "vertical garden", sixteen stories high (Fig. 2.7) adding a green area that contributes to improve the environmental quality of the zone.

In contrast to conventional buildings, where their image deteriorates during the years, this solution provides the building with an always changing aspect with permanent validity. As Browne states: "architecture and vegetation are fused together, turning the latter into a construction material, keeping the building relevant for an undefined time" (Arqa 2011).

The color and density of the vines change according to the seasons, regulating solar light that comes into the office spaces. This in turn also helps to save energy on heating, cooling and lighting, providing a better working place. They also create a moist microclimate in the dry Santiago valley where it is located (Fig. 2.8). Vegetation is also used in the lower floors in the form of full-grown trees to provide shade to pedestrians and protect the façade of lower floors (Senott 2004).

Fig. 2.7 Consorcio Vida building, Santiago, Chile. Winter (*up*) and summer (*down*). *Photo credit* Guedi Capeluto

Fig. 2.8 Consorcio Vida building, Santiago, Chile. Details of the trellis with vegetation in the flowering stage. *Photo credit* Guedi Capeluto

2.3 Recent Developments and Examples

2.3.1 The Integrative View

The most recent generation of intelligent envelopes combines the availability of new active technologies, such as smart materials and robotics, with a wider flexibility in the application of passive strategies. It also makes use of expanded and improved computational capabilities, for implementing more reliable electronic envelope elements. It also uses this new computing power for routine energy analysis of multiple options in shorter time, and through more user-friendly interfaces.

Such advances allow intelligent envelopes the possibility to reach higher levels in the list of intelligent agents presented in Chap. 1. Computing advances allow artificial intelligence principles to be programmed in the processing areas. The entire composition of the building envelope starts to emulate more the principles of a living organism.

These improvements are also required by necessity: low energy consumption and ecological principles have become part of the mainstream in many countries, and are no longer the ideas of visionaries. Building codes and directives now mandate maximal energy usages that cannot be trespassed, they also oblige designers the incorporation of certain energy saving measures, as well as specific performance evaluation methods.

The possibilities to plan intelligent envelopes have increased with the integration of passive and active technologies, due to the increase of reliability in electronic devices. Intelligence in a building is no longer a one-off product that has to be started from scratch. Currently there are commercially available protocols such as KNX, LonTalk, ZigBee, DALI, etc. that make computer-based building envelope management to be standardized and relatively accessible in terms of price and operation. Advanced sensor devices providing better integration of different devices within the envelope and with other parts of the building (KNX 2016) by monitoring also the physical capabilities of passive elements.

Novel material technologies have also gained ground in recent times although still require wider market diffusion. A wide range of the so called “smart materials”, since they “know” how to behave in a regulated way according to each situation, still need to be thoroughly tested through experiments before being applied on the field. Nevertheless, it is a field of research that promises new and groundbreaking directions that will change the way that we think about construction.

Some examples that can be mentioned, of intelligent envelopes created using these new principles, include the 18-story *San Francisco Federal Building*, completed in 2007 and designed by Morphosis. HVAC systems are present only in lower floors with high occupancy and equipment concentration. It also pushes the concept of outer envelope in a literal way, through the use of a folded metal sun shading pattern which also becomes the signature aesthetic of the project (Arcspace 2007) (Fig. 2.9).

Fig. 2.9 San Francisco Federal Building by Morphosis, South-East facade. *Photo credit* Guedi Capeluto

The building relies on a series of smart controls, directed through a computerized control system, to enforce a series of climatic strategies such as cross ventilation, night ventilation and maintenance of lighting levels. The interior planning maximizes also airflow and daylight penetration, together with direct outside views for all the workers.

On the other side of the Atlantic, at a smaller scale, the *Oscar von Miller Forum* in Munich was designed by Thomas Herzog and completed in 2009. It is a mixed-use project that combines offices, learning spaces and temporary housing. The building is also a good example where different passive and active strategies were combined in order to minimize energy expenditures. Examples include automated control of natural ventilation and shading with overrides, district heating systems whose flows take into account the amount of heat obtained by passive thermal mass, domestic hot water collectors, use of roof gardens, etc. There is also some self-energy generation through the use of photovoltaic panels (Fig. 2.10).

These systems are managed by different computer control centers that “know” how to combine energy gained from both active and passive systems. The control centers are also programmed to combine the strategies used by one system for the benefit of other systems (Herzog 2010).

The *KfW Westarkade* high rise in Frankfurt, completed in 2010, was also designed by Sauerbruch Hutton. One of its main peculiarities is having a very low energy consumption for its built area and height. Following the recent line of thought about intelligent envelopes, a series of passive and active features are

Fig. 2.10 Shades, photovoltaic panels and hot water collectors Oscar von Miller Forum, Munich. *Photo credit* Carlos E. Ochoa

combined. One of its distinguishing features is the so called "pressure ring". It is made of a double façade that takes advantage of prevailing wind directions and has the serrated shape that characterizes the project. This allows natural ventilation through operable internal windows, neutralizing any turbulence effects associated with high towers. In turn, the building does not require being sealed and natural ventilation can be used even in the highest floors.

The openings and external flaps allowing air inside are computer controlled according to the internal requirements and prevailing wind conditions. Sunlight redirection systems allow savings in artificial lighting, and a better use of the plan distribution. The main heating sources are geothermal and activated slabs, but any excess heat generated by loads such as machinery or computer equipment is also reused (CTBUH 2011).

We have presented these well-known available examples, to prove that a wide variety of possibilities for intelligent envelopes exist. They have been shown as the result of different design philosophies, which affect the final arrangement and dependence between systems. Historical developments have also shown what can be learned from over-dependence on a single mechanical or electronic system, which is not recommended. A more integrative approach is preferred, since it can take advantage of the benefits from both passive and active systems. It also provides an enriched design with high intelligence potential.

2.4 Classification System for Intelligent Envelope Components

Trying to understand the large variety of envelope components is complex. To do so, a systematic approach is required. The use of such approach is to take advantage of what is available nowadays, and to have a hint of what will be available in the very near future. A classification system is presented in this section, with the aim to organize the component inventory and motivate possible new research.

As it has been seen, there are currently numerous options and approaches to develop an intelligent envelope. An overview is offered in this section, where elements are classified to understand how components work. By this, readers can clarify and organize design efforts, exploring the development of new elements where few of them exist. The classification system intends to be indicative, as there are always innovations in the fields of new materials and management systems. Categories and divisions in the classification system also follow the separation made of intelligent elements into sensors, processors and actuators. Different sub-categories are also noted.

2.4.1 Class A—Perception/Input Elements

Elements belonging to this class gather information about the internal and external environment, and also monitor any changes in them. They can also receive signals from users that are interpreted as commands for an action to be taken. Both feeds constitute the input to the intelligent envelope. The main sub-categories in this class are:

(a) *Sensors*: They can be placed inside and outside the envelope, and can measure one or many environmental aspects at the same time. Some of these include: internal and external temperature (dry/wet bulb), external and internal relative humidity, wind speed, illuminance over a given surface, human presence or absence, electrical appliance usage, etc. Although composed of artificial materials, and only dedicated to collect information, they have been compared to the nerves of a living being due to the information that they can sense from the world (Giurgiutiu 2007).
Their size is much reduced and can be almost undetected by casual passers-by. They work by conductance, resistance or sensitivity. For example, a photocell is composed of semiconductors that absorb photons from a light source, modifying the resistance range (Diffenderfer 2005).
Sensors can be connected to the processing centers either as part of a wired network or through wireless communication (Towler 2011). This allows their strategic placement in different locations, thus having to endure different environmental conditions or connection requirements.

(b) *User interfaces*: They can vary in complexity from classical on/off switches, thermostats, to remote controls and touch-screen panels. Although one action is performed by the user on the interface, the control themselves can interpret such action as the instruction to regulate different activities at the same time. Different degrees of sophistication exist in the way that orders are entered and the information is presented to the user (for example, electronic displays, turn knobs, etc.). Nevertheless, the area of user interfaces requires further developments in order to exploit the full potential that intelligent envelopes offer to end-users, facility maintenance, developers and architects. Their usage can also be tied to different conditions unrelated to performance, such as budget available to use touch screens instead of switches; also to the type of project, as it might add further layers of complexity that are not desired such as adding a computer interface for a room that is seldom used, etc.
The implementation of now-familiar interfaces for electronic devices such as smartphones or tablets still has to find widespread application in the controls used within intelligent buildings (Henson 2012).

2.4.2 Class B—Control Processing Elements

In this class we can find the components that gather information collected in the input phase through sensors and interfaces, and “decide” on the course of action to take. These decisions are based on different logical steps, pre-defined policies to be carried out by actuators and that were decided by a design team. The orders, translated as electrical impulses, are then sent to the relevant parts. For this class we shall discuss the key policies that must be taken into account by any intelligent envelope protocol, and the main types of control systems available.

Policies must be applied when specific events occur outside the envelope or within its enclosure. Designers have to consider beforehand the desired actions that actuators will take according to limits imposed by changing weather and occupancy events. These policies, expressed as strategies, will then be translated to specific commands. As seen in Chap. 1, there are different ways to express the reasoning for an intelligent agent. Some include only reactions to the environments as the most basic unit. Using logic systems might comprise a sensing of the internal and external environment, to decide on the best policy to implement. More advanced logic systems can include a simulation being done, with evaluation of the possible alternatives. Nevertheless, at the moment it is more common to encounter reactive elements, while the programming complexities of logic systems limit their wider application.

As an application example to control overheating, when sensors detect that direct solar radiation goes beyond a certain threshold, shading elements should be deployed potentially to a given angle that blocks solar radiation. This is a reactive case.

As a second example, the user can enter directly the number of occupants that will be present in a space for a given period. Therefore, the system can then simulate and calculate the amount of time that openings must function in order to provide additional ventilation so that the expected number of users will have enough quality ventilation, and keep this result in case the processing center did not receive any feedbacks or modifications during the planned occupancy time. This is an example of a learning system.

The main policies that can be mentioned are the following:

(a) *Lighting*: How illuminating elements will be used to fulfil daylight supplement, task visual performance requirements, controlling glare, etc.
(b) *Shading*: Operation types of internal or external shading devices to avoid overheating and glare according to their type (e.g. shades, blinds, etc.), activation limits and modes such as angle variations of different blind sectors.
(c) *Thermal comfort*: Regulation of temperature and relative humidity for human comfort according to the number of occupants and activities performed, as well as the needed actions to protect equipment and furniture from climate extremes when the building is not occupied.
(d) *Ventilation*: Strategies to promote or cancel the entrance and movement of air in a space. Air movement can be within the same area, or there can be an introduction of air currents inside or outside the space.
(e) *Energy management*: This strategy relates to how energy is administered in terms of consumption, and in certain cases, for energy self-generation. It also concerns the usage of energy from certain envelope elements that use electric energy in order to keep a balance.
(f) *Administrative policies*: It is referred here to envelope operation in case of unusual events (such as, for example, extremely high winds), maintenance, diagnostic, power failure, emergencies and security (for example, giving an order for blinds to be deployed during night time in order to prevent break-ins). They are necessary in order for day-to-day functions to be carried out, even if they are not directly related to energy or climate.

Processing elements are the ones in charge of administering the policies according to the conditions pre-set by designers and imposed by end users. They carry out instructions to perform a series of actions that will result in the regulation of the envelope or the internal space. These elements can be programmed to have diverse degrees of adaptation to changing conditions. There is also a large variety in the type of logic that can be applied, and the order of strategies or their combination that need to be implemented through actuators.

The following options to manage the policies are available, listed in decreasing order of electronic or mechanical complexity. They also show how different selections for control centers are available according to project constraints such as available budget, or maintenance scheme:

(1) *Building management system* (*BMS*): Almost every aspect of the building is supervised by a central computer decision center. This includes acclimatization, mechanical systems and building administration. The most advanced models incorporate current advances in artificial intelligence for computers.
However, in order to avoid general failures, BMS are composed of modular elements where each of them is dedicated to a given function. Thanks to their complexity, a number of scenarios can be programmed for different types of responses. This setup is suitable for buildings that are administrated or maintained in a centralized fashion. A BMS is the most commonly found type of management system in intelligent buildings and envelopes.
(2) *Synchronized controls*: In this arrangement, there is no central decision center, and all policies are administered by different management modules. Sensors, processors and actuators are grouped to perform one activity and have one specific goal. Coordination is necessary between the different sub-systems.
An advantage is that failure of any system is contained to one sector, and does not affect the operation of the entire setup. One of the main disadvantages is the elevated number of sensors and modular control processors needed, and that their maintenance might take longer. However, it is highly convenient for buildings with different and changing tenants. One example of these type of controls was implemented in the New York Times building (LBNL 2016a).
An important variation of this system occurs when there is no processing center, and actions are performed as direct physical or chemical response to the environment. Many smart materials operate under this principle. Examples include independent shape memory alloys, electrochromic windows or dimming elements connected to an array of light sensors, among others.
(3) *Modular management*: as a hybrid between BMS and synchronized controls, entire prefabricated envelope modules are constructed. Each of the modules contains their own management system for lighting, ventilation and shading. An example is the conceptual TEmotion façade (Wicona 2016).
(4) *Schedule programming*: These correspond to fixed, cyclical operation modes. There is no immediate response to short-term environmental changes, but they are adequate for long term operation of certain systems, such as ventilation or HVAC. They are performed by very low cost components such as thermostats or timers, and their operation is almost intuitive.

(5) *Passive building*: Although there is no control system involved, strategies are administered by the physical properties of static elements in the envelope, which cover the policies mentioned previously. In this case, intelligence resides in careful architectural design and material selection, using well-studied bioclimatic design principles that are appropriate for each climate. They can co-exist with highly sophisticated electronic building systems (Fig. 2.11).

Fig. 2.11 A passive shading system as second skin for a building and signature design feature. San Francisco Federal Building, designed by Morphosis. *Photo credit* Guedi Capeluto

(6) *Users operation*: Direct human interaction occurs with building components, which are operated to restore visual or thermal equilibrium. For acceptable results, good design provides with different mechanisms for fine-tuning this operation. Examples are segmented window openings, division of lighting arrays into different sectors, operable shading devices and ventilation flaps. Behavior patterns can be abstracted and predicted from research and probability theories (Reinhart and Voss 2003).

2.4.3 Class C—Actuator Elements

This class contains a large and always increasing number of elements, and the most visible in the intelligent envelope. Actuators usually perform one function in order to execute the objectives set out in the policies. Elements themselves can be conventional but operate under dynamic modes, or they can be innovative and depend on material properties or specific technical developments, such as "smart materials". The main system groups that can be currently found are the following:

(a) *Daylight and shading management*: They regulate direct and diffuse solar radiation that enters a space and can help with privacy (Fig. 2.12). The most advanced models provide solar tracking capabilities in order to maximize daylight utilization. Some of them can also provide movable insulation. They can be subdivided into sun shading elements (shades, blinds, louvers); daylight redirection elements (lightshelves, reflective blinds); and daylight transport elements (fibre optic pipes, etc.).

Fig. 2.12 Solar radiation reactions from the façade to a cloudy day (*left*) and a sunny day (*right*). Oscar von Miller Forum, Munich. *Photo credit* Carlos E. Ochoa

(b) *Fenestration*: Elements are related to the openings in the envelope (windows and clerestories). Glazing constitutes the majority of components found in this division, and can range from conventional panes to specialized innovative applications such as insulating, light redirecting or electrochromic changing glass (Compagno 2002; LBNL 2006).

(c) *Cooling, heating and ventilation*: Elements in this group help to mechanically or naturally achieve a given air temperature while reducing overall energy consumption when compared to conventional systems. The main subdivisions constitute passive and active systems. In passive systems materials are used to store or release heat. New developments include super-insulating materials with minimal thickness, materials that provide high thermal absorption and adequate time-lag heat release (Jelle et al. 2010). For active systems, the overall U-value of the envelope is varied according to the climatic needs of the season, by increasing ventilation rates in a double cavity in order to generate additional heat, or by circulating fluids inside a tube system that becomes heated by the sun (Fig. 2.13). Examples include water- or solar-based cooling, concepts in opaque movable insulation, or solar vented cavities.

(d) *Energy generation*: This section includes the different options available to generate electricity, ranging from typical grid connection to self-generation such as envelope photovoltaics, wind turbines, and even conceptual panels that

Fig. 2.13 Solar thermal collectors on the roof as supplemental heating system. Oscar von Miller Forum, Munich. *Photo credit* Carlos E. Ochoa

generate biomass for a building (Arup 2016). Some of these technologies interweave with other systems such as fenestration and daylight (Fig. 2.14). The total output of generated energy has been increasing in recent years compared to earlier developments.

Fig. 2.14 Solar photovoltaic panels used also as shading devices. Oscar von Miller Forum, Munich. *Photo credit* Carlos E. Ochoa

Table 2.1 Summary of the classification system for intelligent envelopes

Class	Category	Sub-category
A. Sensor/input elements	Sensors	Internal and external environmental aspects
	User interfaces	One-function buttons and switches
		Remote controls
		Computer monitors and touch screens
B. Control processing elements	Policies	Lighting
		Shading
		Thermal comfort
		Ventilation
		Energy management
		Administration
	Policy management	Building management system
		Synchronized control
		Modular management
		Schedule programming
		Passive building
		User operation
C. Actuating elements	Daylight and shading management	Sun shading
		Daylight redirection
		Daylight transport
	Fenestration	Conventional glazing systems
		Innovative glazing systems
	Cooling heating and ventilation	Active options
		Passive options
	Energy generation	Grid connection
		Self-generation (PV, wind, etc.)

A summary of the classification system is presented in Table 2.1. It presents the groups where different technologies can be placed. Every day more examples of each category are being developed. This table also demonstrates the large potential of element combinations that can be made available.

2.5 Comparison of Two Smart Actuator Systems

This section describes how the existence of different technology levels in actuators can be used in different design levels. The apparent lack of technological complexity in traditional elements does not imply that they are less efficient than novel materials. For such purpose we shall contrast the features and design involved in the determination of light redirecting elements such as lightshelves, with those composed of modified materials.

A window without adequate treatment can be a source of potential comfort problems, due to the excessive contrast between the zone close to the window and that in the opposite end of the office room. Uncontrolled penetration of solar radiation can increase thermal loads during summer, producing an additional load to air-conditioning systems.

2.5.1 Lighting Redirection Systems and Their Calculation

Lighting redirection systems are used in situations where it is desirable to extend the reach of natural lighting, balancing contrast, elevating illuminance levels at the back of a room, and in the process save energy by reduced usage of artificial lighting when this is zoned between different areas of the room (Ochoa and Capeluto 2006). Two widely used systems include lightshelves and anidolic systems (Fig. 2.15).

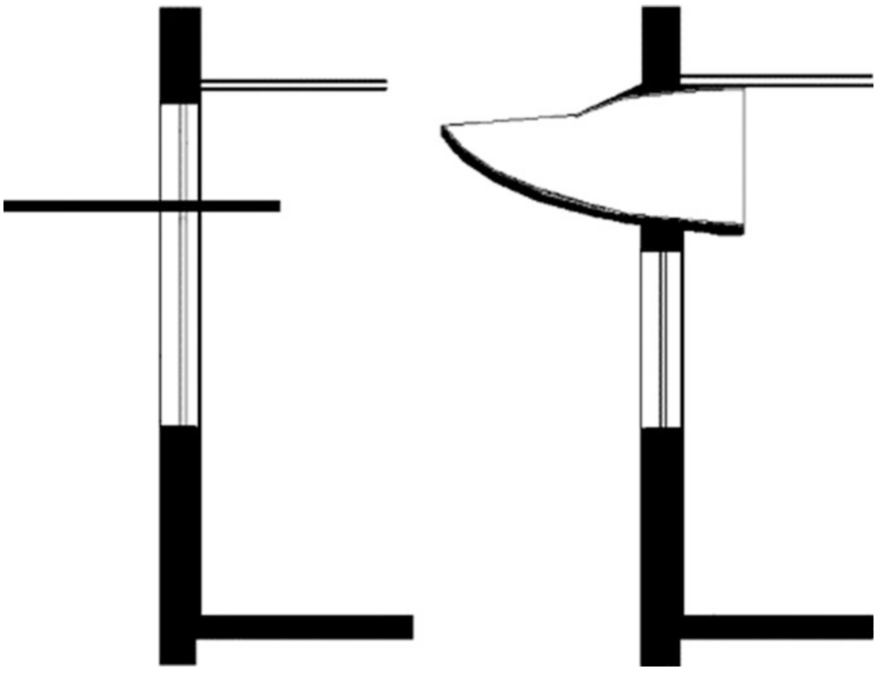

Fig. 2.15 Sections for typical configuration of a lightshelf (*left*) and an anidolic concentrator (*right*)

In the first one, a reflective element is placed horizontally in the clerestory section of the window. Usually this element has a very shiny top surface for light bouncing. On the second element, two parabolic mirrors are placed substituting the clerestory part. They have an entrance and exit glazing, and their mirrors are placed in such way that they can bounce light rays to the desired back portion of the room ceiling, where it reflects back to the inner space (LESO-PB 2008).

For a system with fixed geometry, determining its most appropriate geometry can be a fundamental decision, which can also become limiting in its future performance. Nevertheless, certain elements can be taken into account. Determining the geometry of the daylighting systems can be done by using the angle of incidence of solar rays for an intermediate position for shading during summer and winter time.

The evaluation of the systems can be done through specialized programs for daylight simulation such as Radiance (LBNL 2016), although the subject will be dealt in more depth in Chap. 4. A complete study will consider adapting evaluations for light quality and quantity, since studying one variable, such as illuminance, can be misleading if human factors are not incorporated. It is a known fact that users will react to correct the amount of light entering a space in order to achieve visual comfort, and can even sabotage such systems. Therefore, glare analysis should also be incorporated.

The expected results from the analysis could be similar to Fig. 2.16, which shows the results for glare simulations. The results provide an assessment of the

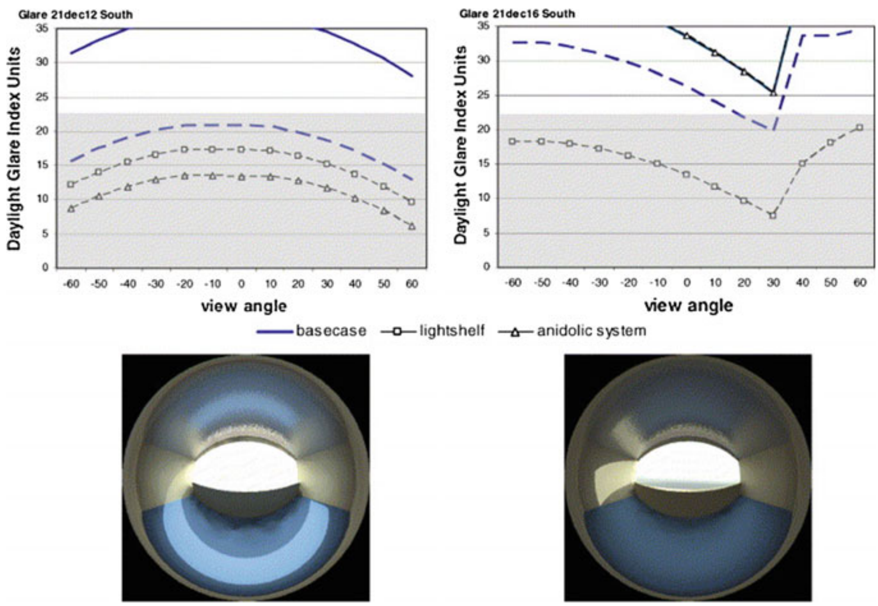

Fig. 2.16 Glare analysis results in analytical (*top*) and graphical form (*below*). *Gray* area in the graph represents the comfort zone. *Dashed lines* indicate the use of horizontal blinds

contribution of the different solutions to reduce glare probability, compared to a basecase without solar protection. The user would then, based on these results, evaluate the most favorable model according to the particular situation. Therefore, although the elements do not have any moving parts, careful and intelligent study is still needed prior to their application in the intelligent façade, as they have significant impact on its morphology.

Summarizing this example, the generic methodology that is followed for these type of devices is the following:

(a) Definition of project objectives.
(b) Selection of potential candidate elements to fulfill the objectives.
(c) Dimensioning and testing (through computer simulation or prototyping).
(d) Feedback from testing results and final detailing.
(e) On-site implementation.
(f) Monitoring and adjustment.

On-site implementation for these devices refers to the actual constructive phase. For bespoke designs, there might need to be an intermediate stage for full-sized prototyping. This stage is different from the one made for energy performance, and is used for verification of structural and manufacturing features.

2.5.2 Smart Shading Systems and Their Implementation Process

The development of materials with enhanced properties through different chemical, physical or fabrication processes, has become one of the most significant innovations for the construction industry (Lazarovich 2012). Although there are precedents in the architectural use of innovative materials, such as in photovoltaic cells or photochromic glazing, new possibilities are opened by the blurring of previously known material limits.

Nevertheless the excitement they can produce for new possibilities, the horizons that can be explored, and the amount of research invested in them, it is hard to find an adequate definition for smart materials. A satisfactory statement describes them as “materials whose properties can be varied controllably in response to changes in their environment” (Bhavsar and Vaidya 2008).

This makes the study of their properties to be closely related to developments in other fields, such as chemistry and materials engineering. Nevertheless, currently the transmission of information is not as fluid as it should be between engineers and architects. Knowledge generated in one field needs a translation for usability in the other. Some reasons behind this gap are the different aims followed by each discipline. Architects require definite properties to conceptualize a space; material engineers usually are researching how to incorporate new features to their products, even though they might not have clear which ones.

To exemplify this process, we summarize the process for a smart façade shading system (Lazarovich 2012). Its development began by defining the design priorities. These consisted of providing a modular stackable system, which incorporated geometrical movement for optimal blocking of solar radiation throughout the year, while providing a visual focus element.

These priorities were then set forth as purposes the system had to comply with, namely providing blockage of solar radiation in different stages, operation under different temperature ranges in a geographical location, geometry change, maximum foldability for storage when not required, ease of maintenance, and usage of familiar technological analogies to carry out the response mechanisms. These requirements were expressed in an objective data format.

During the exploratory phase, different possibilities were examined. The solutions were collected as a catalogue of materials that detailed their main physical properties. Information was then presented in the catalogue in a search system that is useful for architects (Lazarovich et al. 2012). Examination of this catalogue of solutions revealed that for the desired system, a combination of nickel-titanium shape memory alloy metal springs, which acts as sensor and thermal actuator, and canvas shading materials could fit the requirements. It also provides for use of smart materials with low installation cost and requirements.

The next step required a detailed exploration of different options for the shape memory alloy and the folding systems. For the smart metal section, it required filtering the many options available for shape memory alloys, and knowledge on how to specify the required components. For the folding canvas section, a detailed study was made on several alternatives of folds and mechanisms that would allow meeting the requirements. Exploration was made on conceptual mockups with shape polymers that did not have the final materials, due to its high cost.

When a suitable solution was determined, it was then tested experimentally on a proof of concept. The prototype used a scaled down sample of the shape memory alloy and 3D printed components for mechanism and the canvas support. The proposed shading component's opening/closing mechanism is based on equilibrium between two compression springs, as mentioned previously: the shape memory spring and a simple steel spring. When ones compression force is greater than the other, the component changes its state (Fig. 2.17).

This setup was tested indoors for its response at different temperature ranges. The final pattern mimicked flower petals opening and closing when heat was applied and when it cooled down, respectively. The pattern is dynamic since each hexagonal component on the building envelope can sense its particular exterior temperature or radiation level and respond directly (Fig. 2.18).

An initial evaluation of the shading potential and the radiation exposure on a glass façade was done, evaluating the incident radiation on the façade during summer. The results show that, in the opened state of the components, there is no direct exposure to the sun. In the semi-opened state of the components, the façade absorbs half of the radiation that is absorbed in the closed state, in which most of the façade is exposed to the sun's radiation. In order to allow the use of diffuse daylight inside the office spaces, materials like fabrics or polymers with different

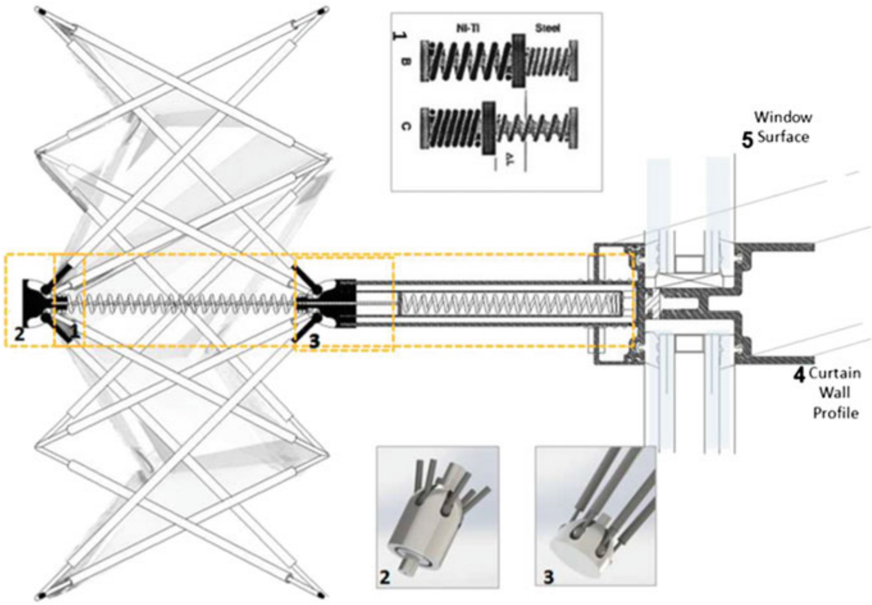

Fig. 2.17 Sections and views for the smart shade using memory alloys. *Image credit* © Courtesy Noy Lazarovich

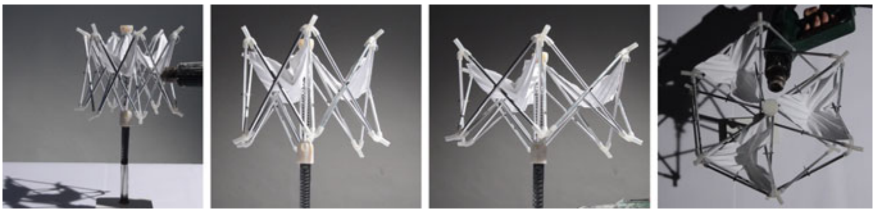

Fig. 2.18 Prototype testing of a smart shade using memory alloys. Screenshots from video. *Image credit* © Courtesy Noy Lazarovich

levels of opacity can be used according to the specific needs in each section of the building envelope. As a conclusion from this example, it can be said that the development stages for smart materials can be generalized for most of them. They would include the following steps:

(a) Definition of general project objectives.
(b) Specification of requirements from the material(s).
(c) Search for existing solutions, based on the requirements.
(d) Selection of candidate materials for meeting the requirements.
(e) Testing of prototype systems that will use the material(s).

(f) Calculation of expected impacts, based on general objectives and results from prototype testing.
(g) Full-scale implementation.
(h) Monitoring and adjustment.

However, carrying out each stage is practically a custom process, since each case is different and will have its own requirements. There is also the risk that requirements asked from a smart material have not been developed yet. Or in the worst case scenario, that the desired material does not exist.

The last step of the suggested process is also composed of a series of sub-stages, since many smart materials are at this stage expensive for architectural use and only available for small components. It is expected that a study on their industrialization process might be required, in order to meet the desired characteristics for a complete building project.

Therefore, caution must be taken when using these types of smart material actuators, as depending on them for carrying out all the desired envelope functions will make the building dependent on a given technological development.

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