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Multi-Functional Building Envelopes: Key Properties, State-of-the-Art Technologies and Visions for the Future

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Preface

This master thesis distinguishes all the functions of the building envelope, explains the key properties responsible of their achievement and proposes a review of the multi-functional technologies to fulfill them. Eventually, visions for the future of multi-functional building envelope are proposed as well as original ideas.

Many articles address one particular function such as thermal insulation or the use of renewable energy in buildings. Others review one specific technology as aerogels or vacuum insulation panels for instance. The point here is to go further and propose a global view of all functions of the building envelope, focusing on technologies achieving them.

It was very important to carry our study out of the beaten tracks, thus to have all along the article a broad and conceptual view of the building envelope. The aim was to be as open minded as possible in order to propose visions for the future. Even if no technology breakthrough is given here, ideas and concepts are proposed in this paper which hopes to lead future technological research. This conceptual approach of the future materials and technologies is important for SINTEF researchers. Indeed, it is in their belief that the future may lie in *thoughts not yet thought of.*

The writing of this paper has been achieved under the supervision of Bjørn Petter Jelle, professor in Norges Teknisk-Naturvitenskapelige Universitet (NTNU, Norwegian University of Science and Technology) at the Civil and Transport Engineering and senior research scientist in SINTEF Building and Infrastructure, Department of Material and Structures. I would like to thank him for offering me the opportunity to work on this project. By its broad subject, this master thesis has given me a wide knowledge in building technologies and also a deep understanding of the underlying building physics phenomena. The conceptual approach used to distinguish the functions and propose the visions for the future was intellectually stimulating and interesting. I want also to thank my french supervisor, Carmen Vasile, whose scientific rigor concerning building physics has been helpful. Eventually thanks to Arild Gustavsen for his time and advices during the brainstorming.

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Abstract

A broad and original definition of the building envelope is given as *a shelter aiming at controlling various fluxes in the building*. This paper reviews the underlying key properties ruling the phenomena enabling the completion of the multiple functions ascribed to the building envelope. The functions of flux control are emphasized. Indeed the thermal conductivity of a material, thermal inertia of buildings, transmittances of a window, solar energy production, sound attenuation or absorption of a concrete wall or moisture permeability of a protection sheet are all key properties ruling the control of fluxes such as heat, sun, sound or moisture and will be explained here. A non-exhaustive review of the principle state-of-the-art multi-functional technologies using these key properties to achieve the different functions is given. Hence the review of building integrated photovoltaic solutions, phase change materials, smart windows, double skin façades, green envelope, aerogels, multi-functional concretes and photocatalytic materials, among other technologies. The focus is put on the technologies explanation and the performances, in the multiple roles they have, are highlighted. Through a definition and a description of the ideal multi-functional building envelope as *assuring safety, providing comfort and any other desired functions without any drawbacks* this paper aims to orientate technological breakthrough of the future towards multi-functionality and to a total control of all the fluxes. Eventually, based on the association and the understanding of existing technologies, original ones achieving multiples functions are proposed as possible visions for future developments.

Keywords: Multi-functional, Building envelope, Key property, State-of-the-Art, Technology, Visions, Future

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1 Introduction

Building envelopes (BEs) are complex systems designed to achieve various functions. In the current energy context the research focuses mainly on energy savings or renewable energy use in order to provide comfort within respect of the environment. The attention given to energy consumption of building is entirely justified by the growing price of energy. However, the future of BE technologies lies for sure in the multi-functional ones. Furthermore when choosing which technology to use for a given BE part, the knowledge of its behaviour considering all other functions is something building's designers cannot afford to ignore.

As research stands nowadays we can highlight two types of literature: studies about one specific technology have been made and often give their characteristics regarding multiple functions. Hence several reviews about aerogels, Green Roofing Systems (GRS) or Vacuum Insulation Panels (VIP) for instance are available, giving the performances reached in several domains as thermal insulation or sound attenuation. The second type of articles gives a list of the technologies available to achieve a single function, for example thermal insulation, passive use of solar energy or photovoltaic energy production. However, in the knowledge of the authors, no paper covers almost all the BE envelope functions while giving the different technologies to fulfill them as well as the reached performances. This is the first objective of this paper as the second one is to propose visions for the future. That is to say to envision new multi-functional materials or technologies or to enhance existing one by adding original functions.

To that purpose this paper firstly identifies the various functions which can be achieved through a BE. This first stage is done with an open-minded and broad point of view, trying to ascribe the BE originals functions it does not have yet, in order to propose solution beyond the beaten paths. By pointing out basic functions as well as more sophisticated ones; this identification work leads to the definition of a BE peculiar to this paper. One important notion standing out of this definition is the control of different fluxes as the heat, the sun and the sound for instance as functions of the BE. This original consideration determines the angle of study of the key properties and the different multi-functional technologies.

Once the functions are determined, the key properties responsible of the functions fulfillment are highlighted. By that way for example, the physical phenomena ruling the solar, heat and sound flux are explained and the key properties enabling their control are detailed. The understanding of the underlying physical principles is fundamental to apprehend today's technologies, even more to propose these of tomorrow.

The different technologies used to achieve the numerous functions are presented. Both traditional (mineral wool, multilayer glazing…) and state-of-the-art technologies (Vacuum Insulation Panels, aerogels) are detailed. Two reasons explain that choice: some of the BE functions are currently mastered and the used technologies can no longer be called state-of-the art but still deserve to be quoted. Furthermore, their knowledge is helpful in the innovation process. Monofunctional technologies are for this same last reason quickly reviewed. Then multi-functional BE technologies are presented and the emphasis is put on the performance of the multiple functions they fulfill.

Eventually this paper proposes visions for the future of multi-functional BE technologies. This process starts with the definition of the ideal multi-functional BE. Even if the proposed definition can seem futuristic and contrived, it is in the authors believe that the future of scientific research may be directed and influenced by these ideas which seem out of reach today, but may be achieved tomorrow. Then a quick study of the envisioned insulation for the future is done, but once again under a multi-functional angle. Using the review of the existing technologies, ideas are given to create original multi-functional BE as the controllable "fluid building envelope". The point isn't here to propose a technologic breakthrough but to submit ideas, open creative discussions, to *think thoughts not yet thought of* (Jelle et al. 2010).

2 Building Envelope Functionality

In order to go off the beaten tracks of traditional functions given to the BE, this paper will perform a basic review of human needs and expectations and try to ascribe them as a BE function.

2.1 Functions Induced by Maslow's Hierarchy of Needs

To have a large overview we can start at the basis of human needs. Maslow's hierarchy of needs is a common and recognized concept (see Poston 2009) to define them.

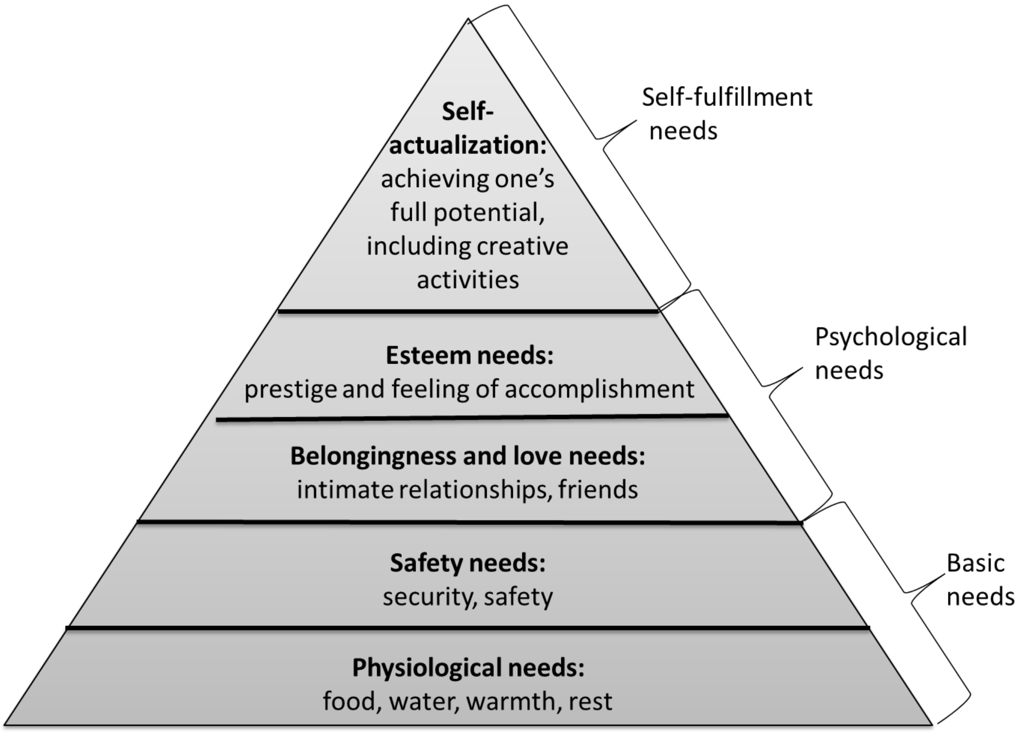


Figure 1. Maslow's pyramid of needs redrawn (Poston 2009).

The following needs can be achieved thanks to the BE:
Among the *physiological needs*:

- *Food and water:* highlight the fact that a building has to provide satisfactory conditions to allow one to bring, keep and consume food and water in the BE.
- *Warmth* gives the BE the function of producing heat and/or retaining the created one. Moreover, this function implies the protection against harsh climate such as rain, snow, wind… Note that excessive temperature must also be avoided.
- *Rest* forces the BE to provide a sleeping environment what can be considered as thermal, sound, and daylight conditions. Sound insulation and daylight control functions can thus be induced.

Safety needs:

- *Safety:* The physical protection of the buildings occupants is one of the most basic building functions, that means the BE has to be a protection against all the external natural threats (harsh climate but also dangerous animals or insects) and also be a safe construction (i.e.: be stable regarding its own weight, climate loads but also resist earthquakes and fires). Moreover, a BE must present safe characteristics for the occupants such as healthy materials, no dangerous fume emissions, prevent hazardous effects of exceeding moisture…
- *Security:* A building is a place to store resources (food, money, documents…) which will have to be protected from thieves or visitors, hence a control of people authorized to enter the BE is necessary.

Belongingness and love needs:

- A building will be a place of social gathering and thus has to be a welcoming place to meet with friends and acquaintance even though it must also be able to offer privacy for intimate relationships. The concept of intimacy leads us to the opacity of the envelope.

Esteem needs and self-actualization:

- The BE has to provide optimal indoor conditions for a given purpose so a person can reach the last needs of Maslow's pyramid, their self-fulfillment. A school for example has to reach better acoustical conditions than a simple dwelling as it has to be a quiet place to offer the student an optimal studying environment. Other buildings will have different requirements in term of indoor conditions which can be offered through the BE, for example: hospitals, cinemas, malls, offices…

2.2 Functions Induced by the Comfort Needs

Now that the fundamental needs have been looked through in order to be completed by BE functions, we have to study the comfort aspects of buildings to draw other functions. The comfort of a building mainly consists in the Indoor Environment Quality (IEQ), according to Andersson et al. (2011). The following criteria can be distinguished

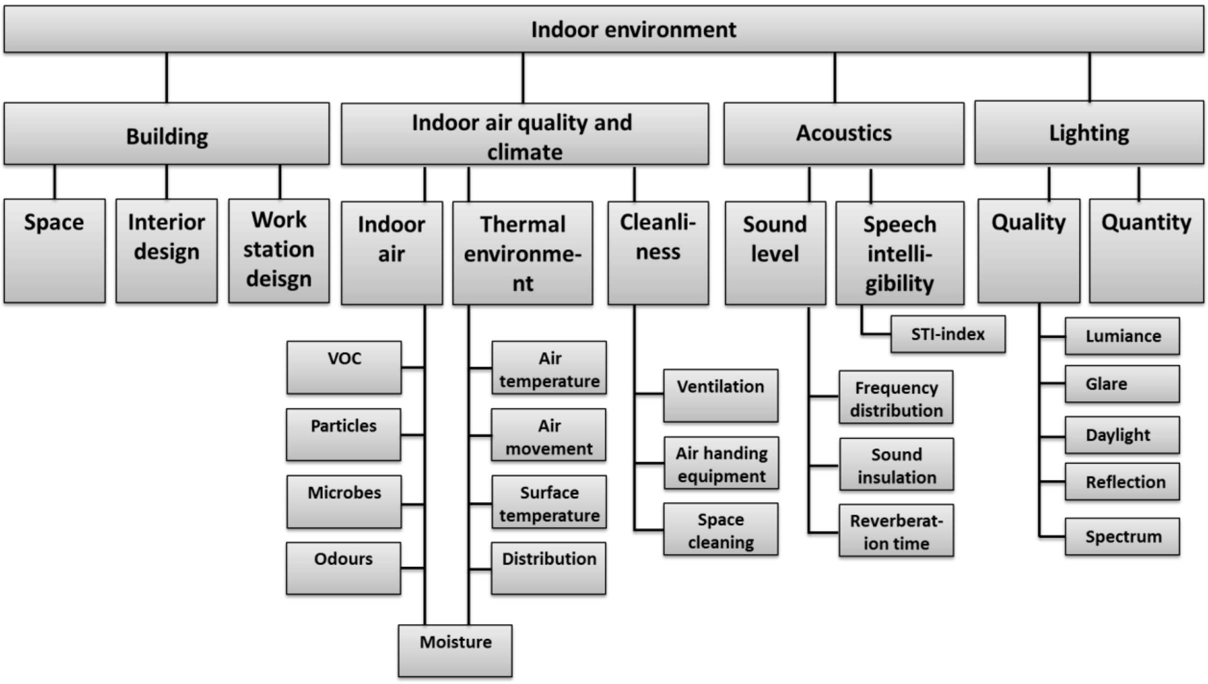


Figure 2. Parameters included in the definition of Indoor Environmental Quality (IEQ), redrawn from Andersson et al. (2011).

The following comfort needs can be fulfilled through the BE:

Building: The need for space indicates us that a BE has to offer a maximum of space. For a given construction area, the BE print is lost space, its thickness will thus have to be as low as possible.

Indoor air quality and climate:

- *Indoor air:* The indoor air provided by natural or mechanical ventilation but also infiltration has to be controlled in terms of quantity, velocity, temperature, moisture and pollution content.
- *Thermal environment*: the indoor air temperature has to be easily controlled (to stay between defined comfort temperature thresholds) but some phenomena as "cold surfaces" induced by thermal bridges or draughts must also be avoided.

Acoustics: The indoor sound level must be adapted to the building use and often external noise level has to be lowered.

Lighting: A given light intensity has to be maintained in the BE, the sun's daylight has to be used considering glare and excessive solar gains as issues.

2.3 Sustainability Concept

But nowadays, focus on fundamental and comfort needs to define the functions of a BE is not enough anymore. Indeed other BE's functions are today unavoidable:

- Costs of construction: these have to be reasonable especially regarding: materials costs, transport and installation costs, etc…
- Costs of use: especially heating, cooling and lighting costs are current major issues.
- Limit the use of fossils energy and CO_2 emissions.
- Promote the use of sustainable energies.
- Create buildings adapted to all kind of budget, especially social housing.

All those criteria can be separated into three different concepts: social, economic and environment, and thus can be gathered under one term: *sustainability*.

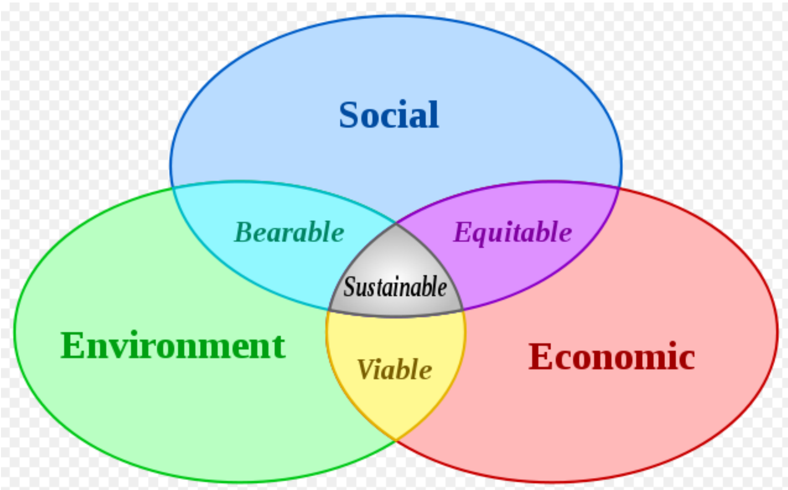


Figure 3. The three pillars of sustainability (Wikipedia 2007).

2.4 Definition of Building Envelope

From basic needs to comfort expectations we have highlighted different categories of functions: firstly a BE has to be a shelter against external aggressions (loads, fire, earthquakes…) but mainly to try to control various fluxes, such as heat, sun, moisture, rain, sound, particles, entering people etc… In order to achieve our goal which is to reach new multi-functional building concepts we have to keep a large and open overview of what a BE is and what are the expected functions. That is why this paper gives a conceptual and broad definition of the building envelope:

A building envelope is a shelter aiming at controlling various fluxes in the building

This extensive definition can be specified as in most of the cases; this shelter will have to be durable and, as explained previously, will have to fulfill its functions within sustainability. Thus we can give the following narrower but more pragmatic definition:

A building envelope is a durable shelter aiming at controlling various fluxes in the building with respect to sustainability

2.5 Multi-Functional Building Envelope

A BE is commonly achieving several functions: even a very basic cabin will normally block the rain, the wind and assure some sun shading for instance. Can it thus be called a Multi-Functional Building Envelope (MFBE)? This question is debatable and the concept has to be clarified. This paper will therefore separate two categories of functions: the *common* and the *additional* ones. The *common functions* are these typically associated with the BE nowadays. *The additional functions* will have required some specific modifications, products addition, or special thoughts. But a second question is raised yet: what are the common functions of a BE? This is also a debatable question, the common functions expected will be different according to the culture (not the same in Africa that in Europe), on the money resources and on the climate for instance. Of course this division may be difficult; nevertheless, using one's common sense, the distinction is quite clear and easy. The same separation is possible to distinguish the multi-functional technologies. One last interesting aspect is that the cutting edge MFBE of today may be the common BE of tomorrow. All in all we can now define a MFBE:

A multi-functional building envelope provides one or several additional functions while assuring the common functions within its envelope.

3 Key Properties

This section will present the physical phenomenon allowing the completion of each function. The emphasis is put on the key properties ruling the phenomenon and which will be used by technologies to achieve the functions.

3.1 The Shelter's Properties

The word "shelter" indicates that safety functions are expected in a BE, protecting occupants from all kind of threats. A BE has to resists those threats for a given time-span: the service life. This introduces the notion of durability. Durability is a very wide and complex subject which raises many issues, among these:

- The absolute durability does not exist and moreover, there is a compromise between the money spent to reach the durability and the cost of replacing the building part or the cost and consequences of the building part not assuring its functions anymore (or partially assuring it).
- Which are the building parts the most easily replaceable? The answer depends on the accessibility of the BE's part (it is easier to replace a tile than a bearing wall). But also on the discomfort created by the operation.

The expected durability of a technology is partly determined according to the presented issues. An insulation material, which is easily replaceable, will have to keep assuring its functions (to assure the heat flux lowering) for a shorter time than a bearing wall (with a structural and acoustic role). And even if a better durability may be possible, it will not be technologically achieved if it is not valuable.

Beside typical physical threats as the own weight, harsh weather, fire, earthquake etc…There is also the climate exposure factors, harming days after days the BE. Jelle et al. (2011b) gives a comprehensive list, the following ones will be studied here:

- Solar radiation, that is, ultraviolet (UV), visible (VIS), and near-infrared, (NIR) radiation
- Ambient infrared (IR) heat radiation (the resulting elevated temperature increases the rate of chemical degradation reactions, and also the rate of growth of rot and fungus up to limiting temperatures)
- High and low temperatures
- Temperature changes/cycles (temperature induced relative movements between different materials, and number of freezing/thawing cycles)
- Water, for example, moisture, relative air humidity, rain (precipitation), and wind-driven rain
- Physical strains, for example, snow loads
- Wind
- Pollutions, e.g. gases, particles in air like radon
- Microorganisms, e.g. mould for instance

3.1.1 Structural Design Adequacy

Indeed a building is subject to multiple loads where the structural design of the building will be the key property: that is to say climate threats like snow and strong winds but also accidental loads as earthquakes or tidal waves. The adequacy of the structural design will depend on several points, the most important will be:

- *Strength of the materials*: materials used to assure the "structural" role must have a given strength to assure their role, the compressive and the tensile strengths will be the most important factors in this case.

- *Load sharing:* Using strong materials is not the only solution to carry heavy loads (and is also expensive!), one can also share the loads wisely. Wind bracing to carry horizontal loads in trusses structure or to add a support under a beam to reduce its bending and thus its section, are typical examples of load sharing. The idea to keep in mind is that the structural material may have low strengths if the right load bearing structure is designed.
- *Dynamics loads:* Considering dynamic loads, the most important are earthquakes. The danger lays in the internal strains in the materials resulting from relative movements. Thus the solution is to have the whole building moving during a seism.

However, it is important to note that the BE is not forced to have this structural function, and can only be a non-bearing façade. The bearing of the loads can be assured within the building thanks to columns or metallic trusses for example.

3.1.2 Fire Threats

Fire threats are a particular type of incident: the occurrence probability is very low, but the consequences can be devastating both for the building and human life if no fire safety engineering is applied. Safe evacuation is at the base of any fire policy. All the parts of a building are actually concerned but paying attention to the BE we can highlight several functions it must assure during a fire episode (Hens, 2011a): *Keep fire to spread to surrounding buildings* and also *guarantee structural integrity during a sufficiently long time span*. This time span will be used to evacuate the occupants and also allow the fire brigade work. We can distinguish three BE's key properties:

The construction material behaviour under high temperature: most of them have their mechanical characteristics (tensile and compressive strength, E modulus) drastically lowered during a fire. Purkiss (2007) and Buchanan (2001) give us the following typical construction materials behaviour:

- Steel is a non-combustible material which mechanical characteristics are lowered temporarily by approximately 80 % when the temperatures exceed 600 °C, after an exposure of more than 15 minutes, steel will quite visibly deform, twist and buckle thus losing all structural function. Usually after a prolonged and hot episode, steel will suffer such large extensive damages that replacement, rather than strengthening or repair, will be prudent.
- Concrete is also a non-combustible material and its mechanical characteristics have the same behaviour under high temperature; i.e. losses occur around 600 °C. However, as the concrete thermal conductivity is much lower than steel and offer more massive members compared to steel structures, it provides a desirable heat sink for absorption of heat of a fire, hence its use as fire barrier.
- The timber's situation is different: first it is a combustible, secondly outer layer of the timber structure losses all its strength during a fire while retaining a role as an insulating layer which prevents excessive temperature to rise in the core of the timber. Mechanical characteristics drop around 300 °C.

The *fume emission* is the second key property. Indeed, if a building keeps it structural integrity during a fire, the heat of the flames will not be the most harmful but the suffocation and the lack of visibility caused by fumes. The chosen materials must also have nontoxic fume in case of fire and also as low in quantity as possible. An efficient ventilation system to evacuate the fumes has also to be designed, this function can also be given to the BE.

The last point is the *fire escapes* implemented in the BE, their structural strength, their widths and locations.

3.1.3 Corrosion

Steel is broadly used in construction, in BEs it is mainly found in steel frame with cladding and in reinforced concrete's rebar. However steel (Fe) is a thermodynamically unstable material and tends to be transformed into rust (hydroxides, for example $Fe(OH)_2$). Corrosion of steel (rusting) only requires water containing dissolved oxygen (Myrdal 2011). This mechanism is an electrochemical reaction and thus is characterized by an electrical current and an electron exchange:

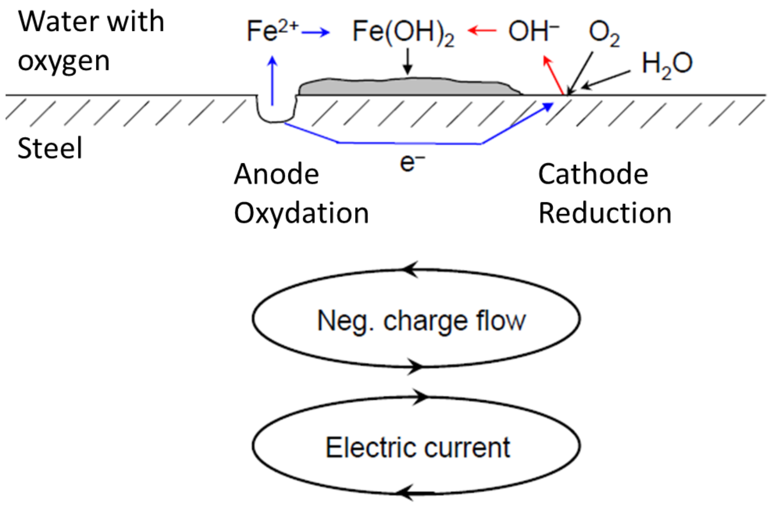


Figure 4. Mechanism of the corrosion of steel, redrawn from Myrdal (2011).

In basic environments (such as concrete), the corrosion reaction creates a very thin and impermeable oxide layer which protects the steel against further corrosion (the steel is *passivated*). However, depassivation, and thus further dangerous corrosion, can occur because of two major causes:

- *The acidification of the pores water by carbonation:* during carbonation the CO_2 in the surrounding air penetrates the concrete pores, reacts with H_2O to produce H^+, thus making the pore water more acidic from 13.5 to 8 or 9. In this neutral environment, the passive layer cannot resist and is slowly and uniformly destroyed. This reaction can be easily noticed and is not as dangerous as the second one.
- *The presence of aggressive ions in the pore water:* Those aggressive ions are typically chlorides Cl^- from de-icing salt or sea water or atmosphere. They directly attack the passive layer and create pitting corrosion. This corrosion is local and no visual damages are noticeable before the ruin of the structure, hence this type is the most dangerous.

The key properties of corrosion of steel in general are thus the exposure to water and oxygen, the presence of aggressive ions as Cl^-, as well as the electrical current produced. For corrosion in concrete we can add the pH of the concrete, and thus the CO_2 penetration responsible of carbonation. Hence key properties have to be quoted about concrete such as its porosity and permeability.

3.1.4 Solar Radiation

Solar radiation damages are almost unavoidable and affect many building materials. At the earth surface, the radiations roughly range from 290 to 3000 nm in which we can distinguish as explained earlier the ultraviolet (UV) radiation between 290 and 380 nm and the visible (VIS) light from 380 to 780 nm. Finally, the near infrared (NIR) radiation located between 780 and 3000 nm which contains almost half of the solar energy (Jelle et al. 2007). Building material, especially organic materials as natural polymers (wood) or synthetic polymers (PVC), are subjected to solar radiation deterioration. Indeed, the chemical bonds of those materials (C=C and C=O) can be broken by the higher energy parts of the solar radiation through photons, that is to say mainly UV radiation and short waves of VIS light. The photodamages range from simple (but undesired) discoloration to loss of mechanical integrity. Discoloration is due to chemical changes in the polymer structure, yellowing or darkening are the results from those changes. Moreover, the synergic combination of water with UV radiation will enhance the phenomenon and provoke erosion and fading at the surface of some type of polymers, the so-called chalking phenomenon. When the photodamages continue, micro cracking can be observed, and finally losses in mechanical characteristics occur. The temperature reached by the polymer will also affect the deterioration, the higher the worst for the material. (Andrady et al. 1998). In general a high temperature of a construction material has only drawback on its durability, as faster chemical reactions, and an increased rate of rot and mold growth. Thus, the lower the temperature the better the durability of the material.

It is also important to note that solar radiation can harm human health. Indeed human skin subjected to solar radiation will experience sun tanning, or more serious problems as sun burning or, in the worst cases, loss of skin integrity (Jelle et al. 2007).

3.1.5 Frost and Thaw

Frost deterioration is due to the water phase's changes inside the pore of some material, thereby only porous materials as bricks, concrete or some insulation materials will suffer those damages and steel frame and cladding will not be affected by this physical attack. The physical phenomenon of frost deterioration is currently not surely explained, though two major theories stand out. The first one put the emphasis on the *hydraulic pressure* while the pore water changes its phase and thus has a volume rise of 9 %: this pressure will be responsible for cracks or bursts. The second one charges the *osmotique pressure* difference caused by increased ionic concentration in surroundings unfrozen water pores with the same consequences. Eventually two key properties rule the frost deterioration mechanism: The *pores structure* their size and the geometry of their distribution. In the other hand the degree of saturation of the porous material is also crucial. Indeed if it is under a certain threshold depending on the material characteristics, there will be no frost deterioration. The emphasis will thus be put on the *permeability* of the material. (Jacobsen et al. 2011)

3.1.6 Thermal Dilatation

Thermal dilatation is a concern during the construction, especially for concrete, but also all along the building life time, only the second one will interest us here. A change in the ambient temperature of $\Delta\theta$ will induce a strain ε according to the following relation

$$\varepsilon = \alpha \, \Delta\theta \tag{1}$$

where α is the dimensionless thermal dilatation coefficient, this last is for common construction materials (hard concrete and steel) roughly equal to $1.0 \cdot 10^{-5}$ (Jacobsen et al. 2011). The thermal dilatation can harm the material because of the induced strains and also the total structure because of the deformation if this last is not designed to handle small deformations. Moreover, the thermal stresses induced; according to Hooke's relation, can produce cracks in low tensile strength as concrete. The key properties of this durability issue are thus the *thermal dilatation coefficient* and the *induced strains and stresses.*

3.2 Flux Control

Various fluxes are passing through the BE: from heat, sun and moisture, to particles as radon or pollen, even people can be consider as a flux going in and out the building. Most of these fluxes are linked; indeed, through the air flux comes as well heat, sound, moisture, particles for instance. We will now study the main fluxes and give their key properties ruling the phenomenon.

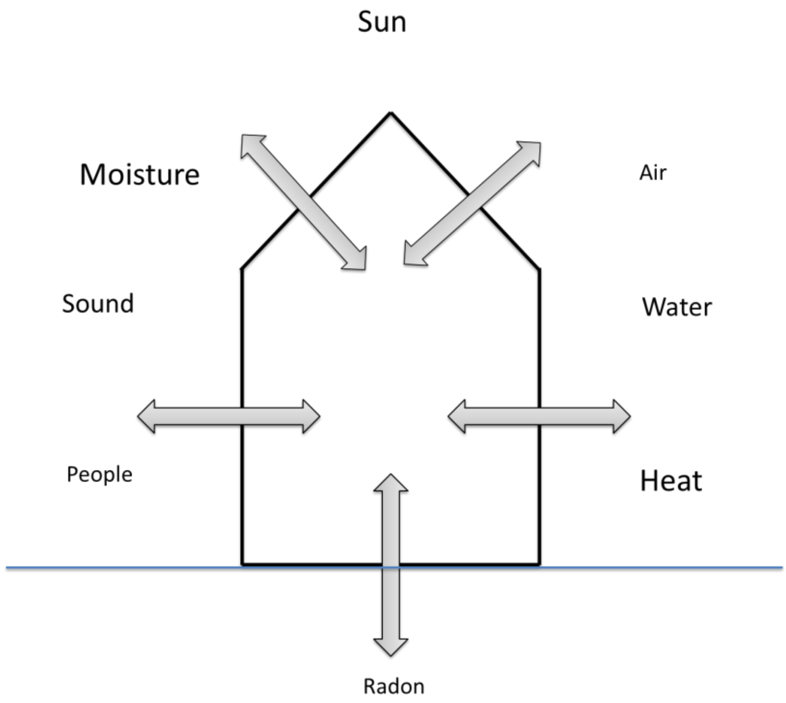


Figure 5. Main fluxes passing through the building envelope.

3.2.1 Heat Flux

Heat energy always tends to transfer from high temperature to low temperature regions until the temperature balances. This equalizing of temperature can occur by three basic processes of heat transfer, from McMullan 2007. Other phenomena involved in the heat flux as latent energy and thermal mass will be studied here. In the following equation, T will of course be the temperature but in Kelvin (K).

Conduction

At the place where a material is heated, the molecules gain energy and this energy is transferred to the neighbouring molecules which then becomes warmer. This transfer of energy is achieved by the drift of free electrons (especially in metals) or by vibration waves called phonons in non-metallic materials. Poor thermal conductors are so called insulators; porous materials that trap a lot of air tend to be efficient: the fewer molecules to conduct energy, the better. The equation to describe the heat conduction is (NTNU and SINTEF 2007):

$$q_l = \lambda \, (T2\text{-}T1) \, / \, d \qquad (2)$$

We can thus recognize the key properties of this phenomenon: the *thermal conductivity λ, in W/(mK)*, it measures the rate at which heat is conducted through a particular material for a given thickness *d (m)*. This lead to the *U-value in W/(m²K)*, which gives the heat exchange through 1 m² of a surface for a 1° temperature change. This value will be used to describe a material, a fenestration technology with several glass panes and gas for instance. It will be the main value to describe a BE’s part.

Convection

Convection, the second process of heat transfer, can only occur in gasses or liquids. It consists in the transfer of heat energy through a fluid by the bodily movement of particles. Indeed a hot fluid is subjected to the stack effect, that is to say that it has a lower pressure and will move to the upper stories heating the replaced air. The phenomenon is ruled by the following equation (NTNU and SINTEF 2007):

$$Q_c = h_c \, (T_2\text{-}T_1) \qquad (3)$$

Where h_c is the convective heat transmission factor in W/(m²K).

Radiation

Radiation is the transfer of heat by electromagnetic waves which wave lengths and frequency will depend on the temperature of the emitting surface. The higher the temperature, the lower the wave length. It is also important to note that unlike convection and conduction, this heat transfer can occur in the vacuum. The amount of heat emitted or absorbed by a surface will once again depend on its temperature but also on its absorbance. The more the surface absorb heat, the more it emits (the theoretical black body absorbs all the heat and then emits it). The intensity of the radiation heat flux E in W/m² is driven by the next equation:

$$E = \varepsilon \sigma T^4 \tag{4}$$

Where $\boldsymbol{\sigma}$ is the Stephan Boltzmann's constant, T the temperature in K and *ε the emissivity* of the material, it is here the key property, from (NTNU and SINTEF 2007)

Total Conductivity

To define the insulation power of one material concurrently subjected to convection, radiation, or containing gas in the pores, etc… the total *overall thermal conductivity* λ_{tot} *(W/(mK)* is defined and enables an accurate and easy comparison. By Jelle (2011):

$$\lambda_{tot} = \lambda_{solid} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coupling} + \lambda_{leak} \tag{5}$$

Where λ_{solid} = solid state thermal conductivity, λ_{gas} = gas thermal conductivity, λ_{rad} = radiation thermal conductivity, $\boldsymbol{\lambda_{conv}}$ will describe convection heat losses, $\lambda_{coupling}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities and finally λ_{leak} accounting for the leakage (through air or gas) heat losses;

Latent Heat

The latent heat is the heat energy absorbed by or released from a fluid during a change of state, with no change in temperature; this energy is used to break the bounds between molecules. The latent heat is released or absorbed according to the following changing state senses:

Gas into liquid: latent heat of vaporization released

Liquid into solid: latent heat of fusion released

Thermal Mass

The *specific heat quantity (c) (J/kg K)* of a material is the quantity of heat energy required to raise the temperature of 1kg of that material by 1K. At this point we could assume that water (c=4190 J/kg K) is a better insulation material than concrete or brickwork (3300 J/(kgK)) (MacMullan 2007), but we have to consider the density of one material. The higher the density, the better its heat regulation. This is called the *thermal mass* and is a key property of the heat flow.

Thermal Bridges

A thermal bridge is a portion of a structure with higher thermal conductivity that increases heat flow and lowers the overall thermal insulation (U-value) of the structure. The most common thermal bridges occur at the following BE parts: junctions of wall with roof or floor, mortar joint around concrete wall block, steel lintel above windows and doors, window frame and sills, etc.... Thermal bridges are not avoidable in all the building, but can be lowered drastically by a correct design and installation of thermal insulation, from McMullan (2007).

3.2.2 Solar Flux

According to MacMullan (2007) light is energy in the form of electromagnetic radiations, they can be described either as a wave motion (thus with a frequency and a wave length) or as "packets of energy": photons. Firstly we will consider the solar flux as a wave motion in order to highlight the key properties of both natural lighting and solar heat gains and then consider it as packets of photons in order to explain the principle of solar cells. Nevertheless some factor are general to solar flux, they will be explained here:

General Characteristics of the Solar Flux

First of all: *the sun exposure,* it depends on several factors:

- The geographical latitude which determines the height of the sun in the sky.

- The orientation of the building.
- The season of the year affecting the height of the sun in the sky.
- The local cloud conditions, which can partly block solar radiation.
- The angle between the sun and the building surfaces: the incidence angle.

Solar radiation falling on a material will be transmitted, absorbed or reflected regarding the wavelength (λ), the incidence angle, and essentially the optical properties of the material. These properties are called *transmittance (T), absorbance (A) and reflectance (R)* with the next relation (Jelle et al., 2007):

$$T(\lambda) + A(\lambda) + R(\lambda) = 1 \ (100\ \%) \qquad (6)$$

The figure 6 gives the characteristics of these properties in function of the wavelength for a float glass.

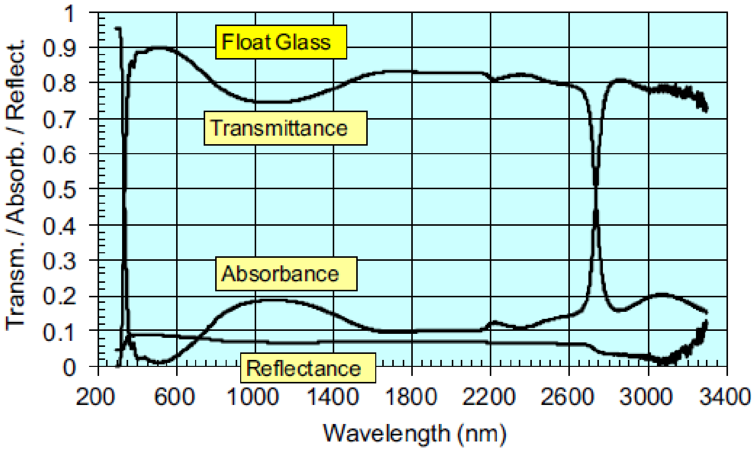


Figure 6. Transmittance, absorbance and reflectance versus wavelength in the whole solar spectrum measured for a float glass (Jelle et al. 2007).

And we can also distinguish three different transmittances (Jelle et al. 2007):
- T_{sol}: The total solar transmittance
- T_{vis}: The visible solar transmittance (380 nm< λ <780 nm)
- T_{uv}: the ultraviolet solar transmittance (100 nm< λ <380 nm)

Properties of Lighting

The BE will have a major role in providing natural light into the building. The usual unit to measure the desired light intensity is the illuminance (in lux): it corresponds to the density of luminous flux reaching a surface. A low domestic lighting is around 50 lx, although a bright day reaches 50 000 lx, but of course that level of intensity directly in a building must be avoided because of the induced glare (Mac Mullan 2007). Windows are the ones with the role of regulating the illuminance in the building; however we cannot characterize a window by the number of lux passing through, because of the changeable weather conditions. We thus introduce the *daylight factor*: it is the ratio between the illuminance at a point in an interior to the illuminance at the same interior point due to an unobstructed sky without the tested window. The daylight factor depends especially on the ratio window/frame, the angle of visible sky, the transmittance T of the window and the sun exposure (D.C. Pritchard 1999).

Properties of Solar Heat

Solar heat is a particular type of heat transfer by radiation coming from a very hot body: the sun. It is important to underline that sun provides 5-10 times more solar energy on an ordinary single family house than the needed quantity to heat a whole year, hence the importance of the solar heat gains study (NTNU and SINTEF 2007). One of the two key properties will be *the radiation intensity I* in W/m², this value is highly changeable and depends largely on the sun exposure parameters but an average value can be fixed at 500 W/m². Another factor to consider is the portion of solar radiation that passes through the window pane when there is approximately 90° perpendicular incoming sunshine, it depends on the type of glazing (transmittance) and the type of gas used to insulate, the so called *solar factor "g" or "S"*. g is a constant for a given window and leads to the *effectively radiated surface* A_S given by:

$$A_s = A\ F_s\ F_f\ g \quad (7)$$

Where A is the total area of window (frame included), F_s and F_f are two factors giving respectively the shading and the ratio of frame influence. The actual solar heat gains can thus be approximate by the solar radiation *I* times the effectively radiated surface A_s.

$$\text{Solar gains} = A_s\ I \quad (8)$$

Of course solar heat gains are profitable in the heating season, but most of the time they will have to be avoided in summer to keep a comfortable indoor temperature. Thanks to the previous formula we deduce that for a given window and a BE location, g and F_s are the factors to be modified to reduce the heat gains (NTNU and SINTEF 2007).

Solar Cells

Solar energy can be directly converted into electricity with the help of solar cells. The photovoltaic generation of power is caused by radiation that separates positive and negative charges carriers in absorbing materials. In the presence of an electric field, these charges can produce a current for use in an external circuit. When this electricity helps to practical uses, the solar cells are called photovoltaic (PV) cells; those ones are in majority silicon semiconductors. A semiconductor works on the following principle: when a photon is absorbed by the silicon molecule, a covalent bond will break and an electron is released, at the same time it leaves behind an empty state treated as a positive charge. If the silicon is connected to a wire, electrons will flow through the wire, and the "positive charges" will drag electron from this wire, creating an electrical current (Agrawal et al. 2011).

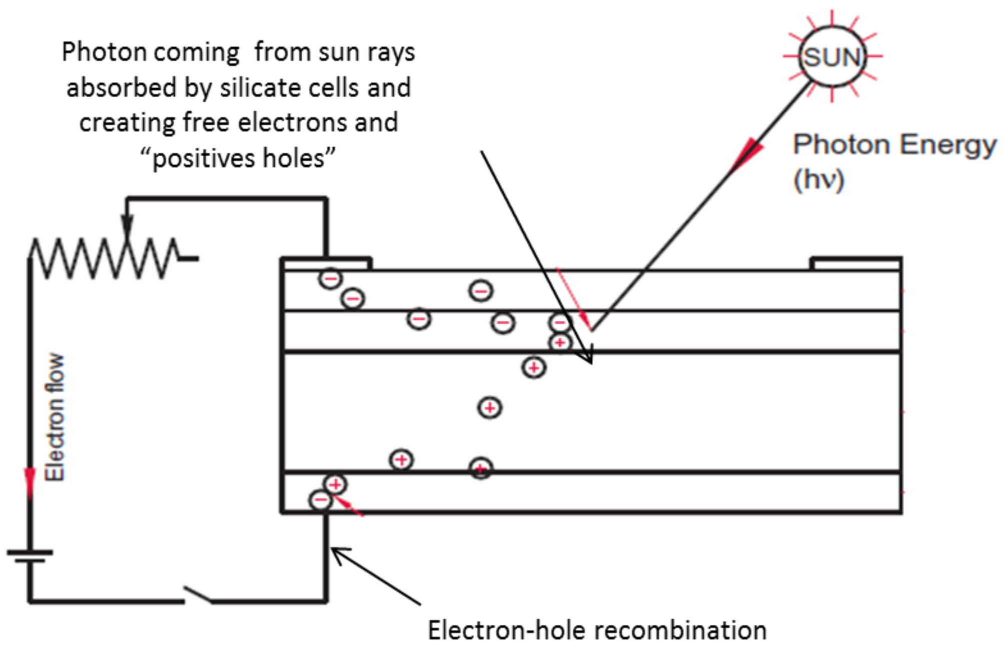


Figure 7. Photovoltaic solar cell, adapted from Agrawal et al. (2011).

The comparison of several types of PV modules implies the following characteristics: (Jelle et al. 2012a)

- The power per unit area in W/m² or Wp/m²
- The efficiency of one module which is simply the maximum power produced by a module in W or Wp compared to the total irradiance, in W, for a given area.

3.2.3 Water and Moisture Flux

Indoor air moisture content is settled ventilation (and influenced by infiltration), thus its control will not be discussed here. The BE has to be resistant against two major types of air/water damages. The distinction will be made between two different "water flows", the *liquid water infiltration* and *the moisture flow***.**

Liquid Water Infiltration

We can distinguish five liquid water driving forces: (Kubal 2008)

- Natural gravity: the water, driven by its own weight, can infiltrate a BE.
- Surface tension: when water clings to the underside of a horizontal surface thanks to the different attraction forces between molecules.
- Wind/air current: water is driven directly into the BE by wind or the wind can create a hydrostatic pressure on the façade.
- Capillary action: typically for porous materials as concrete and masonry in contact with water this will spread in all the material by capillary penetration.
- Hydrostatic pressure: it most commonly affects below grade portions of the BE that are subjected to groundwater. Special care must be given to the termination and transition parts.

The main property in this situation is the *liquid water tightness* of the building.

Moisture

In winter, the warm and moist indoor air is drawn to the drier air outdoor, by the difference in vapor pressure, this is called negative vapor drive. In summer, on the opposite, the moisture from outdoor moist and warm air is drawn indoor to cool and dry areas, the so-called positive vapor drive. (Kubal 2008)

Moisture, which can be conducted through air (airborne water) and vapor (water vapor), is responsible of many construction damages such as frost damages, drop of the insulation power or mold for instance. The transport of air will depend on the air tightness of the used materials. Water vapor is not so different from airborne water, except for water droplet size. There are many materials that resist the transmission of liquid water or airborne water but allow vapor water to move through. Materials that permit vapor to move through are called hygroscopic, the more easily moisture moves through, the more permeable they are. Permeability, measured in perm, is here the key property (Walker and Felice 2008).

3.2.4 Sound Flux

The sound is a wave motion, i.e. a vibration in the pressure of the air or another material, but to be heard it has to go through the air until the eardrum (MacMullan 2007 and Peters et al. 2011). These pressure variations transfer energy from a source of mechanical vibrations through the air (vocal cords for example) which has a certain frequency f (Hz) and a wave length λ (m) linked by the following relation:

$$v = \lambda f \tag{9}$$

In this equation $\boldsymbol{v}$ is the velocity of the sound in the air (340 m/s). The frequency range to which human ear responds is approximately from 20 to 20 000 Hz. There are two types of sound encountered in buildings: *airborne sound* which has to be born (to have its source) in the air and the *impact sound (or structure-borne***)** created on a material different than air: a partition (an impact on a hard surface for example). The pressure in the air can be considered as an intensity I (in W/m²) but is not practical. The unit used to measure sound level and its effects on human ears is the logarithmic scale dB(A) (the A means this unit has been weighted in order to match the frequency-related sensitivity, more sensible around 4000 Hz). 80 dB(A) is considered as a suburban sound level and a 30 dB(A) level is often recommended by standards in a bedroom (MacMullan 2007). Here comes the concept of lowering the sound level, hence some definition to give. The figure 8 gives the sound behaviour against an obstacle, L represents sound level in dB (Peters et al. 2011).

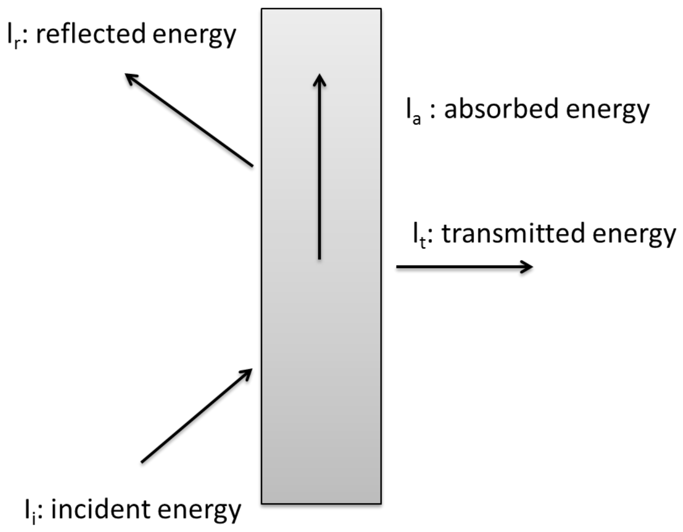


Figure 8. Sound intensity transmission, reflection and absorption at a wall, adapted from Peters et al. (2011).

- *Sound insulation (or sound - noise attenuation - reduction)* is the most general term and simply means the reduction of sound level by whatever means: reflection, interference, Helmotz resonator and also sound absorption. The *sound reduction index (or transmission loss)* describes how a partition will lower sound level, it is defined by the following equation:

$$R = 10 \log(I_i / I_t) = L_i - L_t \tag{10}$$

  Where I_i and I_t represent the sound intensity (in W/m²) and L_i and L_t are the sound levels in dB.
- *Sound absorption (or damping)* is the process whereby sound energy (at first mechanical) is lost into heat as a result of a frictional process between the vibrating molecules: *Ia*
- *Sound isolation*, is the reduction of structure-borne sounds by the use of resilient materials interposed between the vibrating surface and the surface to be protected.

And more specific to our subject, sound level attenuation through building envelope, two types of material have to be distinguished:

- *Sound absorbing materials*, used to lower reflection, commonly porous materials, mostly used inside a room to lower reverberation sounds.
- *Sound insulation materials*, used to lower transmission, commonly heavy materials, used in BEs to reduce the inside sound level (Peters et al. (2011).

There are four key properties of *sound insulation*: (MacMullan 2007)

- *Heaviness*: the high density of heavy weight materials restricts the space for the sound vibration inside the material and the outside face of the insulation material vibrates less (thus transferring less energy sound). This property is governed by the mass law: *the transmission losses increases of 5 dB for each doubling of the mass density* (kg/m²). Another induced law is that *transmission loss increases of 5 dB whenever the frequency is doubled.* That also means that low frequency sounds (and thus large wave length) are more difficult to attenuate.
- *Completeness*: Area of small insulation (poor quality door for e.g.) or small gaps in the construction (opened windows, cracks in concrete) have a great effect on overall insulation.
- *Flexibility*: Stiffness is a physical property and depends upon factors such as the elasticity of the material or the fixing of the partition (nails through some insulator can transmit great amount of sound energy). High stiffness can cause loss of insulation at some frequencies and flexibility between partitions has to be sought. We can also note that the sound velocity in the material depends on its stiffness, the stiffer the material, the faster the sound. The sound insulation will be better if the sound is slow.
- *Discontinuous construction*: it can be effective in reducing sound transmission through a given structure but has to be studied carefully. In this principle the sound energy is firstly lost by reflection, secondly as the sound is converted into different waves motions at the junction

of different materials energy is lost and sound insulation is gained (the idea is to break the wave motion). Nevertheless this kind of structure is easily ruined by rigid links like nails.

Every surface has a critical frequency for which the transmission loss is critically lower due to resonance phenomena. This critical frequency depends on the mass density and from the rigidity of the surface. The more rigid the surface is, the lower the frequency of resonance. It is interesting to note that theoretically the transmission loss resulting of doubling the mass density is exactly 6 dB. However experimental results concluded that the value is closer to 4 or 5 dB due to the resonance phenomenon for some frequencies.

3.2.5 Radon flux

Radon (^{222}Rn) is a decay product of radium (^{226}Ra), both of them part of uranium series (^{238}U). As soils and bedrocks contain uranium in various quantities, radon which is a noble gas can be released from soil pores, migrate to the ground surface and accumulate in buildings. Radon and its short-lived progenies can be deposited into lungs and be responsible of cancers. As stated earlier, the soil of the building is the most important source of radon (in Norwegian dwellings), the function of the BE in this case will be to insulate the building in order to keep the radon concentration under a given threshold (200 Bq/m^3 in Norway for instance). This concentration in indoor air depends on the *permeability of the ground*, the *airtightness* of the foundation structure and the *radon diffusion resistance* of the used materials; these are the key properties (Jelle et al. 2011b and Jelle 2012).

4 Mono-Functional Traditional and State-of-the-Art Technologies

Functions have been identified as well as the inherent key properties of the involved phenomena. Some of these functions are mastered and only require a proper and rigorous design and workmanship. The total mastery of other functions is still in progress and research is done to enhance their completion. Hence we will present the current state-of-the-art technologies in these fields. It is important to start with the mono-functional technologies as their knowledge and their understanding will help us to give innovative visions of the future.

4.1 Structural Design Adequacy

The materials or technologies used to achieve the structural design adequacy depend largely on the type of the building. For a traditional building common ones will be largely enough, however for a skyscraper for example, state-of-the-art materials or technologies could be required. Thus for a regular building: sufficient material's strength is assured by concrete, steel, timber or masonry. These are today's most common building construction materials. The load sharing is assured by typical structural design techniques such as concrete beams and columns, wind bracing systems, steel trusses structures… The choice of the right connection is also one solution: a clamped-clamped beam will have five times lower deflection as a simply supported beam. Another technique using both concrete and steel cables technology is commonly applied in building construction: prestressed concrete by pre-tension. Using steel cables to compress the concrete and giving him more bending resistance and durability, this process is nowadays commonly used in BE construction (for concrete slab for instance). Concerning dynamic loads, especially earthquake consequences, they are traditionally handled by linked concrete foundations, thereby the whole building is moving at the same time, and the internal stresses and strains are reduced.

The state-of-the-art of concrete technology tends to give it even more mechanical resistance or to make it more workable during casting. Nowadays, other concrete's appellation exists such as High Performance Concrete (HPC), a more precise description will be given further in the report as they are fitted with additional characteristics, however, their resistance can exceed 200 Mpa. That kind of concrete is normally not used in buildings, but the higher the compressive strength of the concrete, the greater are the possibilities for skyscrapers or towers (CIMBETON 2005).

4.2 Fire Threats

Pure steel members in steel framed structure can be insulated from damaging fire heat effects through various means of protection such as spray-on materials, intumescent paints, membrane/gypsum boards, or concrete encasement or filling, water filling, all with the purpose of delaying the temperature rise in the steel.

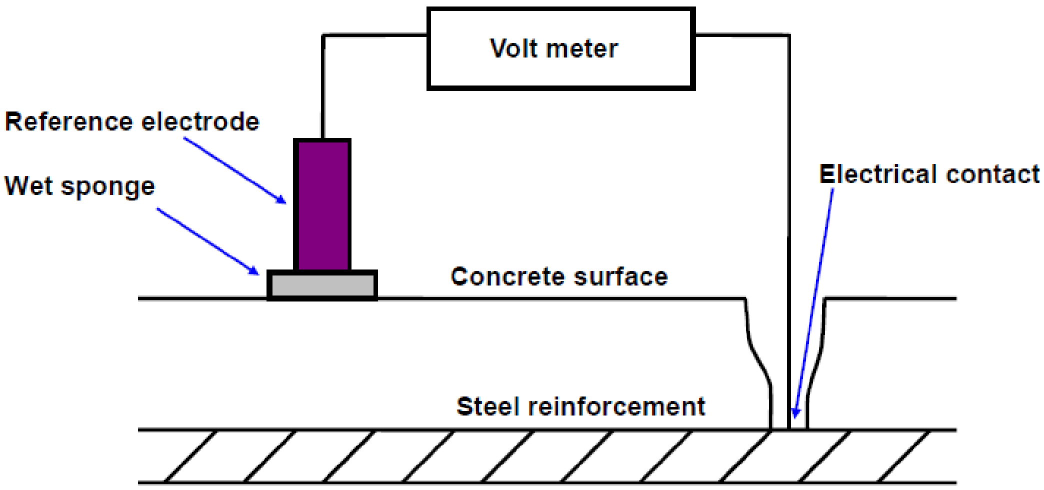
For typical reinforced concrete, the temperature developed within the steel governs the fire resistance rating. Usually, the so-called concrete cover provides enough fire protection. Other properties will influence the concrete's fire resistance such as its density, its compressive strength, the water content (w/c ratio), the higher they are, the better for all of these concrete's characteristics.

Wood structures, which are intrinsically fire-resistant for a given time, can be treated with fire-retardant treatment. The objective is to reduce the rate of flame spread over the surface of the wood. Two applying techniques are used: surface painting and pressure impregnation which is considered more efficient as the wood's fibers are protected more deeply. Moreover, wood structures will have to protect their connections or fixings (usually steel nails and screws) by shielding them within the wood itself or with additional typical fire protection. Special attention will be given to the adhesive used in laminated wood sections regarding its behaviour to fire (more details are available in Purkiss 2007 and Buchanan 2001).

4.3 Corrosion Damages

First we will shortly remind the main aggressive factors creating corrosion; the exposition to O_2 and H_2O dissolved into water, the chlorite Cl^- concentration causing pitting corrosion, the CO_2 concentration (carbonation) lowering the pH and creating global corrosion. The electrical current E in Volt is the intrinsic consequence of the phenomenon. As preventing reinforcement in concrete or steel to be in contact with environmental threating agent is difficult, corrosion will in practice never be totally avoided; therefore most of the solutions consist in slowing down the process, or replacing polluted zones.

As far as concrete is concerned the traditional answer to this threat is an acceptable concrete cover thickness, the less permeable it is, the better. This concrete layer prevents the penetration of aggressive content until the reinforcement bars still passivated. To replace polluted concrete zones (i.e. the ones carbonated, with a high pH, or with high chlorite content) with sound one is a solution once the concrete is depassivated, there are different techniques to locate them thanks to for example volt meters.



Figures 9. How to locate the corroded parts (Myrdal 2011).

To be more specific about steel, it exists several techniques to avoid corrosion of reinforcement bars: epoxy-coatings, galvanized, glass-fiber-reinforced-polymer coatings, solid stainless-steel or stainless-steel-clad reinforcing bars (see more details about the specific techniques in Basham, 1999) all of them use chemical processes to slow down the corrosion rate although they have different uses and characteristics (especially their prices and how much longer they resists to corrosion compared to black steel). One more radical solution consists in connecting the steel structure to a continuous electrical current E opposed to the one of the corrosion reaction to inverse the electro-chemical reaction, the steel is thus protected from rust.

4.4 Solar Radiation Damages

The life time and durability of organic materials used in BEs can be enhanced by the use of photostabilizers in the case of polymers and protective surface coatings for wooden elements. Photostabilizers are specific for a given solar radiation range and several types can be found as for example effective light absorber or inorganic opacifers. The objective is to prevent the harmful solar radiation wave length to reach the polymer (A.L Andrady et al. 1998). Windows also provide some solar protection for materials and skin by having different transmittance ranges, stopping harmful wave lengths. Two factors will quantify the solar radiation protection: the Solar Material Protection Factor (SMPF) and the Solar Skin Protection Factor (SSPF). Their values are different depending on the type of window, however, the more a window blocks solar energy the better its SMPF and SSPF factors. The windows absorbing or reflecting solar energy are for example solar cell glazing, glazing with low-e coatings or with layers of gas. More detailed can be found in Jelle et al. (2007)

4.5 Frost and Thaw Deterioration

As the pore structure is one key property, air entraining admixtures are added in the concrete to reach the right pore structure and be frost resistant. The permeability of the concrete, second key property, is lowered by the use of a low w/c ratio and also by good curing conditions, see Jacobsen et al. (2011). One last solution is to protect directly the concrete from environmental threats responsible of frost damages such as moisture, de-icing salts or water splashes.. Original and sustainable techniques are studied to enhance the frost/thaw resistance by adding rubber crumbs in the concrete paste by recycling used tires. A 0.5 % rubber crumb addition shows good results in terms of frost resistance and the inherent loss of mechanical characteristics can be balanced by a raise in the cement content. (A. Richardson et al. 2011). However, frost deterioration is a deeper concern in bridge or road durability

4.6 Thermal Dilatation Protection

The solution to this phenomenon is simply to permit slight deformations in the building; this is achieved thanks to expansion joint in concrete slab or for metallic beams.

4.7 Heat Flux Control

4.7.1 Traditional Technologies of Heat Flux Control

Traditional Insulation Materials

The traditional insulation materials are typically based on the following levers: Reduce the conduction heat loss by using low thermal conductivity (λ) materials and an adapted thickness (d), thus reaching the lower U-value possible. We can briefly state the principle insulation materials, which values are issued from Jelle (2011):

- *Mineral wool* (also includes glass wool and rock wool), λ = 30-40 mW/(mK). It is a highly flexible material as it can be used as mats, boards or even be injected. Moreover, it can be cut and adjusted.
- *Expanded polystyrene (EPS) and extruded polystyrene (XPS),* λ = 30-40 mW/(mK), the emphasis has also to be put on their high flexibility of this material although some moisture complication must be quoted. It is nowadays the most used insulation material.
- *Cellulose and cork,* λ = 40-50 mW/(mK), is mainly used as filler, but can be found as boards. This material also offers ecological characteristics.
- *Polyurethane (PU),* λ = 20-30 mW/(mK), has a considerably lower thermal conductivity and high flexibility, but the toxic gasses emitted during a fire are PU’s major drawback.

Traditional Insulation Techniques in Fenestration Technology

Even though *multilayer glazing* are implemented in BEs in order to creat natural lighting, the research tends to limit the heat flux by increasing their U-value, the natural lighting depending on T_{vis} is secondary. Those fenestrations will use low thermal conductivity gasses with an adapted thickness. Low emissivity coatings are also nowadays quite common to reduce radiation heat transfer. The following fenestration technologies are studied in Jelle et al (2012b). The U-value of a multilayer glazing will depend on the type of gas used as insulation (Argon or Krypton usually) and the width of the gas layers (which is usually around 12 mm, a too large gap would raise convection issues). An average value of 0.50 W/(m^2K) is fair. It is also important to note that the greater the insulation of one multilayer glazing, the lower the solar heat gain.

Low Emissivity Coating

Low emissivity (LE) coatings, by reducing the emissivity ε, are reducing the heat radiation and thus the total heat transfer. Note that different metal coatings can have different characteristics in terms of emissivity and optical characteristics (ε, T, A and R factors will be different regarding the material: gold, tin oxide…) and that the layer's thickness is limited in order to prevent the daylight sunbeams obstruction. The LE coating can be added during the glass production (hard coating, more durable), or on an existing glass (soft coating, less durable and has a higher infrared reflection) hence usable for retrofit purposes. (Jelle et al. 2012b)

4.7.2 State-of-the-Art Technologies of Heat Flux Control

Suspended Film Window

In this fenestration, the middle fenestration of a multilayer glazing window is replaced by a suspended film. Thus the weight and the thickness of the window are lowered and the best U-value for a commercial window is provided, around 0.28 W/(m^2K)(Jelle et al 2012b).

Vacuum Insulation Panel (VIP)

As reviewed in (Baetens et al. 2010c), VIPs are usually composed of an open porous core of fumed silica enveloped in several airtight and water vapor tight metallized polymer laminate layers. Vacuum has theoretically the best thermal conductivity coefficient λ close to zero. However, the surrounding foil can currently not assure its waterproof function for a long time, hence losing its insulation properties after a few years. Their thermal conductivity λ ranged from 3 to 4 mW/(mK) at fresh conditions, and due to water vapor and air diffusion through the VIP into the core, typically 8 mW/(mK) after 25 years (Baetens et al. 2010c). The type of metallic envelope can change the velocity of the thermal conductivity rise, but this last is immutable and represents one of the major drawbacks of this solution. Another major drawback is the lack of flexibility of these panels: no nails or cutting for adjustment are possible. Finally their high price is also a disadvantage.

Nevertheless, the large drop in terms of insulation thickness by a factor of 5 up to 10 times lower (Baetens et al. 2010c), compared to actual insulation solution can make the insulation panels economically profitable. Indeed, by reducing dramatically the building envelope size, in a high living area market, large money savings can be made. Moreover, some money savings are also made through transportation. Thus VIP has a large potential for tomorrow and deserves to be studied thoroughly.

There are four different principle applications of VIPs: the first one is the use of panels to retrofit existing buildings. The second application is the use of vacuum in sandwich elements (VIS) in door, curtain wall, non-load bearing wall but also in window. This technology is studied by Jelle et al. (2012b), an array of support pillars separates two layer of glass, vacuum is created in-between (see figure 10). Low-e coated glass can be added in order to compete multilayer glazing U-value. The main advantage of those windows compared to usual multilayer windows is a sharp decrease in the window's thickness (around two times) which can be crucial when replacing existing windows. The third application consists in adding panels on flat roofs, terraces,… where a thin layer is needed. The last solution uses VIPs as main insulation material for new buildings. More details about these applications are available in Baetens et al. (2010c).

The VIP commercial products are globally ranked as "not flammable", their characteristics are fairly good, but not outstanding. About their sound insulation qualities, VIPs have very low characteristics, and this function will have to be assured by other components or layers. Baetens et al. (2010c)

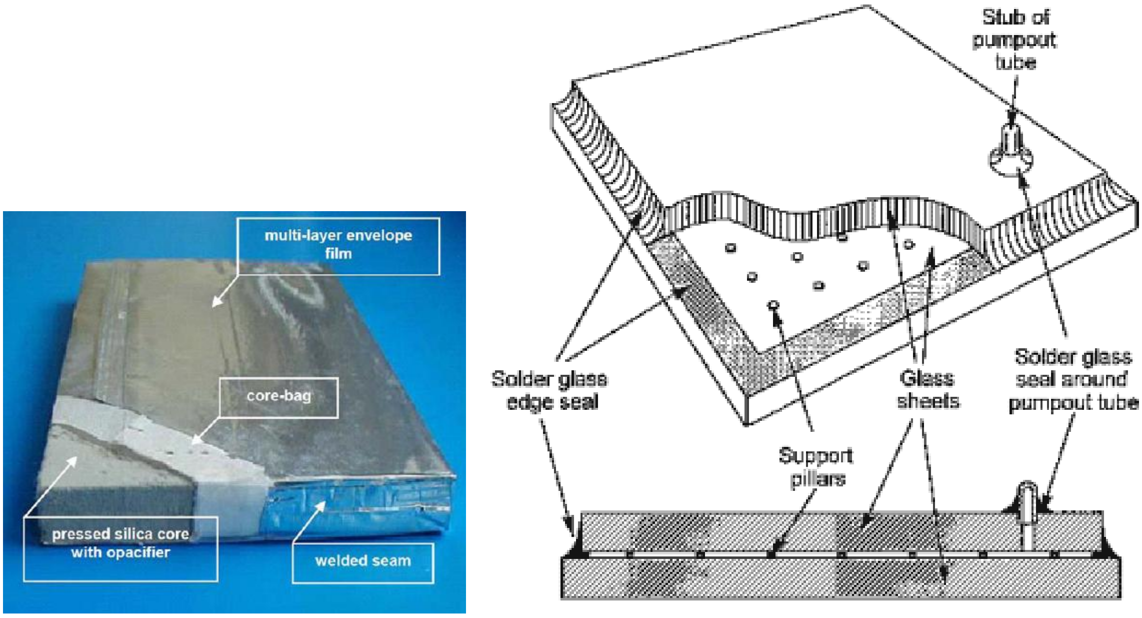


Figure 10. On the left a typical VIP structure (Simmler et al. 2005), on the right a schematic diagram of a vacuum glazing (NSG 2010).

Gas Filled Panels (GFP)

Gas Filled Panels work on the same principle as VIPs, also instead of vacuum, a rare gas as argon, krypton or xenon is added in the metallized envelope. Although vacuum has a lower thermal conductivity than these gasses, GFPs don not need to assure the inner vacuum and are thus more flexible. Despite a low thermal conductivity potential, the lowest values reached nowadays are about 40 mW/m K. Nails, perforations and other cuttings are also prohibited. Note that experts tend to agree that GFPs potential in building insulation is doubtful and that VIPs seem to be a better option (Jelle 2011).

4.8 Solar Flux Control

4.8.1 Traditional Technologies of Solar Flux Control

Transparent Windows with Shutters

Solar flux is controlled for a long time thanks to very basic installations. To have enough illuminance in one building, a sufficient area of glazing is implemented in the BE regarding a fitted answer to the sun exposure conditions (orientation, shading…) as well as the transmittance T_{vis} of the used glass. Mechanical or manual shutters are installed to lower the illuminance when desired and also prevent glare; these can also help to control the heat flow. The external shading devices are the most efficient in reducing the cooling load.

Solar Heat Storage

This technology consists in collecting solar heat radiation to use it either to warm domestic water (Solar Water Heating SWH) or indoor ventilated air (Solar Air Heating SAH). The first one usually transfers solar heat gains to a calorific fluid by convection and, in correlation with another usual heat source, warms the content of a domestic water tank. Assuming good sun exposition factors, an efficiency of 40-45 % can be reached by SWH systems (Pavloski et al. 2010).

4.8.2 State-of-the-Art Technologies of Solar Flux Control

Antireflective Glass

The antireflection (AR) property is the consequence of the creation of a double interface by means of a thin film generating two reflected solar waves and if these waves are out of phase they can partially or totally cancel. This coating reduces the reflectance R on the profit of the transmittances T_{vis} and T_{sol} respectively increased by 7 % and 4 % for a regular float glass (Hammarberg and Roos 2003). Moreover, the reflection which can harm visibility through the window is also lowered, thus the use of this technology in aesthetic purposes for shops façades or museum for instance (Cannavale et al. 2010). The current technologies to obtain antireflectiveness are sputtering and dipping (which is a sol-gel process), furthermore this technology does not change the window U-value and has no effect on the emissivity of a low-e coating when affixed on it (Johson and Roos 2010). Note also that the sol-gel process enables to come over the main drawback of these coatings, that is to say their lack of durability and their costs. In addition a reflectance R of 1 % can be obtained thanks to the sol-gel process (Cannavale et al. 2010).

Daylight Directing Glass Lamellas

This system is based on dynamic lamellas made of solar control glass with high reflectance coating which reduces the solar gains when desired and also can redirect some of the daylight further in the room lowering thus artificial lighting energy demand. As a matter of fact, lower daylight factors have been measured near to the window where there is risk of glare. Furthermore, equal or even higher daylight factors have been monitored at the back of the rooms when compared to a regular shading system with less transparent or opaque shutters (Lausten et al. 2008). Eventually the cooling as well as the lighting energy demand is lowered thanks to this system. The principle is explained on figure 11.

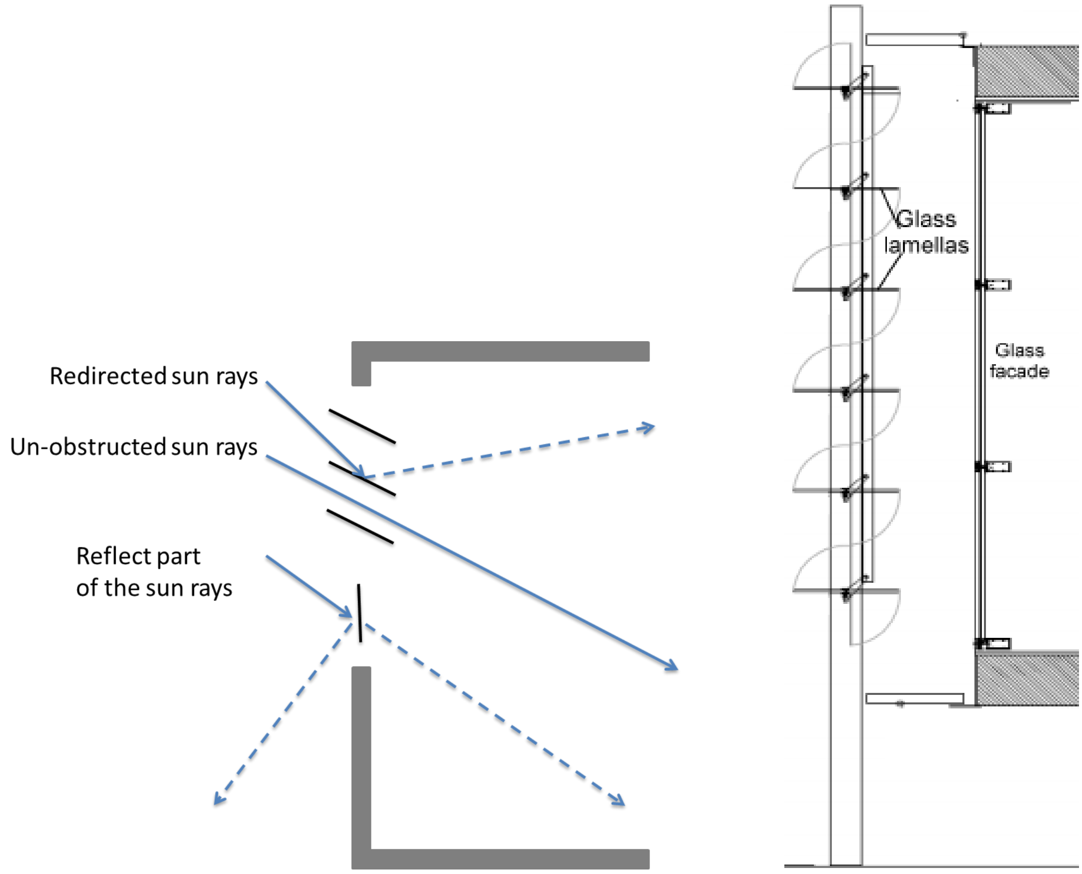


Figure 11. On the left, the daylight directing glass lamellas principle, adapted from Lausten et al. (2008) - On the right, a vertical cross section of the shading system (Lausten et al. 2008).

Photovoltaic Technology

Several technologies can be stated about recent development in PV modules (and a review can be found by Jelle et al. 2012a): The typical silicon based PV cells are separated into three categories: the monocrystalline cells with an efficiency of 16-24 %(Ebong et al. 2010, Green World Investor 2011, Solar Plaza 2008 and Yang et al. 2011), the polycrystalline cells reach 14-18 % efficiency (Green World Investor 2011 and Wawer et al. 2011). The last silicon based product is the amorphous solar cell also called thin-film cell because of its low thickness (and high flexibility) only reaches 4-10 % efficiency (Andresen 2004, Green World Investor 2011, Murphy 2011 and The German Energy Society 2008). Note that thin-film cells do not lose efficiency when their internal temperature rises although other products do. Other non-silicon products exist and are also thin-film. They can be divided into two products: CdTe, although its low production price, it has an efficiency of 9.4-13.8 % (Buecheler 2011, Khrypunov et al. 2011 and The German Energy Society 2008). And finally the CiGS product, which is currently the most efficient thin-film product, reaches 11-18.7 % efficiency (Buecheler 2011, Green World Investor 2011, Ishizuka et al. 2010, Repins et al. 2009 and The German Energy Society 2008). More details about the state-of-the-art of PV modules are found in Jelle et al. (2012a). The recent and rapid expansion in installed photovoltaic panels is linked to the increase of grid-connected photovoltaic systems, they also tend to be integrated in the BE. At the leading edge of this technology are the thin-film photovoltaic technologies (Agrawal et al. 2011). Note that the efficiency of solar cells can be enhanced thanks to AR coatings (Cannavale et al. 2010). Building Integrated Photovoltaic (BIPV) will be studied in another part.

Photovoltaic Hydrogen Production

Photovoltaic hydrogen production prototypes (PHPP) have been developed even if hydrogen is currently not a cost competitive energy type compared to fossil energies as oil or natural gasses. However, the global system produces hydrogen only with solar cells and distilled water, consuming CO_2 in the meanwhile, and is thus a sustainable solution to be considered if hydrogen utilization becomes widespread and is developed. (Roper et al. 2008)

4.9 Water and Moisture Flux Control

Principle

There are three types of protection against liquid water infiltration: Barrier, Drainage and Diversion (Kubal 2008). We will review all protections against each driving force previously detailed:

- *Natural Gravity*: the water must simply be drained away as fast as possible from all the "flat areas" including roofs, balconies… the easiest solution is sloping those area, a ¼ inch/feet slope (approximately 2 %) is here recommended. Then one has also to apply a water repellent product on the exposed surface.
- *Surface Tension*: Drip edges and flashings break the surface tension and divert and prevent the water to infiltrate the BE, see details in figure 12.
- *Wind/Air Currents:* Once again, flashing is commonly used to prevent this phenomenon, the principle is explained on figure 12
- *Capillary Action:* As materials that have large void are not susceptible to capillary action, they are used to protect the BE from the water containing zones, as shown on figure 13
- *Hydrostatic Pressure:* Underground water level may change during rain episodes; a drainage system has thus to be installed. To deal with underground water issues, one typical solution consists in putting an appropriate waterproof membrane between the construction mud slab and the definitive floor slab. A weak point remains in the construction; the joint between the floor and the walls: a Water Stop system is then installed, see further details on figure 13. (Walker and Felice, 2008)

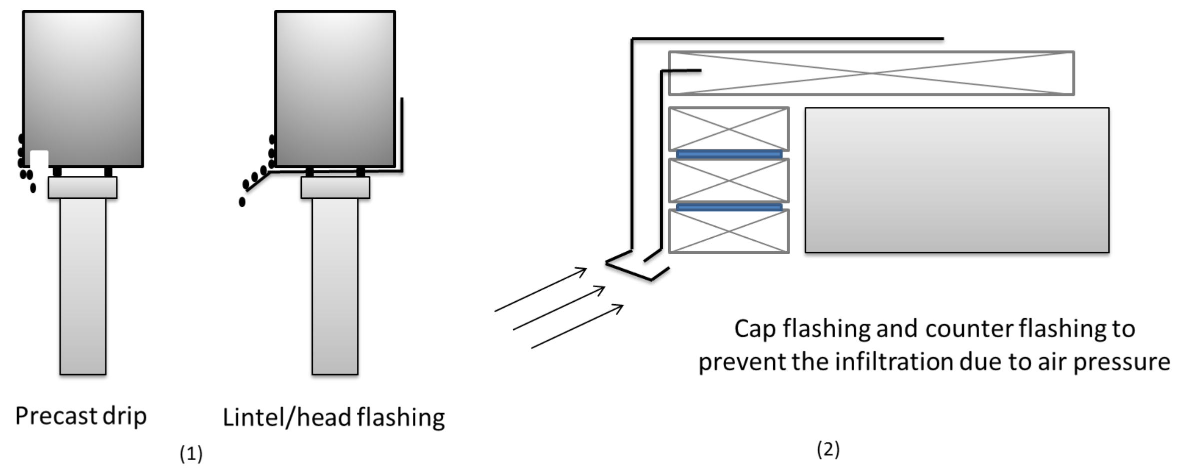


Figure 12. (1): Typical use of “drip edge” and flashing to prevent infiltration by surface tension - (2): Flashing to prevent water under pressure from entering the BE by wind/air current, adapted from M.T. Kubal (2008).

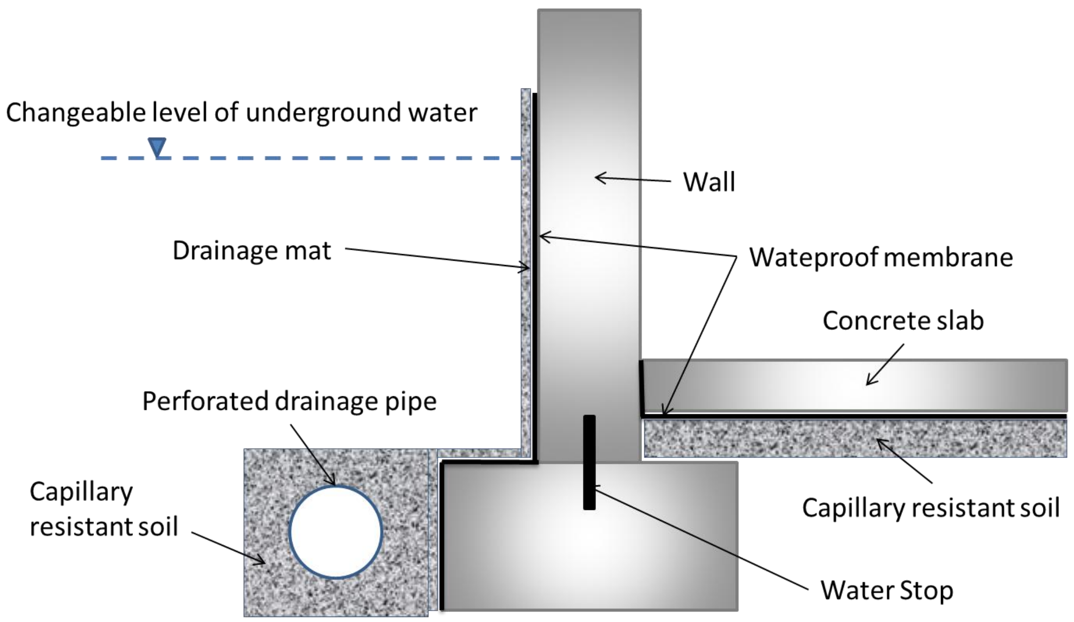


Figure 13. Use of both drainage and water barrier techniques to prevent water infiltration from capillary actions and hydrostatic pressure, adapted from Kubal (2008).

More details about the main materials and technologies used in water and moisture control in Kubal (2008)

Two Stages Water and Moisture Tightening

The principle of this façade is to separate the rain screen and the wind screen by a ventilation gap. Indeed the ventilation gap will have several benefits: it provides drainage of both moisture passing through the rain screen and the negative moisture coming from the indoor. Moreover, it will contribute to drop the pressure difference between the ventilation gap and the indoor reducing largely the risk of moisture transfer from the outdoor to the indoor. (Bøhlerengen et al. 2008)

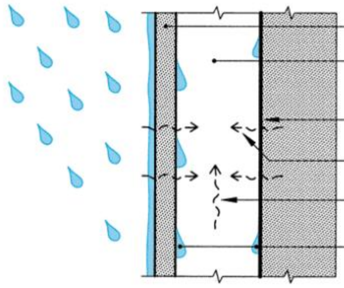


Figure 14. Detailed explanation of two-stage tightening (SINTEF Building Research Design Guides 542.003 (no dates) in Bøhlerengen et al. 2008).

Moisture Control

Vapor barriers are used to prevent upward capillary migration of vapor through soil for penetrating concrete pores in below-grade structure. It is also used in above-grade construction to prevent moisture vapor transmission by allowing this last to condense into water. Vapor barriers are usually available in polyethylene sheets or aluminum foils sheets on laminated reinforced paper. The vapor barrier's performance will depend on the permeability of the material. Windows are typical examples of a perfect vapor barrier (Kubal 2008).

State-of-the-art of Moisture Control

Moisture adaptive vapor barrier differs from earlier type in two ways; its vapor diffusion resistance is almost as high as traditional vapor barrier, but is still able to function under moist conditions. Moreover, it has different diffusion resistances regarding the direction on the diffusion. This specific characteristic has been achieved by laminating materials with different properties and geometry (Kloch, 2008). This type of vapor barrier allows positive moisture flow in summer and prevents negative moisture flow in winter where it is desired.

4.10 Sound Flux Control

Traditionally a simple 15-20 cm thick concrete/brickwork wall is enough to lower the sound to an acceptable level, defined in standards. Indeed those materials, through their porous structure absorb sound energy, and through their high density are also good insulation materials. It is interesting to note here that an 8 cm thick reinforced concrete wall would be structurally enough to most BE envelope (rather small building of course). The rest of the thickness is used to ensure an efficient cover and for thermal insulation reasons, but mostly to provide a good sound insulation. But what are the solutions to increase the transmission losses? Increasing the thickness of the envelope is not a relevant solution as double thickness only increases these losses about 5 dB (and also consumes living space). One will propose to separate two leaves by an air space and thus offering twice as more transmission losses (each leaf with 20 dB would offer 40 dB of attenuation). However multiple other phenomena will occur and reduce the efficiency of a *multiple leaf system*:

- A structural connection between the two leaves allows structure-borne sound to be transmitted.
- The reflection of the sound on the internal surfaces will create a build-up of reverberant sound inside the cavity, increasing the global sound transmission
- An acoustic coupling between the two leaves will occur through the intermediate space, with its own critical frequency: resonance phenomenon is increased.

To solve those problems, several levers are used (see figure 15):

- Isolation of the two leaves from the building structure using resilient materials, thus preventing the building from structure-borne sound.
- Addition of some absorbing material into the cavity to reduce reflection (a porous material as plasterboards or mineral wool).
- The "discontinuous construction" effect previously explained, using also leaves with different thicknesses: creating multiple zones of reflection to dismiss sound energy and breaking the wave lengths. We can also note that the wider the intermediate gap is, the better the insulation.
- The density of the leaves (heavy material as concrete, brickwork, glass…)

This type of technology is the typical example of a double layer glazing window and can also be used to enhance sound insulation of walls, roofs and floors (Peters et al. 2011).

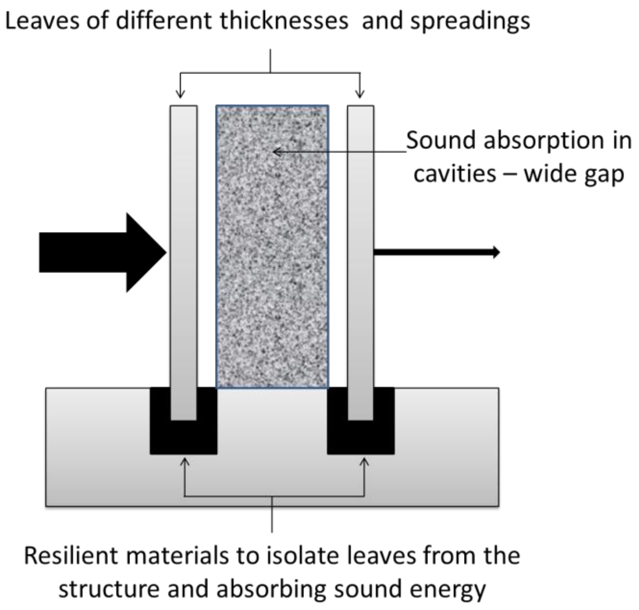


Figure 15. Features of a multiple leaf partition to achieve good sound insulation, adapted from Peters et al. (2011).

4.11 Radon flux Control

According to Jelle et al. (2011b) two types of radon control technologies exist: prevention (when designing a new building) and mitigation (for existing polluted building or refurbishment). These are based on three different principles:

- Sealing of surfaces of the BE from the soil or the application of radon barriers or membranes with sufficient high radon diffusion resistance and airtightness under the ground floor of the building.
- Active (fan powered) or passive (no fan) soil depressurization which gives a combined effect of ventilation of the building ground and balancing the pressure difference between the indoor air and the surrounding soil.
- Ventilation (balanced) of both occupied rooms (indoor air) and unoccupied spaces such as vented crawl spaces. (not part of the BE's characteristics)

The emphasis can be put on the airtightness of the radon resistant membrane and the attention into construction details as grid connections. Indeed, analyses of different measures show that active sub-slab depressurization systems usually are the most effective preventive measure as a stand-alone solution, assuming an airtight construction. (WHO, 2009)

5 Multi-Functional Traditional and State-of-the-Art Technologies

Here are given the traditional and the state-of-the-art technologies of multi-functional BE. Some of those techniques can be considered as traditional as they are well known and applied since a long time; however they are still studied and tend to be enhanced.

5.1 Addition of Heat or Solar Flux Control

5.1.1 Building Integrated Photovoltaic

A PV module can either be attached on a BE's part (thus named Building Attached Photovoltaic BAPV) or be integrated to an existing building part and will then be called Building Integrated Photovoltaic (BIPV) and are reviewed in Jelle et al. (2012a). This appellation also implies some complementary functions as weather tightness and durability for example. As an elevated temperature of the cells, especially mono- and polycrystalline modules reduce the efficiency it is important to create an air gap below those modules (except for thin-film cells). The four main options for BIPV integration are on sloped roof, flat roofs, façades and shading systems. There is a wide range of different BIPV products and the categories to consider are foils, tiles, modules and solar glazing products:

- *The BIPV foil* products are lightweight and flexible, thus easy to install on flat and sloped surfaces. As thin-film product, they do not need a dedicated ventilation system. However, among the current commercial solutions, only a few of them are weather tight and their efficiency is quite low compared to other products.
- *The BIPV tiles* can cover all or part of the roof and will have a tile shape, it can also easily be used to replace existing roof in retrofit projects. Efficiency of 20 % (SolarCentury 2011b) can be reached with commercial product, note that the more the tiles are curved, the lower their efficiency. (a curved tiles can have aesthetic advantages)
- *The BIPV modules* products are comparable with PV modules however they are weather tight, thus some of the products can replace existing roofing, or have their dedicated roofing system to create a water tight solution. 20 % efficient commercial products can be found (SolarCentury 2011a). According to Montoro et al. (2011) these weather tight products are also used as cladding solution. An appropriated ventilation system will evacuate the heat under the modules in order to maintain their efficiency.
- *Solar cells glazing* are weather tight and can be used on windows, glassed or pitched façades and roofs, available in different color and transparencies they offer large architectural possibilities. ''*The technology involves spraying a coating of silicon nanoparticles on to the window, which work as solar cells*'' (Jelle et al. 2012b). A balance has to be found for T_{vis} value: indeed a high value will enhance daylighting but also reduce the solar radiation energy collected. The lever to reach the desired T_{vis} value is simply the distance between the cells, usually varying from 3 to 50 mm. Note that the U-values of those products are similar to these from multilayer windows, that is to say, around 0.50-0.60 W/(m² K), which can be considered high.

Figure 16. On the left: example of BIPV tiles (Solar Power Restoration Systems Inc, not dated) – On the right : ceiling glas allowing daylight fitted with PV modules (Global Energy Network Institute 2009).

In their paper, Montoro et al. (2011) propose another classification for BIPV products including BAPV products, the table x gives each system's advantages and drawbacks (In this table the names of the products have been changed to fit with the one given is by Jelle et al., 2012).

Table 1: Advantages and disadvantages of PV products adapted from Montoro et al. (2011) (In this table the names of the products have been changed to fit with the one given is by Jelle et al., 2012).

Product	Specific Advantages	Specific Disadvantages	Application
BAPV modules	- Suitable for old and new roofs - Well established application - Easy to handle - Very competitive - High efficiency/performance	- Limited aesthetic value due to the level of visibility - Scope of application limited to certain roof types - The multi-functional aspects of PV are not fully exploited	- Pitched roof
BIPV foils	- Very light (suitable for a weak roof) - Easy handling and installation - No roof penetration - Curved installation possible	- It doesn't replace other functions of building components functions; BIPV status at stake - Very low efficiency which results in larger system areas	- Flat and curved roofs
BIPV tiles	- Aesthetic solution, mainly for residential pitched roofs - High-efficiency products - Very light products which eases the installation - Good retrofitting solution	- Small units size lead to longer installation time - Unfavorable cost-performance ratio - High risk of breakage	- Pitched roof
BIPV modules for roof and walls	- Well suited if the PV is to be recognized - Different colors and visual effects can be included - High efficiency systems	- Lower system performance (due to design restriction) - The lower parts of façades are normally not used due to possible shadows - Installation costs can be very high	- External walls - Curtain walls - Roofs
Solar cell glazing	- Most unobtrusive and possibly most aesthetic BIPV solution - Ideal suited for prestigious buildings with well-visible façades and skylights - Marginal daylight elimination / capacity to diversify light intake - Cell shapes can be attractive	- The units can be very heavy - The price are normally high since they are tailor-made products - As they can be seamlessly integrated, the public may not notice the presence of PV modules - Difficulty in hiding the cables - Limited sizes and shapes of cells - Silver tabbing crosses the transparent spaces between cells	- Translucent façades - Skylights - Shading systems

5.1.2 Phase Change Material for Building Applications

Phase Changing Materials (PCMs) change phase from solid state to liquid when heated (when their temperature rises), thus absorbing the *latent heat*, the application of those products into buildings is reviewed in Baetens et al. (2010a). When the ambient temperature drops, the liquid PCMs will return into their solid state while giving off the heat absorbed earlier. Thus the melt temperature of the PCM is the most important factors to consider, the temperature conditions of the envelope have to be studied carefully to choose the best PCM in order to give full efficiency to this process. However the latent capacity per unit area of wall, how the PCM is incorporated in the support material, the orientation of the support material and its location are other complementary factors to consider according to Baetens et al. (2010a). PCMs participate to the thermal regulation of the building: absorbing heat when the building is overheated (and preventing cooling system's energy to be spent) and releasing it at night for example when outdoor temperature drops: all in all the thermal mass of the building is raised. Thermal comfort is increased and if the PCM principle is correctly used, energy savings are made.

There are four different PCM incorporation methods (Zhang et al. 2007), the direct incorporation, the most simple and economic where PCM are added to the construction materials (to the cement for concrete, for instance). The immersion, where the porous material is dipped into melted PCM and the encapsulation. The more the material is porous, the more PCM can be added, some composite material can encapsulate until 60 % PCM (Athienitis 1997). PCM is encapsulated either into tubes, panels, etc… (macro-encapsulation) or the PCM particles are enveloped into a polymer film (micro-encapsulation). PCM can finally be laminated into boards. Current state-of-the-art research is preceded on gypsum wallboards, concrete and insulation materials enhanced with PCM giving these products their multi-functional character.

PCM enhanced wallboards: wallboards which are commonly used in building applications for its sound and heat insulation characteristics but also for its fire safety function, have a porous nature which makes it suitable for the application of PCM. Wallboard enhanced with PCM will provide thermal storage distributed through all the building where a simple wallboard would offer a very low thermal mass. The most important factors will be the choice of the PCM and the manufacturing process. Lamination on the boards and direct incorporation during the wallboard manufacturing seem to be the two most reliable solutions. Several studies have been conducted and conclusions have been drawn by Baetens et al. (2010a):

- An indoor temperature fluctuation average drop of 2 °C can be reached only thanks to enhanced wallboards, hence heating energy savings are made. Furthermore, an economical study has been achieved concluding on the profitable aspect of this solution.
- However climatic conditions such as solar radiation intensity on the enhanced wallboards significantly affect the performance of storage and thus the global efficiency.
- Eventually a great potential in retrofitting has been concluded.

PCM enhanced concrete or the so-called *thermocrete* is another use of PCM. This special type of concrete is a heat storage medium combining an appropriate PCM with a concrete matrix with structural properties. PCM can either be introduced into the pores of concrete's aggregates during curing, or one can use absorption qualities of concrete to achieve diffusion of the desired amount of PCM into it. Their use, in order to reduce the frost/thaw damages on American roads, has been studied and offers good results: about 20 % damage reduction (Bentz and Turpin 2009). However, the use of PCM in concrete in order to increase the thermal mass of the building can be questioned: why should one increase the already high thermal mass of the concrete if the one of other material can be enhanced, such as wallboards? Despite the indisputable increase in the thermal mass, the economical profitability of PCM in concrete, regarding the current high price of those materials, has to be questioned (Baetens et al. 2010a).

PCM enhanced insulation materials have been tested on PU-foam where a reduction of 40 % in the wall generated peak-hour cooling load has been measured compared to a traditional construction. This same system on attic insulation reduced the summer air temperature on the attic from 43 to 32 °C. Other experiments have been made and tend to show good results for PCM insulation materials (Baetens et al. 2010a).

PCM enhanced Structural Insulation Panel (SIP): SIPs are simply lightweight assemblies consisting in two outer skins assuring the structural function (typically Oriented Strand Board OSB) and an inner core of insulation material, forming a monolithic unit. This technology can be enhanced using encapsulated PCM (presents into pipes), thus creating Phase Change Materials Structural Insulation Panels (PCMSIP), see more details on figure 17. Experiments have shown a significant reduce in the peak heat flux about 62 % with a 20 % PCM concentration. Although for the same concentration a drop in the total daily heat transfer of 38 % has been monitored. Thus, PCMSIP walls seem more appropriate for geographic areas where there is typically a large temperature swing. (Medina et al. 2008)

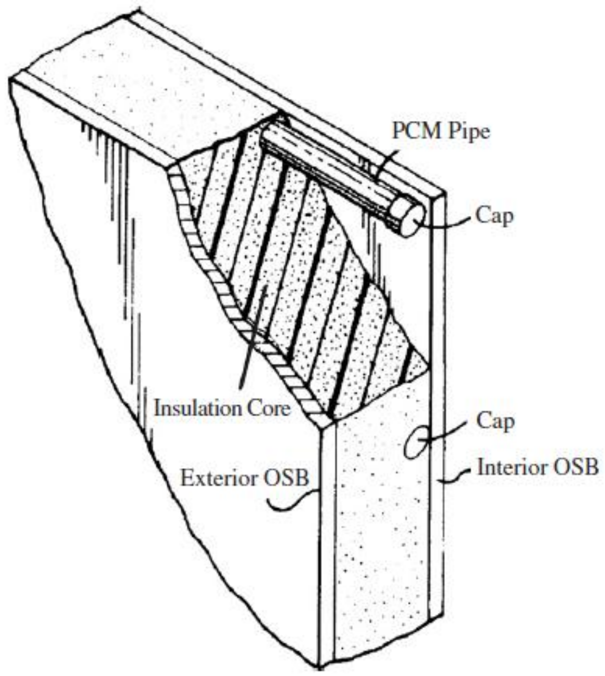


Figure 17. Cross section of a PCMSIP (Medina et al. 2008).

Double glazing windows combined with PCM are studied in Weinlader et al. (2005). The thermal performances are the following: a heat loss drop of 30 % but also a solar heat gains drop of 50% when compared to the same double glazing window without PCM. However the light transmittance (T_{vis}) reached is about 0.4 although a regular double glazing window reaches 0.7, which explains the solar heat gain drop, but will create artificial lighting needs.

PCM enhanced shutters have been numerically modelled (Alawadhi 2012). It has been calculated that solar heat gains are reduced up to 23 %. However, no litterature has been found about experimental results on PCM enhanced shutters.

Despites the numerous advantages of the PCM products some studies suggest that the enhancement with PCM can harm the fire safety characteristics of the product (Banu et al. 1998 in Zhang et al. 2007). No results or studies about the acoustical behaviour of PCM enhanced material have been found.

5.1.3 Multi-Functional Roofing Systems

Very basically, roofs had only structural and weather protection functions. Quickly they have been fitted with heat flux control function as they represent a critical part of the BE responsible of as much as 60 % of heat loss (Sadineni et al. 2011). But those solutions were responsible of overheating phenomenon in summer and had also to limit solar heat gains, thus their multi-functional character. The most common techniques consist in layer of insulation on a structural frame, in addition some antisolar coating to limit heat gains. We can distinguish several techniques or principles most of them reviewed in Sadineni et al. (2011).

Lightweight Roof

Lightweight aluminum standing seam roofing systems (LASRS) are popular on large roofs as commercial buildings, even if sensitive to wind. The heat flux is controlled thanks to regular insulation material as PUR or polystyrene. The solar gains are reduced simply by using light colored roof paintings, indeed, a white painting reduces the cooling load by 9.3 % compared to the same black painted roof (Han et al. 2009).

Ventilated and Micro-Ventilated Roof

The same principle of heat ventilation as in DSF can be used on roofing systems. Two slabs are separated by an air gap; the ventilation can be natural (stack effect) or mechanical (fan-powered).

Cooling energy saving up to 30 % has been measured in Italy and the ventilation can be closed in winter managing enough damping to avoid condensation risks (Ciampi et al. 2005).

Evaporative Roof

As reviewed by Sadineni et al (2011), this technology uses the latent heat of evaporation from water to absorb solar heat gains into the water in summer times preventing this heat to penetrate the building. Some systems using pounds and wetted burlap bag cover can be distinguished from evapo-reflective methods. The former one sees all the evaporated water vanished in the surroundings and is thus not suitable for arid climate in spite of a high efficiency; indeed a drop of 20 °C of the indoor temperature has been measured (Sanjay and Prabha 2008). However, the second system, even if less efficient in heat loss during summer times, will keep the water, which lays in a high thermal capacity bed rock, enclosed between the slab and a radiant barrier as an aluminum sheet, see figure 18. This system can lead to an 8 °C maximal temperature drop in the building (Ben Cheikh and Bouchair 2004).

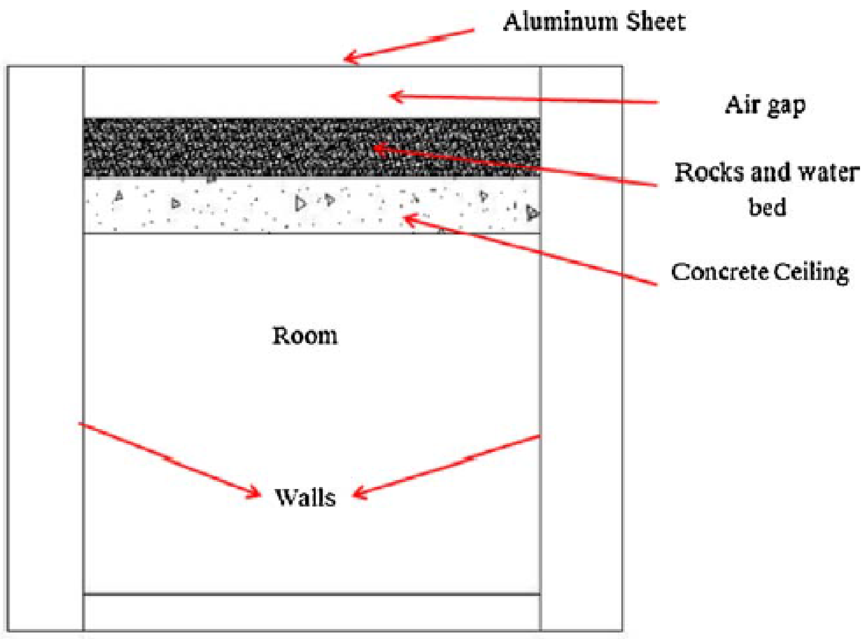


Figure 18. Evapo-reflective roof cooling system (Ben Cheikh and Bouchair 2004).

Radiant Barriers

Radian barriers are a type of antisolar coating and installed especially under the roof, to reduce the heat gain in summer and thus the cooling energy load. Even though it is not their principle function, these barriers also limit the heat losses in winter. Usually, radiant barriers are thin highly reflective sheets; aluminum is commonly applied on one or both sides of these sheets. They are implemented below the tiles or the slab of the BE and two types of installations exist. The first one follows the roof inclination (Truss Radiant Barrier - TRB) while the second one lays horizontally on the ceiling or the slab (Horizontal Radiant Barrier - HRB)(Michel et al. 2008). Although HRB are approximately 5 % more efficient in heat gain reduction, they are also submitted to important dust accumulation, TRB are thus preferred (Medina and Young, 2006). However, a concern with high reflectance metallic coating like aluminum is its low infrared emissivity and thus its temperature rise. Some special coatings exist to raise this emissivity reducing the temperature and thus the heat gain during the summer (Liu 2006).

5.1.4 Smart Windows

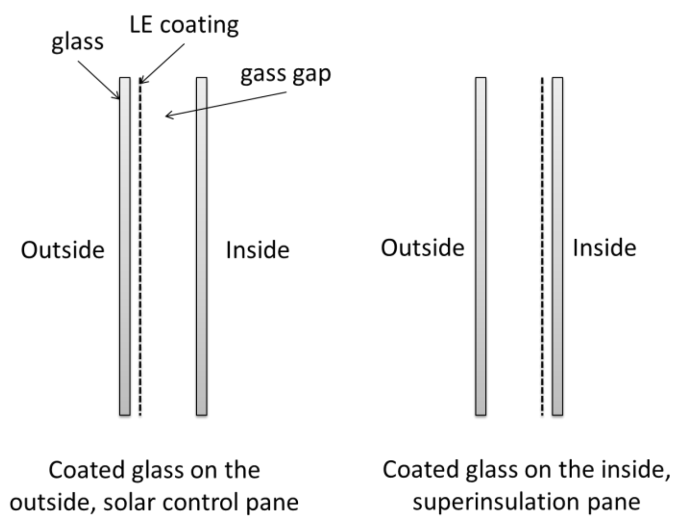
Smart windows are the so-called windows able to change their solar factor SF and their transmittance properties (T_{vis}, T_{sol}) and reviewed in Beatens et al. (2010b). They can adjust to outside and indoor conditions and thus saving energy as well as increasing the indoor comfort. Three different technologies can be distinguished: electro (or thermo- or photo-) chromic materials, liquid crystals and suspended particles devices. The most reliable and promising technology appears to be electrochromic windows (ECWs). Using an electrical current to change from transparent state to the colored one, the objective will be to have the largest possible range of T_{vis} and SF values, thus controlling the solar flux. Existing products permit the T_{vis} value to range from approximately 0.03 to 0.60, depending on the considered product. In terms of U-value, the latest technologies are quite competitive (U-value = 0.50 W/(m^2K) or higher). Note that electrochromic foils can be added to existing window panes and thus be used for retrofit purposes (Jelle et al. 2012b).

AR on a double glazing smart window has been tested: while very slightly increasing the T_{sol} and T_{vis} in the opaque colored state (about 1 %) this coating provides in the transparent state an increase of both values respectively of 5 % and 6 %. No drawback, except the price, is induced by this coating (Jonnson and Roos 2010)

5.1.5 Moveable Low-e Coating

The effect of the LE coating will be changed regarding its position: on the inside, the heat transferred from inside until outside the building by radiation is lowered, and the heat is thus conserved. The LE coating on the outside will have the opposite effect; see NTNU and SINTEF 2007 and figure 19.

Naturally comes the idea of a moveable low-e coating, in this type of window, the low-e coating faces the indoor glazing during the heating period and faces the outdoor glazing for the summer, to reduce cooling energy loads by reflecting the solar heat. Both heat and solar fluxes are controlled. This process has been compared to a usual low-e coating facing the outside glazing both by field tests and on software. The results show an increase in the heat gain up to 38 % through the window during the heating period for a high thermal mass building. Moreover, the windows fitted with low-e coating keep their heat reducing characteristics in summer. The condensation phenomenon that occurs on indoor glazing is also reduced by the process as the temperature of the glazing is increased (Abaza and Sa'ad 2006).



Figures 19. Radiation balance for sealed pane with LE coating, adapted from NTNU and SINTEF (2007).

5.2 Multi-Functional Systems

5.2.1 Double-Skin Façade Systems

According to Safer et al. (2005): "*Double-skin façade is a special type of envelope, where a second skin, usually a transparent glazing, is placed in front of a regular building façade. The air space in between, called the channel, can be rather important (up to 0.8–1.0 m). In general the channel is ventilated (naturally, mechanically, or using a hybrid system) in order to diminish overheating problems in summer and to contribute to energy savings in winter*". DSF are often thought as two layers of glass separated by an air gap, however the interior façade can also be made of some other material. Typical DSF made of two glazing layers will here first be described. An extensive and general review of this technology is given by Poirazis (2006), another one which focuses on energy savings can be found in Shameri et al. (2011). This paper will then study particular techniques using the double skin principle as Trombe wall.

DSF made of two glass layers

In addition of their structural role several functions can be fulfilled by these DSFs, especially heat, solar and sound flux control.

A DSF's first function is the *heat and solar fluxes control*. The ventilation technique will highly influence the control of these fluxes, the principle is the following: (Oesterle et al. 2001)

- In winter, the thermal insulation is improved thanks to the thermal buffer and the greenhouse effects in the intermediate air layer and the thermal bridges are clearly reduced by this system. Moreover, the air used for the building ventilation can be taken outside and preheated in the intermediate space before entering the building inducing energy savings. Eventually, heat losses from building are reused in the ventilation process.
- In summer, to avoid overheating, the air to ventilate the building will not be taken outside, but will remain inside the building. The intermediate air between the two layers will circulate, either naturally or mechanically to ventilate the air gap and lower the solar energy gain as they will be lost to the outside, as explained on figure 20. The use of shutters fixed in the intermediate gap, on the outside window, will reduce even more the heat gains as the heat will be dismissed outside the building.

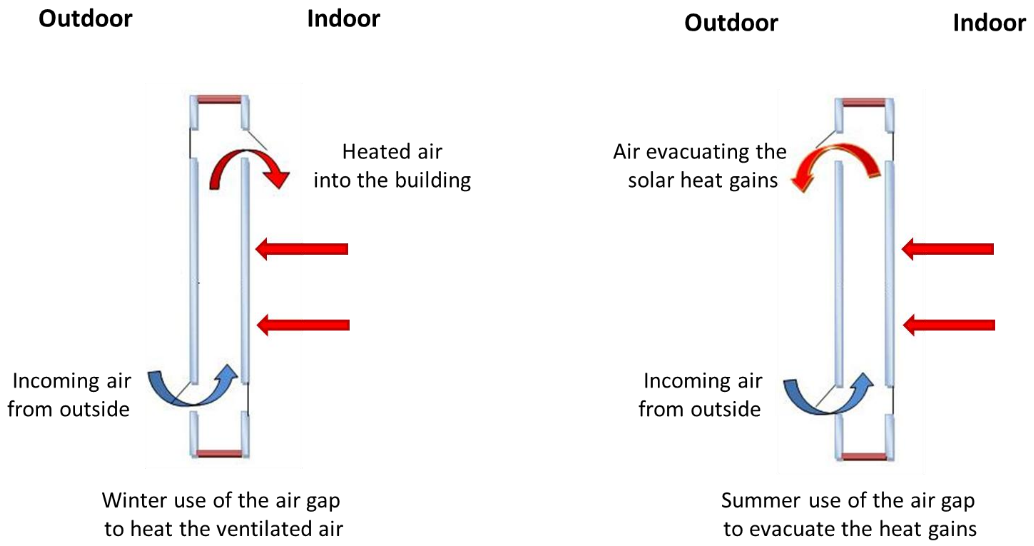


Figure 20. Different possible use of the air gap, adapted from Ekopedia (2009).

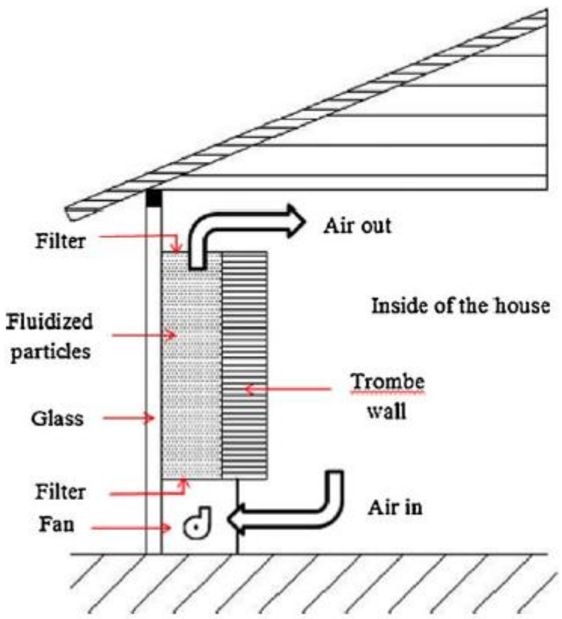
This solution can also be used as renovation technique on existing buildings. Studies made by Ballestini et al. (2005) report a 12 % drop in energy consumption for a naturally ventilated DSF in a Mediterranean climate thanks to the addition of this system on an existing building, which confirms the high potential of this technology in terms of heat and solar fluxes control. Of course, DSFs will allow greater amount of daylight in the building and thus help in reducing artificial lighting energy consumption (Hien et al. 2005 and Gratia and De Herde 2007). The shading devices are also of great importance: as they will be installed in the cavity, their influence on the ventilation and how the solar gains will be used or dismissed has to be studied (Charron and Athienitis 2006). Oesterle et al. (2001) state that the shutter should be installed in the outer half of the intermediate space to optimize the solar and heat flux control. DSF can be fitted with integrated PV on the shutters, more than electricity production, they may also be used for thermal energy creation and daylighting (Shameri et al. 2011). However the energy efficiency of a building using a DSF envelope is very debatable as most of the technologies are not able to lower both heating and cooling energy demands. To offer an energy economical solution all year long one will have to fit the DSF with sophisticated control mechanisms (Saelens et al. 2003).

Sound insulation and fire behaviour: the external façade will work as an acoustic screen, using sound energy reflection, thus offering "*improved acoustic insulation against external noise*" (Ding et al. 2005). For Oesterle et al. (2001) the reduction of the sound level is the most important characteristic of a DSF and the first reason of the choice of this technology. The fire safety of those structures is debatable and the studied focus on smoke evacuation. Rather complicated in general, Ding and Hasemi (2006) demonstrated that smoke spread can be prevented thanks to suitable arrangement of openings.

Trombe wall

Trombe walls are typically made of a 30 cm thick concrete wall, used for its high thermal mass, separated from an external glass by an air gap. The glass enhanced the solar heat gains thanks to the greenhouse effect and the air gap can be ventilated to control the heat flux on the same principle as double glass layers. The internal wall can be insulated or not, depending on the external climate. This device is used to heat the building during winter and should of course be fitted with shading systems to avoid overheating, a review of these products can be found in Sadineni et al (2011). Jie et al. 2007 modeled how PV can be affixed on the inside side of the external glass. Therefore, the heat produced the by the PV can be ventilated inside the building and the efficiency of the solar cells can be maintained. The system is named PV-Trombe wall and is theoretically enhancing the PV efficiency (around 5 %) and also provides a better heating of the air gap, although no literature about experimental results has been found. The thermal mass of the internal wall, which is here the key property, can be enhanced by the addition of PCM (or to keep the thermal mass but reduce the wall thickness). (Tyagi and Buddhi 2007). Some new systems use highly absorbing, low density particles in a fluid contained in the gap to absorb more solar heat before being ventilated in the building (a filter blocks the particles) called *fluidized Trombe wall system*, studied by Tunç and Uysal (1991).

A *Transwall* is a transparent modular wall providing daylight and heat. Those walls use water enclosed between two glazing panes to absorb part of the heat and release it later and a translucent glass is fixed between them assuring some intimacy, more details in Nayak 1987.



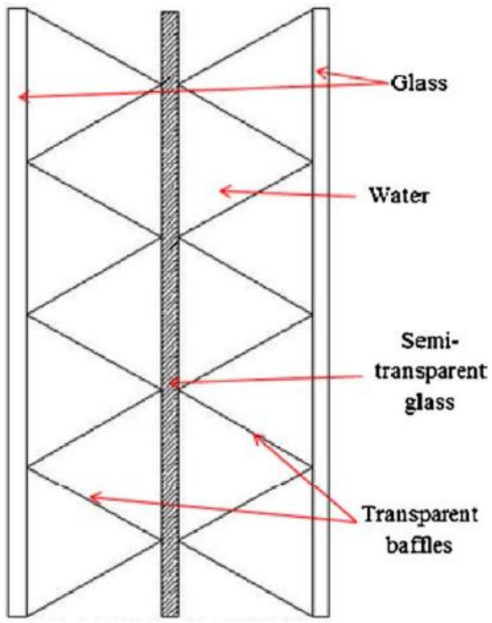


Figure 21. On the left a cross-sectional view of fluidized Trombe wall (Tunç and Uysal 1991) - On the right a cross-sectional view of Transwall system (Nayak 1987).

5.2.2 Green Envelope

Whereas much of the sun energy falling on typical construction materials as concrete or asphalt (for flat roofs) is reradiated as heat, thus increasing the surface temperature and the building underneath, the solar flux reaction of a green layer is very different. Indeed a layer of vegetation will have the following behaviour under solar rays: 2 % of the heat will be used for photosynthesis, 48 % is stored in plant's water system, 30 % is transformed into heat by evapotranspiration and only 20 % is reradiated. Furthermore, a green layer by its complexity and its complex nature (soil, plants and trapped air) is efficient to stop sound flux. Green systems will use absorption and reflection to that purpose. The substrate will tend to block low frequencies while higher ones are blocked by plants (Stec et al. 2005). Plants also help to mitigate the greenhouse effect, to reduce the urban heat island effect, to filter pollutants, mask noises, prevent erosion and calm their human observers (Spala et al. 2008). That is why, the use of plants on a BE either on roofs: *green roof system* or on the building wall as *vertical greenery system* in order to make these BE's parts multi-functional. A special type of VGS will be studied separately, the so called green shutters.

Green roof system

A green roof system is a layered system reviewed in Spala et al. (2008): the ones present in each system are the following: a waterproofing membrane, a growing medium (ground) and the vegetation layer itself. Some systems also present additional layers as a roots barrier, drainage or an irrigation layer. Two types of green roof systems exist: *extensive green roof system*s are fitted with a thin substrate and can be very lightweight. They will require almost none maintenance and will readily survive in a European climate. On the other hand, *intensive green roofs* have a deeper substrate layer to allow other types of plants, bigger and with different characteristics. They are heavier and require a structural adequacy of the building, see table 2 for more information about the differences2

Table 2. Comparison of extensive and intensive Green Roof Systems (Johston 1995).

	Extensive Green Roof	**Intensive Green Roof**
Brief Description	- Thin soil, little or no irrigation, stressful conditions for plants	- Deep soil, irriguation system, more favorabe conditons for plants
Advantages	- Lightweigth - Suitable for large areas - Suitable for roofs with 0-30° slope - Low maintenance - Often no need for irrigation and drainage system - Relativerly little technical expertise needed - Often suitable for retrofit projects - Can leave vegetation to develop spontaneously - Relatively inexpensive - Looks more natural	- Greater diversity of plants and habitats - Good insulation properties - Can simulate a wildlife garden on the ground - Can be made very attractive - Often visually accessible - Diverse utilization of roof (i.e., for recreation, agriculture, as open space)
Disadvantages	- More limited choice of plants - Usually no access for recreation or other uses - Unatractive to some, especially in winter	- Greater weight loading on roof - Need for irrigation and drainage sytem hence, greater need for energy, water, materials, etc… - Higher costs - More complex system and expertise required

Green roof's principle function is thermal flux control, indeed this last's effect is reduced and especially solar heat gains: in summer a black roof can reach 80 °C while a green roof only reaches 27 °C by cooling through latent heat and thanks to its high reflectivity (FiBRE 2007). A German study estimates the money savings due to cooling energy reduce up to 40 €/m² compared to a flat roof covered with gravel (Sabre and Bulteau 2011). More than reducing heat gains in summer, U-values of 0.24 – 0.34 W/(m^2K) have been achieved which assure a good thermal insulation in winter times (A. Niachou et al. 2001), even if, for new construction, lower U-value can be reached with other common technologies. In addition the thermal mass of the BE is highly enhanced for intensive green roof systems due to their thickness. The moist content of the soil affects the heat flux control characteristics: a wet soil will offer a lower thermal insulation, however, in a hot climate; it will allow a larger heat loss by evapotranspiration. The figure 22 offers the comparison of the behaviour of traditional, wet and dry green roof under incident solar radiation. Eventually green roof systems seem to have more potential to retrofit existing poor insulated roofs, (Castelton 2010) or to be used in highly urbanized zones.

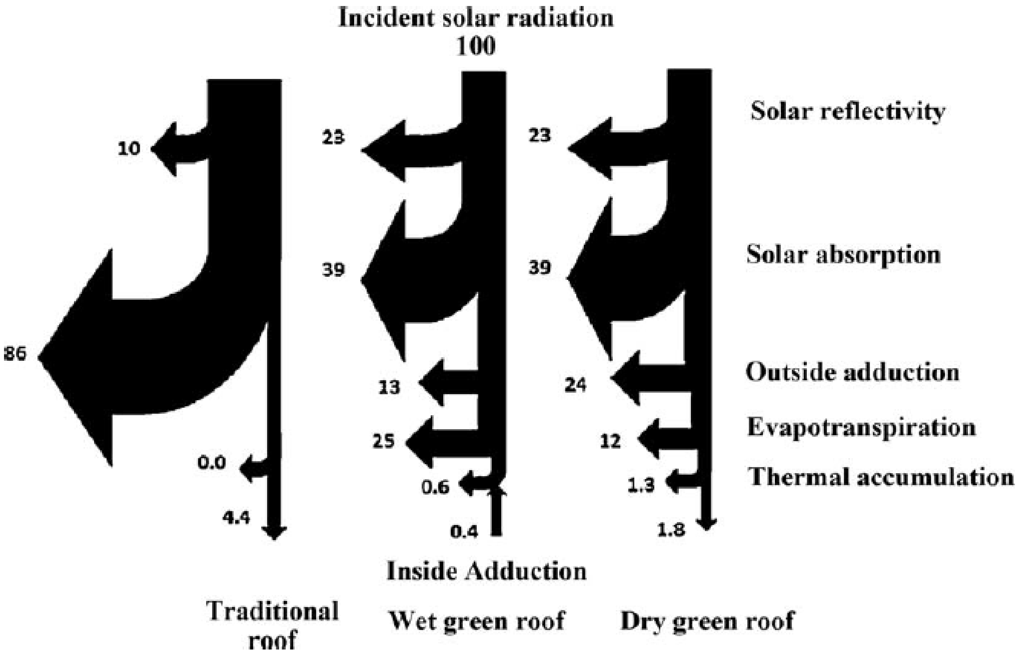


Figure 22. Comparison of the energy exchanges of the dry or wet green roof with a traditional roof, summer season (Lazzarin et al. 2005).

Regarding their sound flux control, an additional noise reduction about 5 - 20 dB has been monitored when comparing a roof with or without green system, on the benefit of the green roof (Lagstrom 2004). According to Sabre and Bulteau (2011) a 12 cm thick layer can provide a sound insulation against airborne sound of 40 dB. They also reported a 15 to 20 dB sound level reduction depending on the water content, compared to a traditional roof. Some other studies have been lead on the attenuation of diffracted sound level by the retrofitting of green roof systems and an attenuation up to 10 dB has been measured (Yang et al. 2012 and Van Rethergam 2011). Once again, the moist content will have an influence and lower the attenuation of sound level. A review about sound insulation of green roofs can be found by Yang et al. 2012 and Wong et al. 2010.

Green roof systems have ecological aspects previously explained as they improve the urban air quality and reduce the urban heat island effect.

Vertical greenery system

Vertical greenery system, also called *vertical garden*, is defined by plants growing on, up or against the façade of a building. A VGS offers almost the same advantages as a green roof without the weight issues and has larger effects as the covered area is more important but with induced fixation complications. Indeed to assure the plant's development different systems exist: planting on the ground level at grade, in planter boxes (wherever desired on the BE: as shading system, only on the walls, etc…) on a vertical hydroponic system. Vines and trees which are the typical plants used, have an inherent height limit and a growth time to be fully effective. To counter those limitations, annual vines at different level can be temporarily installed. Interior greenery walls systems also exist and bring the benefits of improved air quality and greening into buildings (Peck et al. 1999). GVS has been studied particularly in tropical or humid climates. The same phenomenon as on green roofs has been monitored, that is to say a wall surface's temperature drop as well as a decrease in the diurnal range of average wall surface's temperature. More than reducing the cooling energy demand, it also induces a longer life time of the wall's materials as the temperature variation and the UV radiation are much lower. However, other characteristics as the thermal insulation or the ambient temperature reduction (i.e. the temperature at a certain distance from the wall, which is a key property in the urban island effect reduction) largely depend on the type of system used: the type of plants, their implementation, their fixation, etc… (Wong et al. 2010a)

Regarding sound insulation of VGS, the transmission losses depend on the sound frequency and this system is more efficient to reduce low and middle frequencies sounds (which are usually the most difficult to lower). A reduction of 5-10 dB has been monitored: the thicker the green layer, the better the sound attenuation. However, considering the high prices of the installation and maintenance of VGS and the efficiency of other materials, VGS should not be chosen for their sound insulation capacities. Regarding internal VGS, the sound absorption is very high, thus reducing the reverberation. The speech privacy can be increased despite high costs. (Wong et al. 2010b)

Green Shutters

The shutters are a critical part of the building, especially in glazed façades, and can also be fitted with plants (Stec et al. 2005). As mentioned previously, plants have several advantages (thermal regulation, sound insulation, air purity, psychological effects…). The main disadvantages of this system are the daylight intensity control and the maintenance issues. However technological answers have been brought to daylight control by flowerpots installed on rotating slots enabling a direct control of daylight (see figure 23, on the left) or the use of shedding plants (losing their leaves in winter and allowing daylight to fully enter the building). Maintenance issues mainly lay in the short available space to install the plants and the falling leaves (which can be controlled by openings as shown on figure 23 on the right). A validated simulation model of the building with plants in the DSF gives the following advantages: a lower glass layer surface temperature, it never exceeds 35 °C with plants although 55 °C is reached for typical shutters. Even though the heat energy demand may be increased in winter, the cooling demand can be drop up to 20 %.

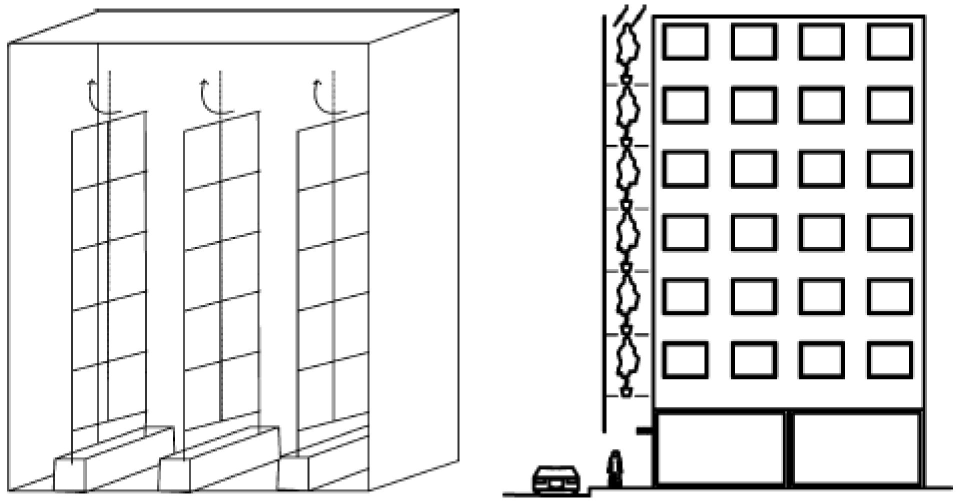


Figure 23. On the left: installation of plants in the cavity of the façade by placing them in the flowerpot on rotating slats - on the right: a DSF with plants: a cavity allows dead leaves to fall on the pavement(Stec et al. 2005).

5.3 Multi-Functional Materials

5.3.1 Aerogels

Aerogels are dried gels with a very high porosity, with a bulk density as low as 3 kg/m^3. Usually made of silica, the ones used in building application have an overall density of 70-150 kg/m^3. As stated in Baetens et al. (2011) who also proposes an extensive review of this material, "*due to its extraordinary small pore sizes and high porosity, the aerogel achieves its remarkable physical, thermal, optical and acoustical properties*", aerogels thus are multifunctional materials.

Aerogels have a very low total thermal conductivity λ_{tot}. Even though the conductivity of the solid lattice λ_s is quite high, thanks to the small fraction of solid, the effect is largely lowered. These panes also use carbon black to lower λ_{rad} the infrared radiation transfer and, thanks to their very small pores, the Knudsen effect to reduce $\lambda_{gas.}$ Basically, this phenomenon describes the fact that a heated molecule will hit the surface of the pore instead of another molecule because of the restricted size of the pores, thus reducing the convection heat transfer in the pores. The gaseous thermal conductivity can be further decreased thanks to several solutions: filling the pores with a low conductivity gas or by applying vacuum in the pores. Aerogels have basically a high transmittance T_{vis} which makes them transparent. If transparency is not desired, T_{vis} can be strongly reduced, up to 50 %, by the simple addition of opacifers during the synthesis process. Two major aerogel utilizations stand out: the first one will be the opaque aerogel insulation material. Those textile-like blankets products are flexible and robust and can be used as traditional insulation material, thermal conductivity of 14 mW/(mK) are reached by commercially available products, which is 2-2.5 times lower than traditional material (Spaceloft® 2011a). Their price is still very high, however it may be crucial wherever the thickness of the BE is an issue. Note that the compression strength of aerogel is quite good, but they remain very fragile due to their low tensile strength. This last could be increased by the addition of a carbon fiber matrix, thus offering possibilities in structural function addition (Jelle 2011).The second option is translucent aerogels insulation materials. The wide range of T_{vis} offers application in translucent roofs or façade with a high thermal insulation as well as fenestration products. ZAE Bayern developed a granular aerogel based window (Reim et al. 2002, 2004, 2005 and Wong et al. 2007) which highlights perfectly the multi-functional character of this product. This fenestration technology is available in three versions with different function using low-e coating with different emissivities or heat exchanger systems:

- A daylighting system, used to allow large quantity of light to enter the building within good thermal performances, has the following key properties: T_{vis} between 0.24-0.55, T_{sol} from 0.33 to 0.45 and a U-value in the range of 0.44-0.56 W/(m²K).
- A sun protecting system, which provides better thermal conditions but still a given amount of daylight: T_{vis} from 0.19 to 0.38, T_{sol} between 0.17-0.24 and U-value from 0.37 to 0.47 W/(m²K)
- An evacuated solar collector fitted with a heat exchanger system.

Figure 24 (on the left) is a good example of the use of aerogels to create a translucent façade allowing daylight. A review of the existing fenestration products using aerogels can be found by Jelle et al. (2012b).

Another function of aerogels is their good sound insulation performances, indeed granular aerogels have intrinsic sound reflecting characteristics which make them excellent sound barrier materials (Donovan 2004 and Gibiat et al. 1995). Experiments have shown that a 7 cm thick panel composed of multiple granular aerogel based layers can provide an average attenuation of 60 dB (Ricciardi et al. 2002).

Safety characteristics of aerogel products are as well discussed: it stands out that they are considered nonflammable (Spaceloft® 2011b). Furthermore they are used as fire protecting materials. The figure 24 (on the right) illustrates the excellent thermal properties of aerogels and their use as fire protection (Aspen Aerogel 2009 and Ratke et al. 2006). Their impact on health is a matter of concern as aerogel insulation sheets containing amorphous silica produce dust. According to the International Agency of Research on Cancer, synthetic amorphous silica is not classifiable as dangerous (Baetens et al. 2011). Even tough, further studies show that amorphous silica can be removed from lungs (Merget et al. 2002, Warheit 2011). All in all, it is nowadays considered as a safe material.

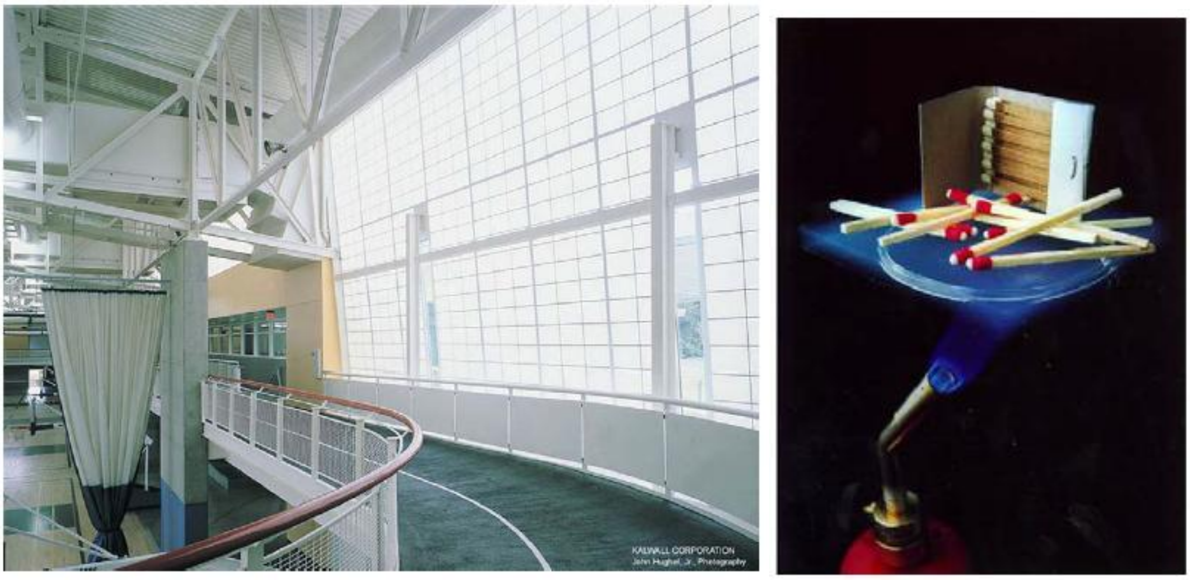


Figure 24. On the left an example of translucent aerogel insulation as a high performance thermal insulation solution for daylighting (Kallwall 2012) – On the right: matches on the top of aerogel are protected from the flame underneath (NASA 2004).

5.3.2 Multi-Functional Concretes

Due to the various possibilities of its formulation, concrete has a very large field of possible functions. With inherent thermal, sound, fire resistance and structural functions, changes in its composition can enhance durability, water and vapor tightness. Concrete, unlike steel for instance, shows large possibilities in making the construction industry more sustainable and many possibilities exist (Swamy, 2008). We will study here the most common multi-functional concretes.

Aerated Concrete

Two main production processes exist; air entraining methods producing gas concrete and foaming methods producing foam concrete. The aerated concrete can either be non-autoclaved (NAAC) or autoclaved (AAC) (particular curing techniques under high pressure and temperature). Aerated concrete is classified as lightweight concrete, thanks to aerating agents the air voids are entrapped in the mortar matrix. Its density varies from 300 to 1800 kg/m^3 (for an average density of 2500 kg/m^3 for an ordinary reinforced concrete). The main properties of aerated concrete depend largely on the dry density, the lower the dry density the lower the compressive strength but also the thermal conductivity which will enhance the thermal insulation power. Furthermore, AAC presents better level of strength and lower the shrinkage, see details on table 3 (Bave et al. 1978). Naturally, as for other types of concrete, all these characteristics depend largely on the age of the concrete, the water content, the curing conditions, etc…

Table 3. Properties of AAC aerated concrete (Bave et al. 1978).

Dry density (kg/m^3)	Compressive strength (MPA)	Static modulus of elasticity (kN/mm²)	Thermal conductivity (W/m°C)
400	1.3 – 2.8	0.18 – 1.17	0.07 – 0.11
500	2.0 – 4.4	1.24 – 1.84	0.08 – 0.13
600	2.8 – 6.3	1.76 – 2.64	0.11 – 0.17
700	3.9 – 8.5	2.42 – 3.58	0.13 – 0.21
Classical concrete C25/30* with a density of 2500 kg/m^3	25 – 30	35	1.0 – 2.5

*classical value of the concrete found in Bamforth et al. (2008)

A review about aerated concrete's properties can be found by Narayanan and Ramamurthy (2000). The durability of AAC is good compared to regular concrete owing to the use of tobermite. However, its high porosity makes it sensitive to froze and thaw. The thermal conductivity is highly influenced by the moisture content: a 1 % raise will produce an increase of the thermal conductivity up to 42 and is thus a major characteristic of AAC (Rilem 1993). Aerated concrete, by its structural and thermal flux control functions, can be used as a construction material without addition of thermal insulation and still meets standard thermal requirements with a reasonable thickness in some hot countries (Radhi 2011). Indeed, AAC construction blocks are able to provide energy savings due to their thermal mass and integrated thermal insulation; furthermore reducing thermal bridges and increasing the airtightness. The same study highlights the other benefits or AAC blocks compared to regular masonry, that is to say the cost efficiency of this solution and also the reduction of the CO_2 footprint up to 350 kg per square meter of AAC block wall. Not only fitted for hot climate, other studies reported the thermal advantages of those blocks compared to traditional brickwork in colder countries as Finland (Lindberg et al. 2003).

The homogeneity of aerated concrete gives an as good as or even better, fire resistance compared to regular dense concrete. Indeed, the homogeneity will reduce the risk of differential rates of expansion (provoking cracks and disintegration); moreover, the numerous air-concrete interfaces reduce the heat radiation transfer (Leitch 1980).

Although the initial interest about aerated concrete was given to its good thermal performances, its light weight is now the principal characteristic. As a matter of fact, the light weight permits savings in materials, in transportation costs, and is easier and faster to install. In addition it has a potential for large scale utilization of wastes like pulverized fuel ashes in its production (Ramamurthy 2010).
These characteristics added to the CO_2 footprint reduce give aerated concrete a sustainable function.

High Performance Concrete (HPC) and Ultra High Performance Concrete (UHPC)

The process to create these performing concretes is fairly easy: one will use strong aggregates and fines, the water content will be reduced and super plasticizer will be added to conserve the workability. Finally the addition of steel fibers will increase the resistance to brittle failure. HPC have a w/c ratio lower than 0.4 and reaches, after 28 days, a compressive strength higher than 50 MPa on a cylinder sample (CIMBETON, 2005) while UHPC must reach a compression strength higher than 200 MPa to deserve this appellation (M.C Tang 2004). In building construction they are of course used for high skyscrapers as the Burj Khalifa (see figure 25, on the right). Both of them present better characteristics in terms of durability and sustainability.

The durability of HPC is better than the one of a regular concrete as it is denser and thus less porous. Actually during the self-desiccation of the concrete, the connection between the pores and the capillary network are disconnected which reduce greatly the permeability of the concrete, and limit propagation of environmental factors to the superficial layers, which induce a higher resistance to corrosion as well (P.C. Aïtcin, 2003). However, according to M.C Tang (2004), the durability, even if clearly higher than regular concrete, is not clearly quantifable as there are no feedback results of old enough structures made out of those materials.

The *fire resistance* of HPC and UHPC is a matter of concern. Indeed, due to their lower porosity, greater internal strains appear and hazardous effects as spalling may occur. However, some products, based on the addition of polypropylen fibers have yet settled this issue. (M.C Tang 2004 and P. Acker and M. Behloul 2004)

The sustainability of UHPC has been studied by Racky (2004), it stands out that for a given load, UHPC drastically reduces the concrete section. Hence lower quantity of raw material, less energy spent to produce the cement, less transport costs and energy and thus less CO_2 emitted. Futhermore construction area is saved thanks to thinner walls.

Self-Compacting Concrete (SCC)

SSC differs from regular concrete by its composition as super plasticizers and a lower w/c ratio are used. Moreover, fines and the absence of coarse aggregates will assure a high fluidity and thus workability. The main advantages of SCC concern its fresh properties: it will ease, accelerate and secure the cast of the concrete, which is not our concern in this paper. SSC in its hardened state presents architectural and aesthetic functions. Its high fluidity enables it to perfectly fill up formworks and thus to create complicated shapes, furthermore it offers immaculate façades both of those characteristics will offer more freedom to architects (see figure 25, on the left). Eventually, the hardened mechanical properties are almost or as good as the ones of regular concrete. (CIMBETON (2005) and Domone (2007)).

Figure 25. On the left: use of SCC in order to achieve aestetic functions (CIMBETON 2005) - On the right: use of HPC for the world current highest building in the world, the Burj Khalifa in Dubai (J. Aldred 2010).

Translucent concrete

By the addition of optical fibres into concrete prefabricated blocks, translucent concretes are created. The light passes through the optical fibres, therefore the fibers have to go through the whole section. The transmitted light will thus follow the optical fibers pattern. The mechanical characteristics of this concrete are fairly good : 50 MPa of compressive strength as the tensile bending strengh reaches 7 MPa, largely enough for typical buildings. However, no values of the solar or visible transmittances have been found. We can deduce here that this concrete is most likely to be used for its architectural functions rather than to provide daylight in the builing. Nevertheless, the transparence could be increased and then offer real control of the solar flux and the daylight. Hence several functions achieved by this material, including architectural possibilities (Litracon 2012)

Figure 26. Translucent concrete used for architectural and daylight control functions (Perera 2012).

5.4 Addition of original functions

5.4.1 Photocatalytic Materials

A surface recovered with photocatalysts, under the combined action of UV radiation and water, will have two major characteristics: the photo-induced redox reaction of adsorbed substances and the photo-induced super-hydrophilicity. The first one will induce a depollution function as the second one is responsible of the self-cleaning function. In the field of construction, the titanium dioxide TiO_2 is the most widely used photocatalyst. This choice is partially based on its following characteristics: relatively inexpensive, safe, high photocatalytic activity, its compatibility with traditional construction material and its effectiveness even under weak solar irradiation. A review of the photocatalytic materials can be found in Chen and Poon (2009).

The self-cleaning windows only need rainwater and solar sun hitting a thin TiO_2 coating on the glass. As water falls on the window it carries organic dirt off on its move (not inorganic dirt as dust!). These windows have slightly higher U-values than the other reviewed products ($U = 1.2$ W/(m² K)). It is important to add that the window will have to be cleaned anyway but less often what represents money savings for high glazed façades. Furthermore, as the TiO_2 film is on the outer glass pane, there is not interfering with low-e coatings, it gives high potential for multi-functional products creation (Jelle et al. 2012b). Note that glass products covered with TiO_2 can also have this depollution function, however current state-of-the-art technologies are mostly at the research and development stage (Derbener et al. 2009).

Photocatalyst in cementitious systems, as concrete, are reviewed in Folli et al. (2012). By adding TiO_2 into cement the two previously explained functions are added. However, the issue with self-cleaning concrete is deeper as it does not only make the cleaning of the concrete easier and less often, but enhances the aesthetic durability of the concrete and also retards the natural ageing of the surface. The other, and probably most interesting function, is depollution. One of the major polluting agents in cities is nitrogen oxides (NOx), responsible of photochemical smog (mixture of hazardous chemicals forming smog in cities) and also partly in acid rain, it can be responsible of several pollution related diseases. Photocatalytic oxidation of NOx is a valid technology for this pollutant remediation, and this reaction occurs in cement containing photoactive TiO_2. Chen and Poon (2009) also reported the elimination of other pollutants as volatile organic compounds (VOCs) or toluene, both presenting health risks. Even if the use of this technology is not common currently, some buildings are already using it mainly to achieve high aesthetic standards for concrete façades. The depolluting function, which can also be used on pavements, is still at the experimental stage, but could be really effective if used at a high scale. Note also that this TiO_2 addition does not change any original performances.

Chen and Poon (2009) also state the utilization of this cleaning and depolluting technology in other construction materials such as tiles, corrugated sheets, or plastic films for instance. Note that the same principle is used in internal construction materials and add them an anti-bacterial function. Concerned materials are paintings, composite sheets or wallpapers.

Note also that the sol-gel process allows the creation of single coating providing several functions. Thus self-cleaning and AR properties have been obtained through a single coating (Zhang et al. 2005). Another multi-functional glazing has been developed through sol-gel process combining low-e properties and photocatalytic activity. As a result heat control, antifogging and antibacterial functions are thus fulfilled (Okada et al. 2003).

5.4.2 Building Integrated Agriculture on Rooftops

This principle is already applied but here is studied its massive use. Building integrated agriculture utilizing rooftops to cultivate crops is especially aimed at large cities as Singapore for example; where due to the high urban density the available space for agriculture is an issue. This solution used massively would allow to limit crops importation (and thus decrease the CO_2 footprint) if implemented on existing rooftops as well as reducing the heat island effect. Inorganic hydroponics, considered as the farming option with the highest crops yield, would here be used. However the existing block typologies and the potential for rainwater harvesting are problems in existing buildings. (Astee and Kishnani 2010).

5.4.3 Multi-functional Joints for Concrete Structures

In order to reduce heat losses through thermal bridges which occur at concrete slabs/wall connection new connection systems are developed made of Glass Fiber Reinforced Polymers (GFRP). These systems have to offer sufficient mechanical characteristics and assure the best thermal insulation possible. Previously steel was used to assure the connection, inducing high thermal bridges. Other systems as hybrid-FRP/steel joint exist in order to limit the heat losses (see figure 27 on the left). The latest technologies go further than hybrid-FRP/steel joint by replacing the steel rebars by GFRP rebars, which thermal conductivity is 200 times lower (Keller et al. 2006). This system called all-FRP joint (see figure 27 on the right) has been tested on software and on field and reports a drop of 50 % of the linear thermal bridges when compared to the hybrid-FRP/steel joint while assuring its structural role (Riebel and Keller 2009).

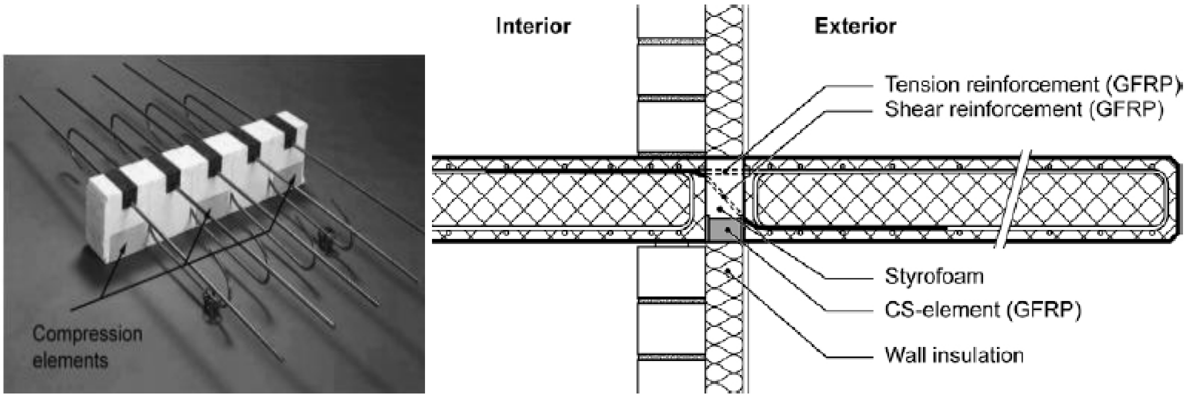


Figure 27. On the left : the typical hybrid-FRP/steel joint (Keller et al. 2006) – On the right: cross section of the all-FRP joint system (Riebel and Keller 2009).

5.4.4 Fire Resisting Glass

Typical glass will soften and even melt around 600-800 °C, but it will most likely break before if exposed to thermal shocks (common during fire episodes). However, with special devices, windows can be used as fire resisting barriers and provide integrity rating for a certain time however; it cannot be used to ensure the structural safety of the building. It must then be assembled with special glass;

either wired glass (reinforced with fines wires in both directions) or specially formulated toughened glass. New types of windows consist in alternating layers of glass or sodium silicate with transparent intumescent materials. These products are transparent at regular temperature but become opaque during a fire episode, achieving fire resistance up to two hours. (Buchanan 2001)

6 Visions for the Future

6.1 The Ideal Multi-Functional Building Envelope

6.1.1 Definition and Perspective

In order to propose new paths of development for the BE's technologies we have to figure out in which direction to lead these research. How do we envision the ideal Multi-Functional Building Envelope (MFBE)? As a building is a very unique answer to a given situation for specific owners, users and stakeholders the only way to answer this question is by a broad definition:

The ideal multi-functional building envelope assures safety, provides comfort and any other desired functions without any drawbacks.

The *safety* function, which includes physical and mental health of the occupants as well as their belongings, has to be total. The *comfort* to be achieved will depend on the building use, the owner resources but will always tend to approximately the same indoor conditions. *Any other desired function* describes the various characteristics one may want on his BE, from the traditional production of electricity to the more original production of vegetables on the roof. The *drawback* to prevent may be very different but we can highlight the most common of them:

- The *cost drawback*; the ideal MFBE's costs should not be a concern during construction and utilization, which involves energy savings.
- The *lack of flexibility drawback*; the ideal MFBE has to be controllable or to adapt to its environment. These changes in the MFBE characteristics should not involve excessive human intervention.
- The *ecological footprint drawback*; nowadays, ideal MFBE should be designed within sustainability.

One may wonder if a cutting edge MFBE of today reaches the given definition of an ideal one for tomorrow. Indeed, one would argue about the solar and heat control and the sound insulation of new BE in addition of the safety and the comfort they offer. As an answer to that question we will here envision the MFBE for the future giving a total control of all functions. To emphasize the realm of possibilities the ideal envelope could offer, we will give dramatic example of its possible utilizations:

I am at home and have a migraine, thus I want to be entirely isolated from sun, sound and wind, while lying in a cool atmosphere. Now I am feeling better, as I am still weak I will stay in my room. However it is a hot summer day and I want sun and a chill wind on my skin but without burning it, neither be glared, nor hearing the street noise or be too warm. A storm is coming and I would like to enjoy the chill summer rain without the contained pollution or the strong winds. The storm is now over and night has felt, I want the fresh and humid air to fill my room while watching the sky and hearing the streets sounds without the traffic noises. For my night I want darkness and silence until 10 in the morning when I want the daylight to wake me up progressively.

6.1.2 The Total Control of All Fluxes

Of course this ideal MFBE may be considered unrealistic and contrived. Moreover, the offered functions may be regarded as useless. However, it gives us a direction in which to orientate the future developments of MFBE which is the *total control of all fluxes on demand*, and this flux control should range "*from all in to all out*". That is to say:

- Control the intensity of the flux: from totally stopped to totally allowed,
- Control the intensity of a given wave length range or content of this flux,

- And have this control in both directions.

We will now distinguish all fluxes and give the major possibilities induced by their total control.

The solar and heat flux are probably the two most important fluxes in buildings. Several technologies already exist or are being developed to enhance their regulation but a total control would enable the following possibilities. A BE which could modify its optical properties, especially the transmittance, on demand, simply by touching the concerned BE parts for instance. The control of the flux direction would allow seeing outside without being seen, or the opposite. To stop only some solar wave lengths would also enable one to bring natural lighting without solar heat gains or sunbath inside without being seen outside. Currently the indoor temperature is mainly regulated by heating or cooling systems, the BE merely slows down the heat flux in order to keep the created temperature. The future of the MBE would stop entirely the heat flux to conserve the created heat. On the opposite, it could allow all the heat to enter the building in order to warm it, or to dismiss all the internal heat to cool the building. By that mean, large energy economies would be made.

The sound and the water/moisture flux are currently not really controlled, the state-of-the-art BE technologies are merely able to reduce them. Here are some possibilities offered by an ideal MFBE: The outside sounds would be stopped totally even with air or wind entering the building. Allowing only a given wave length may prevent from the traffic noise (around 1 kHz) while other sounds would be allowed. Better, it could enhance speech audibility by rejecting or absorbing internal noises from machines for example. The penetration of rain is often not desired; however one could envision an internal garden or green area that would be exposed as well to sun and rain occasionally, which pollutant would be removed (NO_x in acidic rains for example). The moisture flux, in order to assure a comfortable internal relative humidity, would be controlled through the envelope, and the materials used would not suffer its presence.

The air flow is specific as it transports heat, sound, moisture and particles. Only the last aspect has not been developed yet. Most of the particles have simply to be stopped as pollutants, radon, or pollens. Other may be considered as a flux to control as molecules responsible of odors, these could be allowed into the building, be stopped outside or be rejected through the envelope from the building in case of an indoor bad smell.

Some of these functions of this ideal MFBE seem achievable as the total control of the opacity of the envelope. It is the completion of existing technologies like smart windows. Moreover, to stop totally the heat flux is the ultimate objective of materials with high thermal mass or low thermal conductivity, even if the total absence of heat flux appears idealistic as it is not even envisioned by future thermal insulation materials as NIMs. Other functions, on the opposite, seem out of reach. The total control of the moisture flux for instance: it is currently impossible to stop moisture penetration into VIPs, be able to reverse the phenomenon in order to allow moisture to penetrate seems unrealistic. Besides all these controls would have to be applicable simultaneously, which raises even more difficulties. To control solar and air/wind fluxes separately is easy, however allowing wind to enter while preventing sound energy to penetrate the building seems much more complicated.

What about other functions not linked to the fluxes control, as producing electricity, self-cleaning, depolluting? An ideal MFBE should have as much benefic additional functions as possible, which would most likely be directed by the idea of sustainability:

- Produce energy by all means, to be energy autonomous but also for other uses (recharge the battery of the electrical vehicle thanks to the MBE).
- Reduce the costs of construction, utilization and maintenance of the building.
- Make the building as welcoming and environmentally friendly as possible.

Eventually, any drawbacks can result from this multi-functionality which includes ideally no costs, ease of use and controllability, and no excessive need of human intervention neither.

6.1.3 Multi-Functional Building, Envelope and Material

We can also have a more comprehensive view: the future of buildings lies in a Multi-Functional Building (MFB). This includes of course the envelope of the building, thus the Multi-Functional

Building Envelope (MFBE). The multifunctional characteristic will be reachable thanks to the association of materials, of particular technologies, but also to Multi-Functional Building Material (MFBM). This is most likely the most promising solution as it offers many possibilities, just as aerogels do nowadays. But then one could ask why not to use this material for many other applications? To have a wall which could turn into a flat screen? A kitchen table one could change from transparent to opaque? This material might be developed for building application and eventually its scope might be widened, thus creating a Multi-Functional Material (MFM). This ultimate material would ideally have the total control of all the fluxes. The control of the properties will most likely starts at the unit cell scale, and the aim would be to have the control at a macroscopic one.

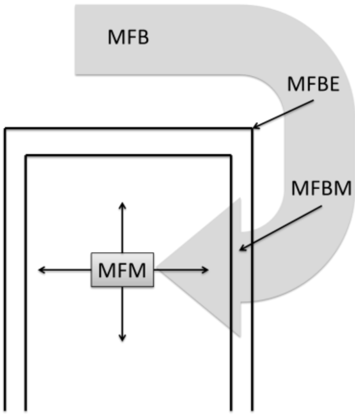


Figure 28. The Multi-Functional Building (MFB) consisting of a Multi-Functional Building Envelope (MFBE) and Multi-Functional Building Material (MFBM) and in general of Multi-Functional Material (MFM).

6.2 The Main Developments of Tomorrow

First the difference has to be made between adaptive and controllable as it is one of the principle characteristics of materials and technologies of tomorrow. In consequence of the current energy context which tends to always more energy savings, the main concern of today in BE is heat and solar fluxes control. Specific materials have been envisioned on that purpose (Jelle 2011 and Jelle et al. 2010). We will here give a short description of these materials and also propose solutions to make them multi-functional.

6.2.1 Adaptive or Controllable

It is sure that the future development of BE technologies will tend to be more adaptive or controllable. But what is exactly the difference between these two key properties?

- An adaptive technology will change its properties in consequence of some external stimulus: for instance, PCM will change its physical state in reaction to the temperature
- A controllable technology will change its properties because of human intervention: A smart window will change its opacity if someone uses a switch.

However, a smart window can also change its opacity automatically when the light intensity of the room reaches a given threshold. In this case, the window will still be controllable as this threshold will have been decided and programmed by a human being; the distinction is thus not always easy. Eventually, to have the control of the technology's characteristic offers much more possibilities than an adaptive one. Technologies of tomorrow should thus be developed in order to have controllable properties, and once again, ideally this control shall not involve drawbacks as energy consumption or difficulties in its use.

6.2.2 Low Thermal Conductivity Materials for the Future

Vacuum Insulation Material (VIM) and Gas Insulation Material (GIM)

A vacuum insulation material is defined, by Jelle (2011), as a "*homogeneous material with a closed small pores structure filled with vacuum with an overall thermal conductivity of less than 4 mW/(mK) in the pristine conditions*". This kind of new material overcomes the drawback of VIP, i.e. it is adjustable to the BE geometry. Moreover, a perforation only results in a local thermal bridge and no overall loss in thermal conductivity. Eventually, VIMs conserve their thermal characteristics under a given threshold during at least 100 years.

GIM is working on the same principle; the vacuum is simply replaced by a gas with a low thermal conductivity. Even if offering lower thermal characteristics, they would reach the same level of flexibility. Nevertheless, VIMs are regarded today as a more promising solution.

Nano Insulation Materials (NIM)

NIMs are based on a closed or opened nano-pores structure and present the same thermal characteristics as the VIMs and GIMs, but are more durable as "*the grid structure in NIMs do not, unlike VIMs and GIMs, need to prevent air and moisture penetration into their pore structure during their service life for at least 100 years*" (Jelle 2011). How does this material provide a total thermal conductivity λ_{tot} lower than 4 mW/(mK), even with the presence of air in its pores?

- λ_{gas} will be the most important factor here, and will be lowered by the so-called Knudsen effect.
- λ_{solid} will depend of the nature of the lattice and will also be of great importance, thus its choice has to be relevant.
- λ_{rad} will depend on the nature of the lattice, but also on the size of the pores: the smaller the pores, the lower the radiation. The overall thermal transfer through radiation remains low if the pores are small.

NIMs could be used in conjunction with concrete, then providing structural and thermal regulation functions, examples of utilization are given in Jelle (2011).

6.2.3 Multi-functional Enhancement of Nano Insulation Materials

NIMs seem to be the most promising thermal insulation material of the future (Jelle et al. 2010). We will thus consider this material on a multi-functional aspect.

Structural and Fire Safety Functions

Giving structural functions to a NIM is presented in Jelle (2011a) as NanoCon. This conceptual future material is a "*homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less 4 mW/(mK) and exhibits the crucial construction properties that are as good as or better than concrete*". Two major options to achieve this function stand out: envision a "resistant lattice" of the NIM with sufficiently mechanical characteristics to assure structural functions. The other solution, presented by Jelle (2011a), consists in the use of carbon nanotubes into a NIM material; this non homogeneous material presents largely sufficient mechanical characteristics and a very low thermal conductivity despite the high conductivity of carbon nanotubes.

To provide fire safety functions two basic properties have to be respected: the lattice should be non-combustible and, in case of fire, no toxic fumes should be emitted by the whole system. However, a NIM could have intrinsic good fire safety characteristics just as aerogels. Indeed as explained earlier homogeneity (which reduces burst and cracks risks) and numerous air-lattice interfaces (which reduce radiation heat transfers) are two assets for fire safety (Leitch 1980).

Solar Flux Control

Could this material have also controllable optical properties? Two major possibilities can be envisioned: controllable optical properties might be an intrinsic property of this material or one could use an electrochromic technology on this material. Even if the first solution would present certainly better performances, it also seems currently out of reach. The use of electrochromic technologies is more pragmatic. One could envision a transparent NIM made of aerogels as, according to Jelle et al. (2010), "*aerogels could be made so they could be considered as NIMs*". Then one or several layers of electrochromic (or electroactive) materials plus the additional typical layers used in electrochromic windows would cover, or be incorporated in, the transparent NIM (more details about the needed layers to achieve smart windows are available in Baetens et al. 2010b). Thanks to this system the originally transparent NIM wall could become opaque on demand. However the daylight provided in the transparent state may still suffer from Rayleigh scattering and thus the transmitted light could be reddened.

Sound Flux Control

Just as acoustical properties from aerogels are good thanks to the lower speed velocity and their high absorbance (Baetens et al. 2011), the sound insulation properties of a NIM should be intrinsically good. However, during the first tentative to add a structural function the possibility of a resistant lattice was given. This one would probably have to be rigid to assure its function what would harm the sound insulation. Hence, the second option involving carbon nanotubes, despite their high rigidity transmitting sound energy, appears as a better solution regarding acoustical considerations.

6.3 Original Multi-Functional Building Envelope

6.3.1 The Controllable Fluid Building Envelope Principle

We have seen several technologies involving a fluid to assure a given function, especially the solar and heat flux control. Those technologies are commonly used either on walls or on the roof. The idea here is to surround the whole building with this fluid from the rooftop until the base (those solutions could be used for below ground level parts, but to surround the foundation would most likely not be relevant). Moreover, the properties would be controllable as the fluid would be changeable, and in most of the envisioned cases, should be changed regarding the season, the climate, etc… Openings may of course be implemented and a particular attention would have to be given to their junction with the “fluid envelope” and also the wall-roof junction to avoid all kind of “flux bridges” (vacuum and PCM will be considered as fluids to be clearer).

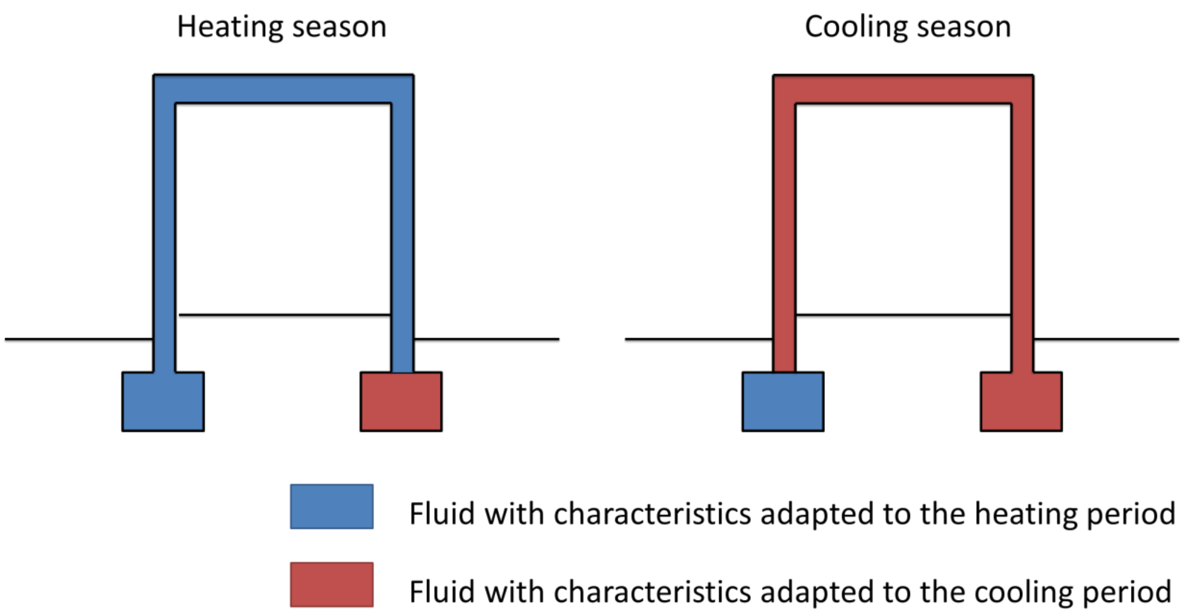


Figure 29. Scheme of the building fluid envelope principle.

The Vacuum Envelope

In this principle the whole building is surrounded with vacuum. This vacuum could be created either in some porous materials as aerogels for instance or in VIPs. A powerful ventilation system could help to maintain vacuum in the VIPs (as VIPs have difficulties to maintain their internal vacuum) and also allow the panel’s content change. The vacuum could assure thermal insulation through the heating season. During the summer, maintaining the vacuum in the envelope would not be necessary, and we could envision replacing it with some other fluids more adapted to limit solar heat gains (gas, air, water…). As it is known that a large amount of electricity is needed to create the vacuum, the summer heat gain could be reduced by many other means.

The Solar Heat Storage Envelope

On the same principle as BIPV, solar heat storage panels could be fitted with structural and weather resistant functions and surround the building as an envelope. The solar energy could thus be collected during the summer period and this heat may be used either to warm the building's water tank or to create electricity with a Stirling engine for example. Whereas during the heating season, the heat transfer fluid would be replaced by a high insulation power gas, vacuum, or simply air to insulate the building. The angle of the panels collecting solar heat should be controllable in order to collect more energy.

The Water Envelope

Based on the evaporative roof, the idea is here to create a water envelope surrounding all the building. In summer the solar energy will not heat the indoor atmosphere but heat the water envelope and then be transformed into latent heat. The transfer of the heat from the envelope into the building will have to be prevented. Once the water is vaporized into vapor, it could be recollected and the heat dismissed in the surroundings by some means. In the heating season, the water may be replaced by another fluid (gas, air, vacuum…). One can also envision the use of rain water and/or grey water to fill this envelope. Moreover, the latent energy released during the condensation of vapor into water could be collected or used to assist the ventilation system, a heat pump or a Sterling engine.

The PCM Envelope

Even though PCMs in their solid state are no fluid, they could be used as panels or in tubes (on the same principle as PCMSIPs) surrounding the whole building. As the role of PCMs is only to enhance the thermal mass they would be combined with classical insulation materials (aerogels, EPS,…) or with a fluid (vacuum, air, gas…). For this kind of envelope, one would not change the product in summer or winter as the benefit of PCM (a higher thermal mass) is as profitable in both seasons. However, regarding the specific melting temperature of PCMs, one may propose a very controllable BE. A unique answer in terms of thermal conductivity and thermal mass for each climate or situation could be offered by using the following levers:

- Change the PCM content of the panels or tubes and replace them with another fluid. The thermal mass would be reduced and the thermal insulation increased.
- Use different PCMs regarding their melting temperature: a high melting temperature could be used in summer; while a lower melting temperature product would be used in winter. Or regarding their location, as north façades will reach a lower temperature than roofs for instance.
- Different panels of PCM, with different melting temperature may also be layered.
- One last solution could be to change electrically, or by some other mean, the characteristic melting temperature of one product.

6.3.2 Green Enhancements

Green Construction Material

Usually concrete has to be protected from mold as it can be responsible of black spots and the growth of plants as their roots development can have adverse consequences. However one could envision the direct incorporation of some plants or micro-organisms into porous materials as brickwork or concrete. Of course the development of the green organism will have to be controlled in order to avoid structural damages and be enclosed to the porous material so it would not spread and damage the rest of the envelope. Furthermore, the development of the organism shall not harmfully modify the physical characteristics of the environment: raise the pH of the concrete for instance and make it more vulnerable against corrosion. However this technology would add to regular construction materials the intrinsic functions of plants. For instance a concrete wall could have a better control of the thermal flux by evapotranspiration, a better regulation of the moisture flux, better sound insulation. If one surface from this wall needs to be protected from this organism, a T_iO_2 coating could be added on the surface. Indeed the coating would, thanks to sun and rain, remove the organic dirt from the wall. Moreover, this system would not face the typical issues of greenery systems as weight, maintenance or fixations.

Use the Plant Diversity

The different species of plants should not only be chosen for their thermal capacities and their resistance. The different characteristics of plants and microorganisms should be studied in order to offer various functions.

- As stated earlier, the moisture content of a green system is crucial. The control of the moisture content as well as the total quantity of water within the system are levers to achieve various functions. Indeed the moisture content will influence the control of the heat, solar and sound fluxes. Moreover, it can influence the fire resistance of the envelope and slow down the fire spreading. The plants have then also to be chosen regarding their water content capacity.
- Natural shading will highly be influenced by the chosen plant, and thus this last should be carefully chosen.
- Enhance the sound insulation by sound absorbing plants and diffraction
- The thermal losses due to wind on a façade could be reduced thanks to a right type of plants
- Other original capacities should be considered when choosing a plant type as the agricultural potential, aesthetic considerations (plants with flowers in spring), CO_2 reduction potential, …

Different building envelope parts may also be fitted with different plants regarding their functions. For light greenery systems, one could use a green mattress simply fixed on the wall or the roof. This mattress could be changed for another one with a different plant; the idea is to adapt the plant's type according to the season.

Growing Medium Enhancements

The growing medium, which has to have a quite important thickness in order to offer space for the plant's roots can be used for other functions:

- One can highly increase the thermal mass of the growing medium with PCM either in tubes or directly added in the growing medium.
- One could envision a porous insulation material used as a growing medium which would not at all or slightly suffer from the roots growth and the necessary moisture needed to their development.

The Welcoming Green Roof

Starting from the current technology of agriculture on rooftops detailed earlier, in which the aim is a high crops yield, thus an economic objective, one could give a social objective of those rooftops. This area could be used as a simple garden for the occupants but also as a park to gather or even a soccer pitch. The main idea is simply to create a green place for people to gather, relax and enjoy the nature. Of course specific devices would have to be added as security barriers and sun shading systems. A swimming pool on the roof top would be the "welcoming version" of the evaporative roof.

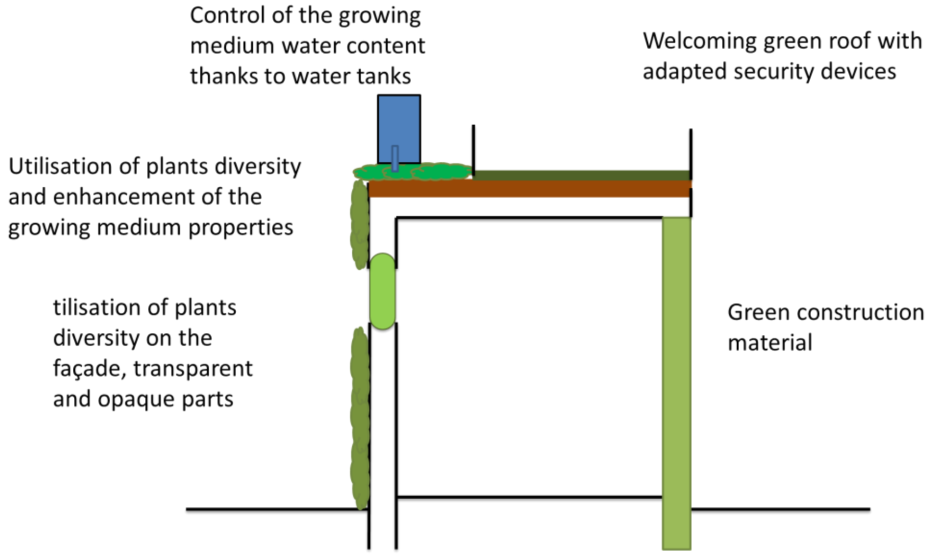


Figure 30. Illustration of the "Green Enhancements".

6.3.3 Aerogels Enhancement

Aerogels have intrinsic good performances in thermal, solar and sound flux control. Thus they have a great potential in MBE application. Here are proposed some visions in order to enhance the material and offer a highly multi-functional material for tomorrow. As aerogels can be considered as NIMs the ideas proposed here are close to the ones to enhance the NIMs.

- As explained previously, the compressive strength of aerogels is quite high, but their low tensile strength prevents them to be used as a standalone solution. The addition of a carbon fiber matrix would increase their mechanical strengths. One can also envision, on the same principle as the NanoCon, that carbon nanotubes would assure the structural role of aerogels.
- Despite their very low thermal conductivity, the low density of aerogel offers them almost no thermal inertia. As they are very porous materials, they could be enhanced with PCM (no literature has been found about this technology).
- The transmittance of aerogels currently depends on their manufacturing process, nevertheless one could envision aerogels products which optical properties would be controllable. Another solution would consist in the addition of an electrochromic layer on a transparent aerogel façade, as explained in for NIMs.
- One can also envision enhancing optical properties of transparent aerogels thanks to optical fibers. Thus aerogel translucent façade could provide more than a scattered daylight.
- The weather and climate protection could be assured by an external glazing layer. This layer could either be directly affixed on the aerogel or be fixed at a given distance, creating thus a DSF and offering the induced advantages.

If the previous functions are achieved, aerogels would be a MBE standalone solution offering multiple functions. The control of the transmittance would allow one to create a daylight entrance wherever desired or make one part opaque to avoid glare or solar heat gains.

6.3.4 Other Visions

Windows with multi-functional shutters

A window could be fitted with high technology shutters providing different functions: first they would provide the classical sun shading function; the additional functions may be the following:

- Fitted with sound attenuation material: once the window is open, the shutters fitted with sound insulation material will have to reduce the sound level, different positions will use different levers on that purpose. Totally close and thus opaque, the shutter will use absorption to create sound insulation. Diffraction and absorption will be used when the shutters are partially or totally open.
- Fitted with solar reflecting material to work as radiant barrier, and/or be moveable so they can reflect the sun further in the room
- Fitted with solar cells to harvest electricity when the shutters are closed (no literature has been found about this technology).
- Fitted with PCM products, to lower the heat peaks when the shutters are closed. (has been studied theoretically, no experimental results found)

Enhanced double skin façade

As studied previously, double skin façade already have several functions as thermal and sound flux control to complete their structural role. DSFs however have a great potential in terms of multi-functionality:

- Fire resistance can be added to the system thanks to fire resisting glazing, moreover, the ventilation in the gap between the layers can be optimized in order to evacuate the smoke and stop the flames spread.
- Smart windows can be used either on all the inner façade (in order to keep and use the heat in the air gap), on the external façade (and thus reduce solar heat gains as much as possible) or on both sides (to offer each solution). Once again highly controllable smart windows would be a great improvement of occupants comfort: with this system, one would be able to touch the window where he wants it to become opaque.
- Those smart windows could control their transmittance so only some radiations pass through in order to have a chosen color inside the room.
- Moveable window panes in order to change the inter-distance between the two glass layers. This system could modify the control of the heat and sound flux, as well as the ventilation system characteristics. Thus giving more flexibility to DSFs.

Moreover, all the functions added by high technology shutters could here be applied on all the building.

Antireflective sound insulation double leaf partition

In multiple leaves partitions the reflection and then the reverberation of the sound waves are used to enhance the sound attenuation of these technologies. On the same principle as an antireflection coating on a window can partially or totally cancel the reflected solar waves by the mean of a double interface. One could imagine using the same principle to cancel reflected sound waves?

7 Conclusions

Thank to this paper many and various functions that can be assigned to the BE have been identified. Some of these are totally natural nowadays and are perfectly achieved by current technologies. For instance it is perfectly natural for the BE to protect the occupants from the wind, the rain or maintaining its structural role during strong winds or snow. These functions were the major concerns of the builders from last century and this can explain their mastery.

Today's principles functions which are the focus of ongoing research are mainly the control of the following fluxes: heat, solar and sound. The underlying objective of these research is to maintain internal comfort within energy and money savings. These functions present characteristic key properties on which almost all technologies rely to achieve them. The most important ones are total thermal conductivity λ_{Tot} ruling the heat flux, the sound attenuation coefficient R responsible of sound insulation through the BE and the different transmittances T which are controlling the solar flux. Multi-functional technologies controlling in particular these functions have been reviewed, their explanation and the study of their performances have been given. Some of them stand out.

Firstly the aerogels: developed in order to propose very low thermal conductivity, they also offer good sound insulation and are used as fire protection. They also have a great potential in solar flux control, as they can be manufactured opaque or transparent, and offer some structural possibilities. Undoubtedly aerogels have a great potential for the future of thermal insulation material, not to consider and take advantage of the other possibilities it offers would be shameful.

Concretes can be considered basically multi-functional. Their principal functions are structural and acoustical, in addition of offering a good durability. Depending on the additive added in the initial mixture, concretes can present multiple other functions. Addition of PCMs can enhance the thermal mass of the concrete. HPCs and UHPCs present a better durability and outstanding structural characteristics which enable the concrete to reduce its section for a given load, which reduces the embedded needed energy and the created CO_2 through the production process. The addition of photocatalytic material will enhance the aesthetic function of the concrete and enable it to get rid of some pollutants. Eventually, translucent concrete can be created.

The use of plants in the BE also deserves great attention as they have multiple functions: thermal regulation through particular sun rays absorption, sound absorption and diffraction, ecological and psychological functions. Commonly employed on roof tops, their installation on façade is increasing and research is still in progress to enhance the performances of these green systems.

DSFs, although complex and often not completely mastered present a large multi-functional potential especially in heat flux control (through the ventilation), solar flux control (through multi-functional shutters and high technologies windows), and the sound flux (the second skin used as a sound barrier).

The reflection about the ideal MBE brought the concept of total control of all fluxes. Even though in the future these fluxes will not be controlled totally, the existing state-of-the-art technologies tend undeniably toward their better control. The proposition of original ideas has permitted to highlight the multi-functional potential of some technologies. The creation of the technologies of the future stands for sure in the knowledge of today's ones, in the understanding of the key properties they are using and in the proposition of original technologies.

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