Rethinking Adaptive Building Skins from a Life Cycle Assessment perspective

Manuela Crespi[1], Sandra G. L. Persiani*[2]

* Corresponding author
1 University La Sapienza, Department of Planning, Design, and Technology of Architecture, Italy
2 Technical University of Munich, Department of Architecture, Germany, sandra.persiani@tum.de

Abstract

Adaptive building technologies have opened up a growing field of research aimed at ensuring indoor comfort while reducing energy consumption in buildings. By focusing on flexibility over short timeframes, these new technologies are, however, rarely designed for sustainability over their entire lifecycle. This paper aims to address an information gap between the research field of architectural Life Cycle Assessment (LCA) and the state of the art of adaptive façades, by presenting an analysis of the main aspects in traditional and adaptive façades that are relevant to understanding whether parallels can be drawn between available LCA databases.

The literature is reviewed following an inductive method based on a qualitative data collection aimed at answering a list of research questions, and a deductive method starting from the descriptions of adaptive building envelopes. The findings highlight four main points: i) where and how adaptivity is integrated, ii) the design targets that are able to reduce the environmental impact, iii) the importance of a qualitative as well as a quantitative LCA of the technology, and iv) lists a number of knowledge gaps currently limiting the diffusion of LCA as a design and verification tool in Adaptive Building Skins.

Keywords

Life Cycle Assessment, building skin, adaptive, systematic mapping, design parameters

1 INTRODUCTION

The building sector is the largest consumer of energy, accounting for over one-third of final energy consumption and carbon dioxide (CO2) emissions globally. According to the European Commission, the energy use during the active life of the buildings in Europe is responsible for approximately 40% of energy consumption and 36% of CO2 emissions. In order to address these issues, research in the building sector has mainly focused on maximising the supply of energy from renewable sources and reducing the operational energy consumption in buildings' life cycle by massively integrating low-energy building technologies and systems (IEA, 2013).

The concept of 'energy' in buildings has often been used in referring to 'operational energy' (OE), while largely disregarding embodied energy (EE) or embodied carbon (EC). This encompasses initial, recurring, and demolition embodied energies (Azari & Abbasabadi, 2018). Although it is true that in many conventional buildings OE represents a relatively larger proportion of the life cycle energy (OE 80-90% compared to EE 10-20%) the rates vary depending on the building type (in an adobe/clay residential building the rate is closer to OE 66% - EE 33%) (Dixit, Culp, & Fernández-Solís, 2013; Ramesh, Prakash, & Shukla, 2010). The need to consider the complete life cycle of the building is therefore significant, especially since the amount of embodied energy is expected to grow with the rising number of low energy buildings that reduce their OE at the expense of an increase in their EE by integrating active and passive technologies and building systems (thicker envelopes, shading devices, etc.) (Azari & Abbasabadi 2018; Dixit, Culp, & Fernández-Solís 2013).

It is mainly in answer to the demands for optimisation of operational energy in buildings that the field of architectural façades has developed a great variety of technological solutions that advocate for higher comfort conditions while reducing energy use. Much of the technological research on adaptive building envelopes or skins (ABS) is centred on developing flexibility of the building surfaces within the timeframes of the human activity cycle, ranging from interactive systems reacting within seconds to seasonal adaptations changing the building skin over a range of months. As most building technologies, ABSs rarely take into consideration other aspects than the energy efficiency or the user comfort, reflecting only a very partial view of the system's real sustainability. Therefore, if the aim of adaptive building technologies truly is to improve on the sustainability of the built environment, ABSs need to be designed and contextualised within the broader framework of a complete Life Cycle Assessment (LCA), evaluating the technologies throughout all building LCA stages, as defined by the European Standard EN 15804:2012 (Table 1).

This paper takes a further step towards the integration of LCA principles in the design of ABSs by reviewing the differences between adaptive and traditional façades, highlighting information gaps and focusing on aspects regarding architectural Life Cycle Assessment which are mostly not considered in the ABS research field. The study is based on an analysis of the state of the art of adaptive façades and integrates definitions and classifications with insights on the possible environmental impacts involved, setting the bases for a Life Cycle Inventory. The aim is to give a more comprehensive understanding of the function and the assembly of materials and technological parts of the building skin, but also of the effects each design choice has throughout the phases in the life cycle, and by extension, its impact on the environment. The outcomes integrate the previously mapped framework by Crespi, Persiani, and Battisti (2017), preparing for a complete LCA system for ABSs.

Production stage (A1-A3)	
(A1)	Raw material supply, including processing of secondary material input
(A2)	Transport of raw material and secondary material to the manufacturer
(A3)	Manufacture of the product, and all upstream processes from cradle to gate
Construction stage (A4-A5)	
(A4)	Transport of the products to the building site
(A5)	Installation/construction (of the product)
Use stage (related to the product) (B1-B5)	
(B1)	Use of the product
(B2)	Maintenance of the product
(B3)	Repair of the product
(B4)	Replacement of the product
(B5)	Refurbishment of the product
Use stage (related to operation) (B6-B7)	
(B6)	Operational energy use
(B7)	Operational water use (not relevant for ABS)
End of life (C1-C4)	
(C1)	Demolition (/disassembly) of the product
(C2)	Transport of the waste to waste processing facility
(C3)	Waste processing operations for reuse, recovery, recycling
(C4)	Final disposal of end-of-life product
Benefits and loads beyond the product's boundary	
(D)	Reuse/ recovery/ recycling potential evaluated as net impacts and benefits

TABLE 1 Building LCA stages according to (EN 15804:2012)

2 LITERATURE REVIEW

Existing classifications of adaptive building envelopes are broadly recognised to be partial and few (Loonen,Trčka, Cóstola, & Hensen, 2013; Loonen et al., 2015; Luible et al., 2015; Sachin, 2016). In order to provide an inclusive review and directly address the aspects relating to LCA, the research is structured according to the method of data analysis of the 5 Ws (Creswell, 1998), aimed to identify basic questions that are relevant to the topic for information gathering and problem solving (Who, What, Where, When, Why, How). With the overview of the ABS classification systems taken as a base, the study proceeds to redefine ABSs from an LCA perspective by answering the research questions in Table 2. Questions Who and Why are answered by the body of the paper and are therefore not further developed.

ABS	ABS IN TERMS OF LCA	LCA STAGES INVOLVED[1]
What?		
1. What is commonly defined as an ABS? 2. What are ABSs in terms of LCA?	- Which parts compose an ABS and how are these assembled? (Fig. 2)	A1-A3 Production stage B6 Operational energy use C3 Waste processing C4 Final disposal, end of life D Reuse/ recovery/ recycling potential
	-.How are distinctions adaptive/static, active/passive relevant in LCA?	
Where?		
3. At which component level, and where in the façade are adaptive proprieties integrated?	- Which are the most common ABS technologies and materials? (Fig. 3)	A3 Manufacturing A4-A5 Construction stage B2-B4 Use stage C1 De-construction demolition D Reuse/ recovery/ recycling potential
	- At which scale of the building skin is adaptivity integrated? - Are users involved in the operation of the technology?	A3 Manufacturing A4-A5 Construction stage B2-B4 Use stage B6 Operational energy use C1 De-construction demolition
How?		
4. How does the adaptation work? (Fig. 4, Fig.5)		A1-A3 Production stage B2-B4 Use stage B6 Operational energy use
When?		
5. Within which timeframe do adaptive processes occur?	- What impact does the timing of adaptation have on LCA? (Fig. 6)	B2-B5 Use stage B6 Operational energy use C1-C4 End of life
	- How can adaptive processes be assessed for an LCA?	B6 Operational energy use

[1] *Life cycle stages according to the European Standards EN 15804 (2012) (Refer to Table 1).*

TABLE 2 'Ws' research questions

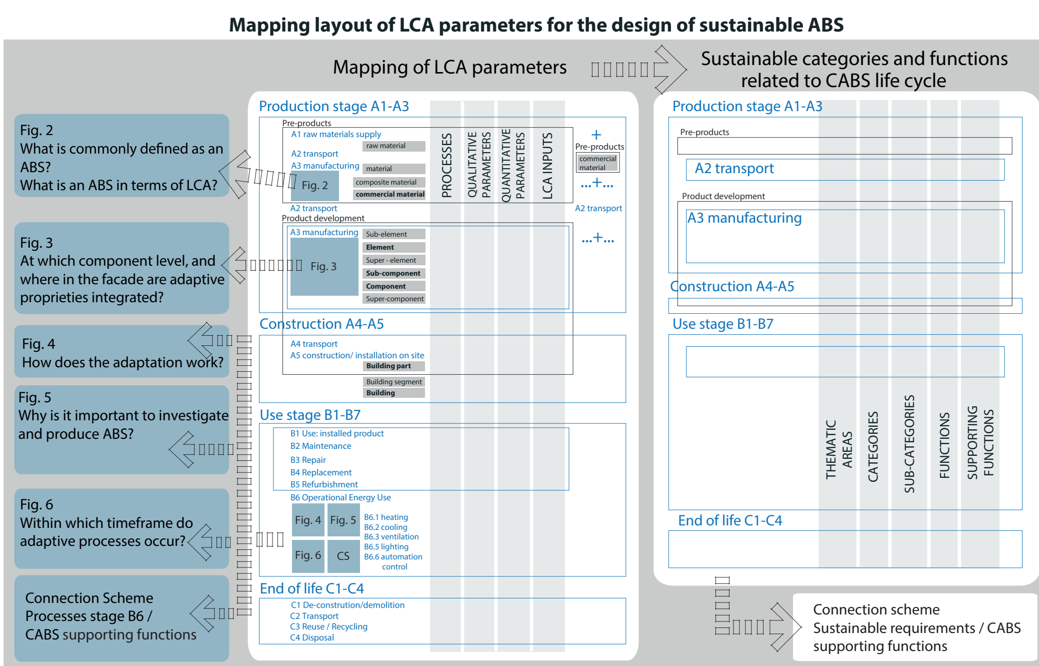


FIG. 1 General mapping of the LCA process and parameters for ABSs (from Crespi et al., 2017), with the layout of how Figs. 2-6 in this paper can be included in the mapping.

The main aspects characterising ABSs in an LCA perspective are summed up in five infographic representations (Figs. 2 - 6), that can be further included in the mapping framework (Fig. 1).

2.1 DATA COLLECTION

Data collection was conducted by reviewing databases such as ScienceDirect, Scopus, and ResearchGate. Among the keywords searched were: adaptive, innovative, dynamic, responsive, climate, building envelope, façade components, building shells, building skins, LCA, materials, and photovoltaic. The academic literature was reviewed following two main paths:

- an inductive method based on a qualitative data collection aimed at answering the research questions;
- a deductive method starting from the aforementioned descriptions of adaptive building envelopes.

In a first step, a broad range of academic publications were selected based on the innovative technologies introduced in the building envelope. Although not directly mentioning 'Adaptive Building Skins', these allowed for the incorporation of a great number of technological solutions that are effectively employed in ABSs, such as photovoltaic systems, which are among the most widespread technologies in active façades. The importance of identifying a method of classification used for existing envelopes' products lies in the possibility of highlighting shortcuts to available information on substances' emission data to be further employed in future Life Cycle Inventories for ABSs (such as the Ecoinvent database, 2007), without needing to reconstruct the emissions path due to the individual production processes of the materials making up the product.

In a second step, the research focused on the more recent findings on adaptive façades, examining only literature published after 2012. The literature was classified by topic, terminology, and methodological approach used (Technological, Life Cycle, Systematic, Biomimetic). The outcomes are summarised in the annexes. This approach helped to identify the many nuances the concept of ABS spans, not necessarily related to specific technological solutions.

2.2 STATE OF THE ART REVIEW

The study of the existing literature on adaptive façades reveals a very broad understanding of these technologies, although, in many cases, 'adaptiveness' is not directly mentioned. Definitions and classifications reveal the recurring features and characters typical of ABSs that are important to take into consideration within the LCA. Existing and emerging building skin technologies have been classified, of which two main aspects were identified:

- A classification of the physical features (Tucci, 2012), with innovative materials to building parts categorised according to behaviour (active/passive) and appearance (opaque, semi-transparent, translucent, transparent).
- A classification of the functional behaviour (Loonen et al., 2015 & 2013) listing eight basic criteria for façade adaptivity: goal, responsive function, operation, technologies (materials & systems), response time, spatial scale, visibility, and degree of adaptability.

The annexes give a further overview of how the collected literature has addressed the evolution of building envelopes through a technological, biomimetic, or systematic approach. The multiplicity of approaches is indicative of the interdisciplinary nature of the topic and the broad category of technologies employed in ABS.

Emerging technologies identified by the literature review (detailed list in annexes) require further integration in ABS inventories to enable a further mapping in terms of LCA. These can be subdivided into three macro-families:

1. Façades that integrate renewables, from solar façades (Quesada, Rousse, Dutil, Badache, & Hallé, 2012a &b), solar cooling (Prieto, Knaack, Auer, & Klein, 2017), Building Integrated Solar Thermal (BIST) technologies (Zhang et al., 2015), and dynamic Building Integrated PhotoVoltaic systems (BIPV) (Jayathissa, Jansen, Heeren, Nagy, & Schlueter, 2016; Curpek & Hraska, 2017).
2. Active building envelopes, integrating smart glasses and motor-based shading devices (Sachin, 2016), robotic materials that combine sensing and controlling features (McEvoy & Correll, 2015), IOT sensor network systems and the several devices associated with them (e.g. sensors, actuators, controllers) (Konis & Selkowitz, 2017).
3. Passive stimuli responsive materials and components. Although being mostly at an experimental stage, these elements are considered to be of strategic importance for the coming generation of ABS. Examples are hygromorphic materials, Phase Change Material (PCM)-based mortars (Curpek & Hraska, 2017; Koláček, Charvátová, & Sehnálek, 2017), self-shading building tiles with shape memory polymers, etc. (among others Aresta, 2017; Bridgens, Holstov, & Farmer, 2017; Clifford et al., 2017; Mao et al., 2016; Persiani, Molter, Aresta, & Klein, 2016b; Ribeiro Silveira, Louter, Eigenraam, & Klein, 2017).

With such a broad variety of technologies and functions characterising adaptive building envelopes, it is understandable that many sibling concepts are used to describe adaptive systems. Adaptive Building Skins are described from a systematic point of view as sets of interacting parts with specific multiple functions, behaviours, and goals. The most diffused way to distinguish between types and categories of adaptive envelopes, however, is to identify their purpose and the dynamic behaviour of the components. Climate Adaptive Building Shells (CABS), for instance, address more specifically the energy efficiency and performance of the building envelope (Loonen et al., 2013).

The review also highlighted further directions for developing ABSs in terms of sustainability.

- A number of studies were reviewed where the generation of design concepts is tackled through a biomimetic problem-solving methodology (Wang, Beltrán, & Kim, 2012; Persiani, Battisti, & Wolf, 2016; Badarnah, 2012, 2016, 2017). From an LCA point of view, investigating the relation Environmental agents – means of adaptation – Building functions – Operation of the technology – LCA can create a systematic design-oriented framework open to innovative and creative concepts. These concepts have been introduced in the early design phases in previous research through a preliminary (simplified) systematic LCA mapping (Crespi, Persiani, & Battisti, 2017). The framework, built on a method for the design and construction of integral façades, aims to enable decision-making in the early design phases of adaptive envelopes and introduces LCA optimisation through an evolutionary design method with a multi-objective solution finding.
- A new methodology which is widely recognised as a reliable means of data acquisition, information feedback, and a solid base for decision making in the context of sustainable design and LCA is Building Information Modelling (BIM). The model enables cross referencing of graphic and numerical information of the building and its parts, allowing not only the system to be controlled during its design and construction phase, but also allows it to be managed throughout its complete lifecycle (Soust-Verdaguer, Llatas, & García-Martínez, 2017; Volk, Stengel, & Schultmann, 2014).

- Research reveals that no single mitigation strategy alone can tackle the problem of transiting to a low-carbon built environment. A pluralistic approach is absolutely necessary, combining better design, the use of low-Embedded Carbon (EC), and reuse of high-EC materials together with stronger policy drivers (Pomponi & Moncaster, 2016).

The State-of-the-Art review underlines four topics of importance for ABS in terms of LCA:

- Different classifications of ABSs and ABS technologies, highlighting possible shortcuts to available information on substances' emission data to be further employed in future Life Cycle Inventories for ABS;
- A list of emerging technologies to be further integrated in ABS inventories and mapping of ABS in terms of LCA;
- Commonly shared definitions of ABS;
- Directions for further development: the biomimetic approach, integration of information through BIM, and a pluralistic approach.

What appears to be missing in the State of the Art is the implementation, comparison, and alignment of the terminology of building products with those in BIM libraries and standards. This would allow a shared base of understanding through the different design and simulation software, from design to facility management, and greatly facilitates the LCA process.

3 ADAPTIVE BUILDING SKINS FROM AN LCA PERSPECTIVE

In order to describe which aspects are relevant for ABS in terms of LCA in a straightforward way, the study is structured through thirteen research questions listed in Table 2.

3.1 WHAT IS COMMONLY DEFINED AS AN ADAPTIVE BUILDING SKIN?

Adaptive façades, or adaptive building envelopes, is a general term used to refer to a new generation of multifunctional façade systems that are able to change their function, features, or behaviour over time in response to transient performance requirements and boundary conditions with the aim of improving the overall building performance (COST Action TU1403, 2018; Persiani et al., 2016a). This emerging research area can be found at the crossroads between environmental architecture, building technologies, and artificial intelligence. As in all emerging fields, the first stages are characterised by an non-uniform variety of terms and definitions with analogous meanings. Adaptive Building Skins (ABS), Climate Adaptive Building Shells (CABS), Adaptive Façades, Autoreactive Façades, and Acclimated Kinetic building Envelope (AKE) are just a few of the many sibling concepts that can be found in the current State of Art. These terms describe variations of entities within the same family of technologies with a common 'blueprint concept', highlighting and focusing on some aspects more than others.

There are four definitions of ABS indicated in the reviewed studies (Wang et al. 2012; Badarnah, 2012; Loonen et al., 2013; Persiani et al., 2016a). While the wording has evolved over time, the core of the concept is mostly shared. The definition focuses on goals and performances to be achieved in a responsive way by the building envelope, which is described of as a system of parts. Physical characteristics or technological solutions are not mentioned, although built examples are given in some cases. The aesthetics of the movement are not considered central to the definition, its potential to involve the users and raise awareness with a positive impact on behaviour is however widely recognised. This approach is shared for the purpose of this research, as it gives the opportunity for façade designers to have unlimited creative boundaries inside a systematic framework driven by specific performance goals and dynamic behaviours.

3.2 WHAT ARE ABSs IN TERMS OF LCA?

As mentioned previously, ABSs enable dynamic responses to changing environmental conditions, boosting indoor comfort and energy performances in the Operation stage (B6) but should also contain environmental impacts in the other life cycle phases, such as Production, Use of the product (B1), Maintenance (B2-B4), Refurbishment (B5), and End of Life (C1-C4), in order to fully justify their use. On the one hand, LCA is a means to measure the real impact of ABSs on the environment, and on the other hand it is a tool to optimise its design, initiating a cycle of experimentation and verification (Table 3). Among many objectives, an LCA identifies opportunities to improve the environmental performance of products at various points in their life cycle (ISO 14040 & 14044 2006). Adaptive Building Skins can therefore be redefined in the broader perspective of the entire life cycle where 'adaptivity' assumes a broader meaning, involving the conservation of natural resources and the reduction of pollution.

DESIGN TARGET	REDUCES IMPACT ON LCA PHASE														
Use low-EC materials	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Use of local materials		X		X					X	X					
Use renewable materials	X								X	X					
Use of materials with low processing energy	X		X												
Include waste, by-products, and used materials	X	X	X												X
Design for disassembly	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Enable re-use and recovery of materials (especially of EE/EC materials)								X	X	X		X		X	X
Enable refurbishment of existing structures extending the product's life							X	X	X	X		X	X	X	X
Develop more efficient construction processes / techniques	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Increased use of prefabricated elements/off-site manufacturing					X	X	X	X	X	X		X		X	
Prefabricate bigger parts of the façade					X				X	X					
Design for autoreactivity	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Enable operation at zero energy						X					X				
Dynamics are embedded in the material, reducing the number of parts	X	X	X	X	X	X	X	X	X	X					

TABLE 3 Design targets to reduce the impact on different phases of the LCA

Adaptive building envelopes are multifunctional façade systems able to change their features or behaviour over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall performance of the building, while contributing to the reduction of the environmental impacts in all the phases of the building's life.

As previously pointed out, ABSs are strongly focused on energy efficiency in the operational energy use phase (B6). For a full LCA approach, it is necessary to identify and evaluate which among the commonly adopted technologies, components, and materials can have a significant impact on the other phases in the life cycle. High-tech components for instance typically have a shorter lifecycle than that of the building and become obsolete increasingly quickly as newer products are developed, with the common side effect of a higher impact on the production (A1-A3) and maintenance phases (B2-B4) of the system.

When designing new ABS technologies, the main variations on LCA impacts can be expected in the following phases (see also Table 3):

- Production phase (A1-A3), due to use of resources to produce specific components, elements and materials, rising complexity and use of high-tech materials to achieve kinetic façade components, etc.
- Construction phase (A4-A5), depending on the effectiveness of the assembly (and disassembly) of the product, construction times, and resources can be reduced.
- Maintenance, Repair, and Replacement phases (B2, B3, B4) and the End of Life phase (C1-C4) can be strongly impacted through designing for disassembly (especially of interest for the replacement of kinetic parts in ABSs).
- Benefits and loads in the phase of Reuse/ recovery/ recycling (D) are mainly considered beyond the product's boundaries, as it enters another system's life cycle when integrated under any of the three forms.

3.2.1 Which parts compose an ABS and how are these assembled?

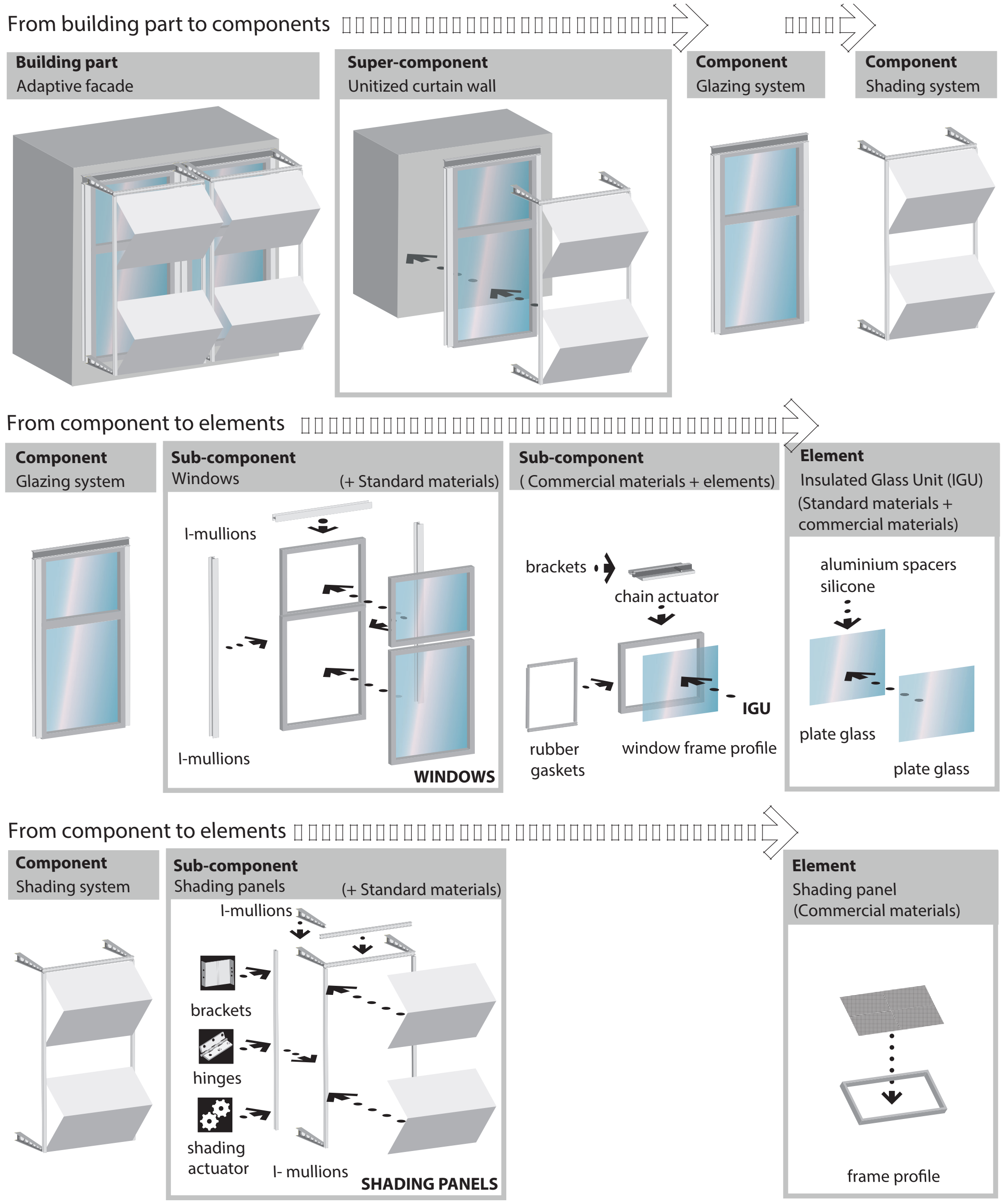


FIG. 2 Study of a hierarchical disassembly of a basic façade unit composed of glazing and dynamic shading (based on *Klein, 2013*). LCA stages involved: (A3-5), (B2-4), (C1), (D).

3.2.2 How are distinctions adaptive/static, active/passive relevant in LCA?

There are fundamental differences between active and kinetic, adaptive and static systems. 'Active' and 'passive' refer to the energy requirements of the technology: while an active system is powered though an input of energy (mainly electrical), a passive system uses the latent energy from its surroundings (as for thermal Phase Change Materials) (Persiani et al., 2016a). 'Adaptive' and 'static' refer to the physical capacity of the material or the technology to change in determinate conditions. Because of the tendency to design increasingly complex façade systems, the boundaries between active and passive systems slowly disappear: adaptive properties are no longer characteristic of active systems, as latent energy reaction can now also be enabled in passive systems (Persiani et al., 2016b). In an LCA, these characters need to be considered, including stratigraphic façade solutions (like shaded double-glazing systems) and spatial structures with climate-regulating purposes (like greenhouses), which may reduce the impacts in the production phase (A1-A3).

3.3 AT WHICH COMPONENT LEVEL, AND WHERE IN THE FAÇADE ARE ADAPTIVE PROPERTIES INTEGRATED?

A great variety of aspects in an LCA depend on the hierarchy of the parts in the ABS, on the assembly methods and above all, the wear of elements or components. A designer aware of these processes can effectively have an impact on:

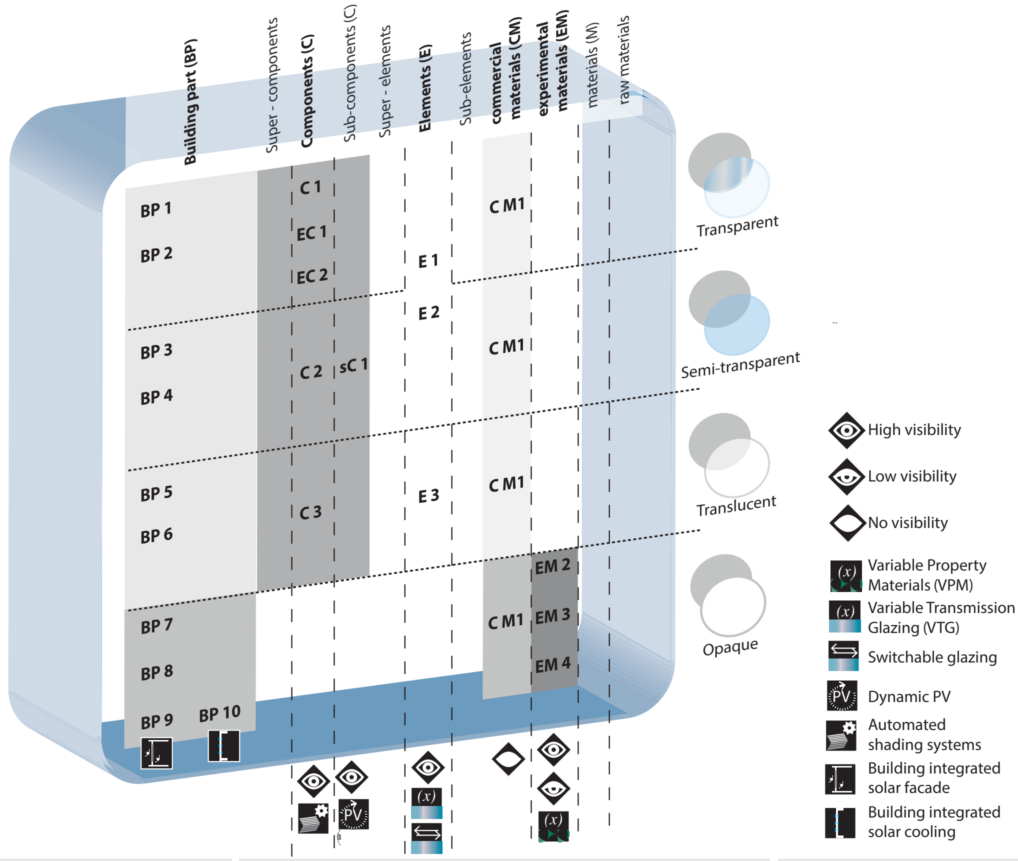
- Controlling at which stage in the production chain the manufacture and assembly takes place (in factory / on site), with the related impacts;
- Design disassembly to reduce impacts in the Use stage (B2-B4), simplify maintenance and repair, avoiding the replacement of a whole when only part is damaged;
- Design disassembly for deconstruction (C1), maximising the possibility of reuse, recycling, and separate materials that need special disposal.

Static envelopes are also included in this framework (traditional passive spatial solutions in Fig. 3), being the technical base for many technologies. These can be implemented with adaptive elements, components, or materials, and can be used as reference for future solutions. The main purpose with identifying these solutions is to highlight the presence of elements with a substantial impact on the production and maintenance phase.

3.3.1 Which are the most common ABS technologies and materials?

Technologies. The most commonly used technologies are different types of glazed components with shading systems (C1 - C3) that may also include elements with controlled solar light and heat transmittance (such as chromogenic E1 - E3).

Mechanical ventilation systems can be found in some static and dynamic building façade technologies (Building Part - BP2) as well as energy generating components (BP3, BP4, BP7, BP8, BP9). A new trend is represented by Building Integrated solar cooling technologies (BP10), where the cooling system, integrated in the façade, also generates energy through solar electrical or solar thermal processes. The cooling generation principles are several (thermoelectric cooling, absorption cycle, indirect evaporation, vapour compression) and the transfer medium can be either solid-based, water-based, or air-based. The delivery systems, depending on the medium, are radiative walls, mounted pipes, induction units, diffusers, or may be absent. In this case, ABSs include HVAC systems and the Life Cycle impact might be consistent.



Building Parts (BP) related to static envelopes

BP 1. - Naturally ventilated transparent facade (NVTF)
BP 2. - Mechanically ventilated transparent facade (MVTF)
BP 3. - Semi-transparent building-integrated PV system (STBIPV)
BP 4. - Semi-transparent building-integr. PV thermal system (STBIPV/T)
BP 5. - Thermal storage wall
BP 6. - Solar chimney
BP 7. - Building-integrated photovoltaic system (BIPV)
BP 8. - Building-integrated solar thermal system (BIST)
BP 9. - BiPV thermal system (BIPV/T)
BP 10. - Thermo-electric facades

Components (C), Elements (E), experimental/commercial materials (EM/CM) related to dynamic systems

sC 1. - dynamic PV
C 1. ventilated double skin facade (DSF) with shading system
C 2. - Prismatic louver
C 3. - translucent ventilated with chromogenic glass & shading system
EC 1*. - autoreactive components
EC 2*. - Ventilation units with PCM for vdsf

E 1. - Chromogenic: Photochromic, Electrochromic, Thermochromic, Gasochromic Chromogenic / angular selective glass
E 2. - SPD smart windows
E 3*. - VTG under development: Micro - ElectroMechanical Systems

CM 1. - Phase Change Materials

EM 1*. - VPM under development:
Shape Change Materials (SCP)
Thermal Expansion Materials (TEM)
Thermobicomposite Materials (TBM)
Shape Memory Foam (SMF)
Shape Memory Ceramics (SMC)
Shape Memory Biosystems (SM-BS)
Bicomposite materials (BM)
Absorbent Polymers (Aps)
Superabsorbent Polymers (SAPs)
Wood based hygromorphic materials
PCM - based mortars
Thin glass
EM 2. - Shape Memory Polymers + Shape Memory Alloys
EM 3. - Shape Memory Polymers + Hydrogel
EM 4. - Thermobimetal

Other most used materials (M)°

M 1. - 3. Wood
Derived timber products
M 2. - 4. Metals
Steel products, Aluminium, Zinc , Lead
M3. - 6. Plastics
Profiles, Elastic plastic profiles, Foils and fleeces, Sealing materials
M4. - 7. Components for windows and curtain walls

* materials, elements and components under development

° Classification from the Ökobau database, built on Gabi database

FIG. 3 Systematic illustration of the typologies of ABSs, with classified the most widespread technologies and materials (classification from the Ökobaudat database). LCA stages involved (A1-3), (B6), (C3-4), (D).

Material innovation in construction depends, to a large degree, on technological improvements in other manufacturing sectors (such as medical or communications). A number of reviewed publications list new materials used in the context of adaptive façades (refer to the literature review in the annexes). During the production phase of the envelope, the most used materials are glass, aluminium, and inorganic polymers for films and textiles, of which the energy embodied in the manufacturing process is hardly ever taken into consideration. However, in 2017, an Environmental Product Declaration (EPD) on an ETFE-based cladding system was published, showing growing concern and interest of stakeholders for environmental issues (Maywald, 2017).

At the current rate of technological development grow rapidly obsolete, the long-term sustainability of specific high-tech solutions becomes challenging with respect to both the Production phase (A1-A3) and to the End of life scenarios (C1-C4). Adaptive materials (EM1 - EM4) for instance, are able to change their physical features in reaction to the action of external agents (humidity, heat, radiance, etc.). These are mostly under development for the field of building technologies, with few exceptions (as PCM, that are already available on the market). The category is expected to grow increasingly wider, adding on new technologies making use of them. In order to fully evaluate the sustainability of these materials and technologies more specific LCA studies are needed.

3.3.2 At which scale of the building skin is adaptivity integrated?

Adaptivity can be manifested either at material or at component scale. Designing for disassembly allows the adaptive parts to be easily removed and replaced, benefitting the life cycle of the whole façade as:

- adaptive parts tend to become worn out more quickly when compared to static solutions, because of their changing characters (as for kinetic adaptivity). Moreover, the duration and resistance of these new materials has not been tested over many years of use;
- technologies grow obsolete increasingly quickly, and disassembly allows adaptive materials or parts to be replaced with more advanced solutions without changing the whole façade system.

So far, major innovations on adaptivity have been developing at material scale, followed by a few categories of elements and components such as chromogenic glasses and shading devices that have existed for many years on the market.

3.3.3 Are users involved in the operation of the technology?

The possibility of users directly interacting with the functioning and the dynamics of ABSs introduces the question of whether the LCA should address the Operational energy use (B6) from a qualitative or a quantitative point of view. As comfort is a very subjective matter, it is difficult to achieve optimal conditions that satisfy all users. From a qualitative point of view, users are therefore often enabled to intervene and bypass the system (e.g. opening the windows for ventilation).
On the other hand, when users are allowed to override the set conditions, the quantification of energy consumption (lighting and HVAC) becomes difficult to control and is likely to rise. Building automated domotic monitoring systems have been suggested as high-tech solutions, that are however difficult to evaluate from an LCA point of view, as the system is tailored to the users and the potential variations are infinite.

Distinctions between transparent and opaque elements can give additional information on the performance, as a common low-tech way to introduce adaptivity is through visual and thermal permeability. The increased daylighting and thermal performance have a varying range of energy efficiency, which very much depends on use.

3.4 HOW DOES THE ADAPTATION WORK?

ABSs are programmed to adapt to surrounding environmental conditions and transfer energy in different forms (radiant, kinetic, potential) to achieve human comfort requirements. The great majority of ABSs are actuated through systems of sensors that analyse the surrounding conditions, communicating with a control unit that takes simple decisions and orders counter-actions. To these systems belong HVAC technologies and active building systems.

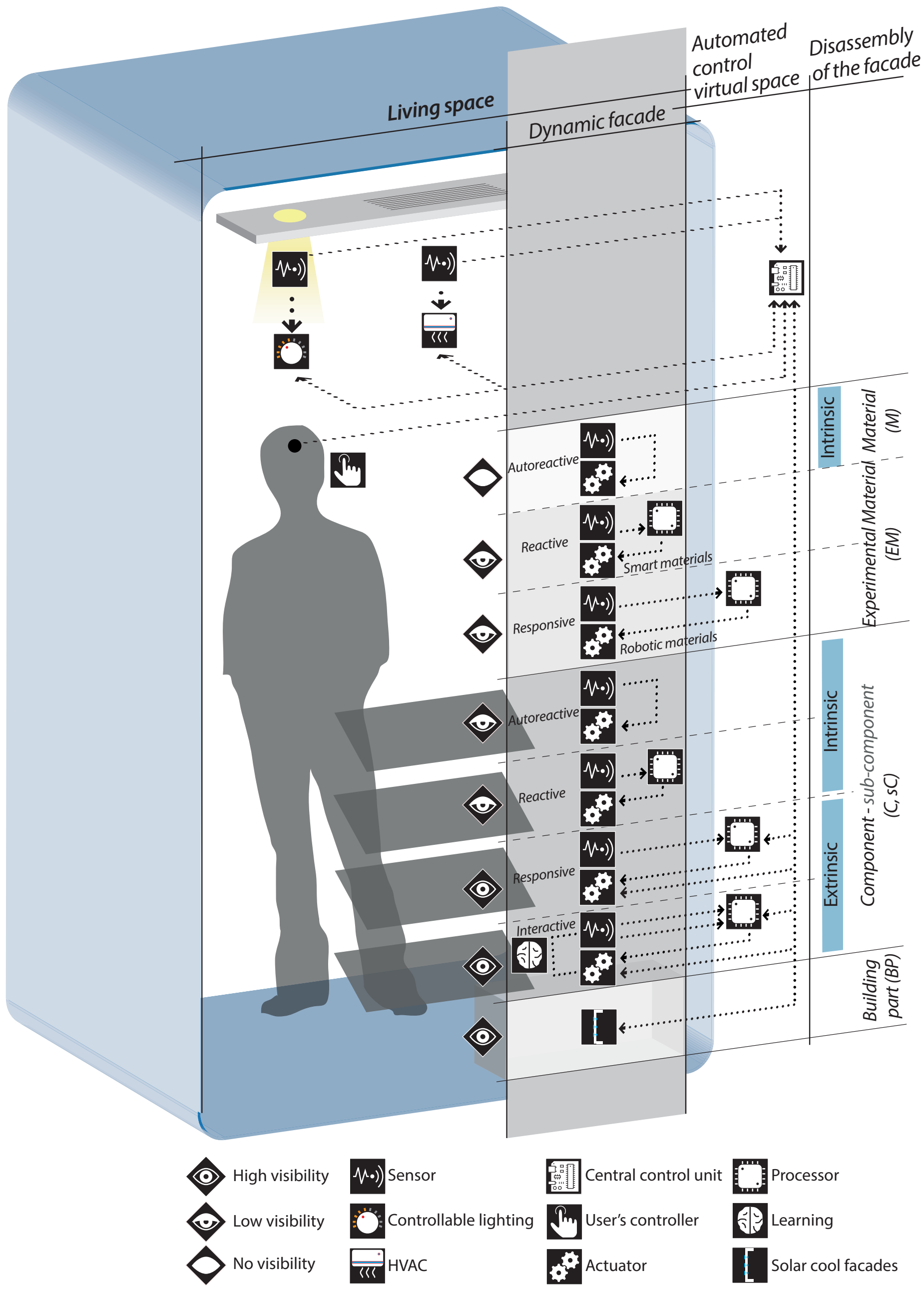


FIG. 4 Systematic illustration of the typologies of ABS through the possible variations in adaptivity (adapted from *Konis & Selkowitz, 2017; Loonen et al., 2013; Loonen et al., 2015; Persiani et al., 2016a*). LCA stages involved (A1-3), (B2-4), (B6)..

Research goals are generally aimed at improving ABS effectiveness by reducing uncontrolled user behaviour and energy (HVAC, lighting, and plug loads) through the integration of smart materials and systems. In continuous dynamic skins, users' interaction is often enabled through an Energy Management and Control System (EMCS), which on one hand aims to optimise but on the other adds up to the energy consumption during the usage phase being an active system.

Developing trends are energy-generating kinetic devices (as dynamic PV sub-components) and unpowered kinetic features that are however still in a prototyping phase (Persiani et al., 2016b). These latter technologies, referred to as "autoreactive", lack the control unit and wiring as reactions to specific stimuli are predetermined and embedded in the material itself. These systems react to latent energy conditions and can therefore be considered as high-tech passive systems requiring zero-energy in the Operational energy use phase (B6). Moreover, the reduction of wiring and Information Technology devices noticeably reduces the impact on the Production stage (A1-A3) and the Use stage (B2-B4).

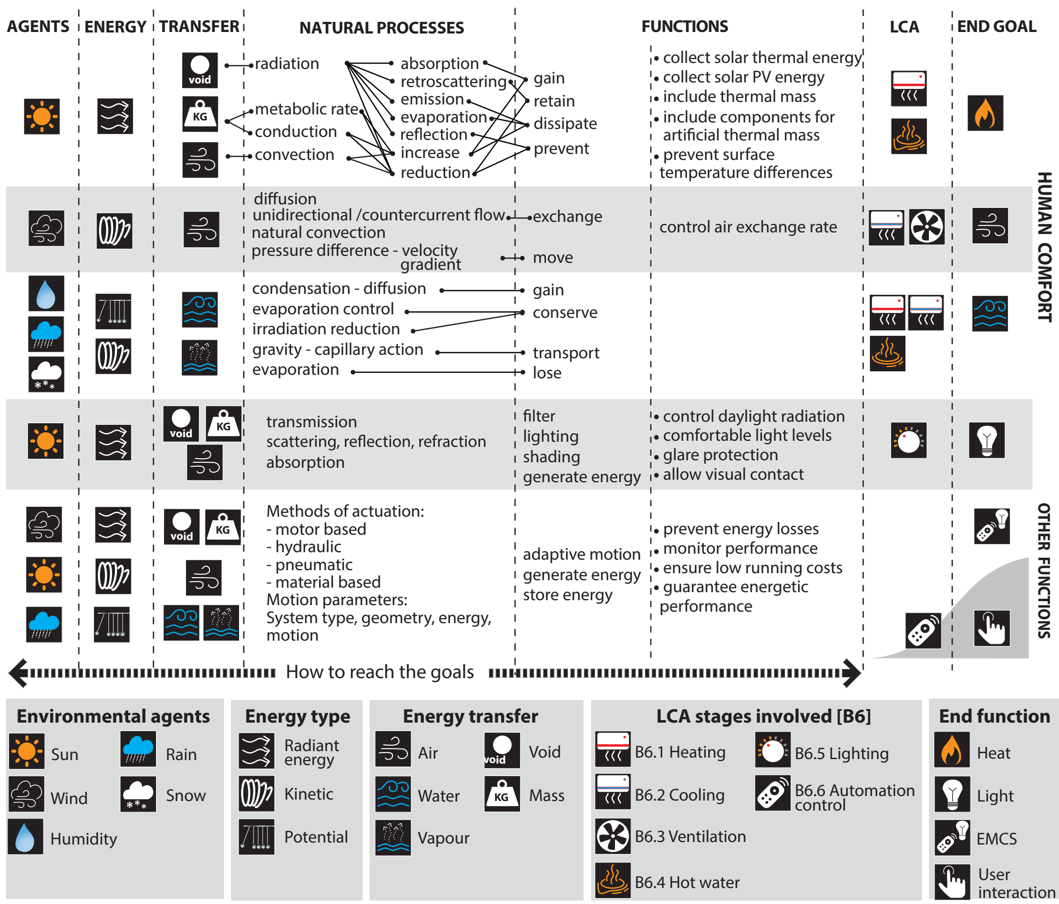


FIG. 5 Summary of the connections between environmental agents and ABSs final goals highlighting the means of energy transfer and the LCA processes involved (B6) (summarised from *Badarnah 2012, 2016, 2017; Persiani et al., 2016a*).

3.5 WITHIN WHICH FRAMEWORK DO ADAPTIVE PROCESSES OCCUR?

As adaptive building technologies adapt to both indoor and outdoor changing contexts, the translation of situational information in real time is among its main advantages and purposes. In this framework, LCA should be carried out considering more aspects than those pertaining only to static building skins.

LCAs are mostly based on the collection of a great amount of hard data describing the system through analysis (EN 15804 2012, Ecoinvent database 2007) and includes information on single materials (embodied energy, recyclability potential), material quantities, usage patterns, and stage processes (as extraction, production, maintenance and recycling processes). This quantitative (calculated) data is largely based on assumptions and estimations, wherever more precise information is not available.

Every LCA, however, is affected by a varying degree of uncertainty derived from the cumulative effect of imprecisions either due to lack of knowledge in the available data or to variability in the data. This is why qualitative considerations (transient or subject to interpretation) can play an important role in determining the overall environmental impact of a given object. Soft data refers to human intelligence and behaviour, and is bound to interpretation, contradictions, and uncertainty but is also very useful to understand environmental occurrences and situational nuances. This is why sensitivity analyses, estimating the effects of the choices made regarding methods and data on the outcome are recommended as part of an LCA (ISO 14040 2006, Budavari et al., 2011). Moreover, as the current technologies quickly evolve towards increased connectivity and Internet of Things (IoT), the relationships between hard and soft data become ever more intertwined.

The integration of variated typologies of information – such as user behaviour – into the analysis is therefore all the more interesting in ABS than in more traditional façade technologies.

3.5.1 What impact does the timing of adaptation have on LCA?

To achieve environmental comfort, the technology will ideally perform better if it can be adjusted more continuously, calling for a very reactive technology that will adapt within short timeframes. From an LCA point of view, however, constant reactivity in active ABSs also means constant use of energy resources, as well as rising maintenance issues due to the frequency of usage.

Energy use in ABSs is hypothesised in Fig. 6, referring exclusively to active systems, as passive systems are intended to operate at zero energy. Timeframe parameters (from Loonen et al., 2015) as seconds, minutes, hours, day-night, and seasons refer to climate adaptivity, while years and decades refer to the capacity of extending the life of building parts through maintenance, repair, replacement, or refurbishment.

ABSs are expected to have a higher energy cost the faster and the more frequent the adaptations, as reacting within seconds requires the system to be constantly ready for change. Moreover, fast movements typically require active and more complex energy-intensive brain elements (Persiani, 2018).

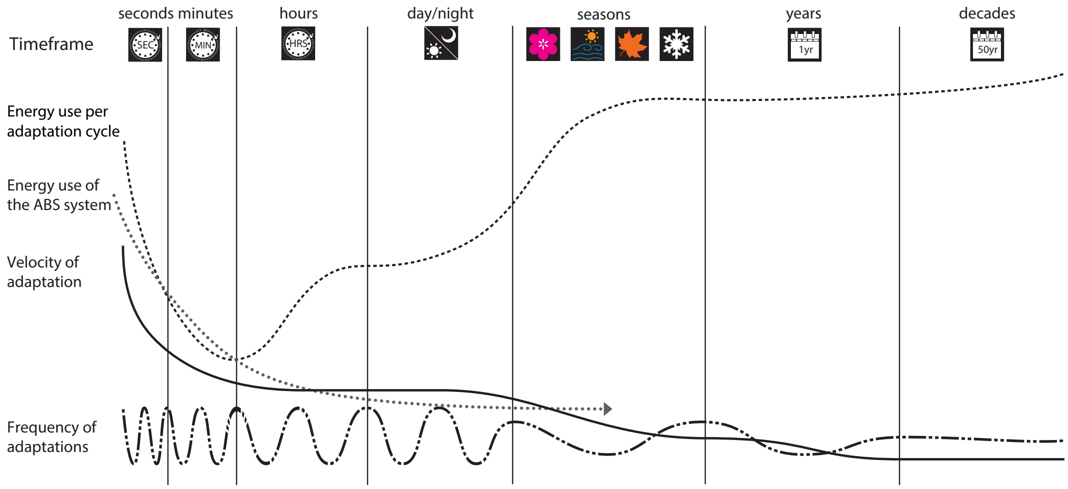


FIG. 6 Temporary and metabolic framework of adaptations in ABSs (timeframe, number of adaptations and hypothesised energy intensity). LCA stages involved (B2-6), (C1-4).

In view of optimising the relationship energetic expenditure/adaptive output, the metabolic cost (energy use per adaptation cycle) of the reactions is hypothesised in relation to the adaptation timeframe. By observing the energy expenditure in animal gaits, where each mechanism reaches its optimal relationship between energy expenditure and kinetic output at specific speeds (Persiani, 2018), the energetic cost per adaptation in ABSs is suggested as higher at slow and very fast speeds. What is of interest is to highlight these aspects in the context of an LCA, where the balance between product's lifespan and operational energy phase must be reached.

3.5.2 How can adaptive processes be assessed for an LCA?

The definition of ABSs being characterised by their specific functioning – and not as many other systems, a set of parts – is in this context of great relevance. It is not only the embodied energy of the system that is of interest, but also its potential to reduce the environmental impacts on the usage phase. For this, other methods of calculation are needed. Adaptive processes can be considered as peculiar characteristics in the façade system and can be assessed separately in the Operational energy use phase (B6). The methods of assessment and calculation of the adaptive features play a decisive role in the evaluation of an LCA, when compared with traditional façades, and hence also in the design of the technology. Assessment of the energy-intensity of ABSs in the Operational energy use stage (B6) is achieved through dynamic simulations during the design phase and is confirmed through monitoring during usage. Post occupancy reports also help to evaluate the optimal response time in relation to the user's ability to intervene in the regulation of ABSs, and whether it interferes negatively with the targeted energy efficiency. For all other life cycle phases (A1-A5, B1-B5, C1-C4) the methods of calculations are essentially the same for ABS as for traditional façades, which, however, does not mean that the results are the same, as the inputs can vary substantially.

4 CONCLUSIONS

The research has suggested an understanding of current and emerging ABSs and their functioning, focusing on aspects regarding LCA which have been mostly unconsidered up to now. The following points have been highlighted:

- ABSs are described as systems characterised by sets of interacting parts with specific multiple functions, behaviours, and goals. An integration to the definition is suggested to include "containing the environmental impacts in all the phases of the building's life" in the scope of the technology. Illustrations of the typologies of ABSs and a summary of the connections between environmental agents, energy transfer, LCA processes, and ABSs' final goals are provided.
- Adaptivity is either integrated by designing completely new technologies and uses or optimising traditional passive building systems with adaptive features. However, as increasingly sophisticated adaptive technologies are developed, the boundaries between active-dynamic and passive-static systems blur.
- The integration of variated typologies of information, as situational and real time information is among the main advantages and purpose of ABSs. Both quantitative and qualitative assessment, such as dynamic simulations and information on user behaviour, play a decisive role in LCA the evaluation of the technology.
- Energy use in ABSs is hypothesised in terms of metabolic costs (energy use per adaptation cycle) through the relationship energetic expenditure/adaptive output.
- LCA is suggested as a tool to optimise the design of ABSs by identifying opportunities to improve the environmental performance of products at various points in their life cycle. To effectively enable LCA as a design and verification tool in ABSs, a number of knowledge gaps need to be filled:
- The terminology and ontology of a building's products need to be implemented for an effective comparison with BIM libraries and standards in order to allow for a shared base of understanding from design to facility management, through the different design and simulation software.
- Future developments of smart materials need to be further investigated in terms of LCA to provide good databases of knowledge to support the integration of new adaptive features in façade technology.
- Designers need to be more aware of the hierarchy of parts, the processes of production, assembly, and the end of use of these technologies in order to be enabled to effectively design better and support industry to develop sustainable solutions. Specifically, designers can contribute by carrying forward specific design targets able to reduce the impact on different phases of the LCA. A study of a hierarchical disassembly of a basic façade unit is provided.

This system mapping is not intended to be exhaustive, but as a base for further implementation on the basis of stakeholders' needs. It is a first step to facilitate the process of Life Cycle Inventory during LCA and Life Cycle design. Adaptive building skins' energy-saving behaviour need to balance out its environmental impacts during the production, the usage, and the end of life phases to be considered fully sustainable. As adaptive envelopes can be expected to extensively grow in use and address an increasingly wider range of building technologies and construction scales, from building parts to components, the need for LCA to support ABS research and development greatly increases. Indeed, with the purpose of broadening the approach to ABSs and consider the full range of their environmental impact, this study will be the basis on which to carry out a comparative analysis between traditional and adaptive façades.

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Annexes

INNOVATIVE TECHNOLOGIES FOR THE BUILDING ENVELOPE					
Author	**Year**	**Topic**	**Approach**	**Answers to Ws**	**Terminology**
Quesada et al.	2012a	Review of solar façades	Technological	What	Building-integrated solar thermal system (BIST); Building-integrated photovoltaic system (BIPV); Building-integrated photovoltaic thermal system (BIPV/T); Thermal storage wall; Solar chimney
Quesada et al.	2012b	Review of solar façades	Technological	What	Mechanically ventilated transparent façade (MVF); Semi-transparent building-integrated photovoltaic system (STBIPV); Semi-transparent building-integrated photovoltaic thermal system (STBIPV/T); Naturally ventilated transparent façade (NVTF)
Tucci	2012	Innovative materials and components	Technological Systematic	What Where	Innovative technologies; Variable Property Materials VPM: TIM, PCM, Dynamic gel; Variable Conduttance insulation VCI, Aereogel, Dielectric glass; Variable Transmittance Glass VTG, Variable Convection Diodes VCD, Chromogenic glass, Prismatic panes and films; Dynamic Trombe Walls; Shading systems.
Klein	2013	Integral Façade Construction	Technological Systematic	What Where Why	Integral Façade; Systematic design; Product levels; Supporting functions
Zhang et al.	2015	BIST and applications	Technological	What Where How	Building Integrated Solar Thermal (BIST): air based, water based, refrigerant based, PCM based
ADAPTIVE FAÇADES					
Badarnah	2012	Biomimetics for building enve-lope adaptation	Biomimetic	Why How	Multi-functional interface: key functions, morphological means, multi-regulation; Environmental challenges; Processes
Wang et al.	2012	Review of Acclimated Kinetic building Enve-lopes (AKE)	Biomimetic Technological	What How	Acclimated Kinetic building Envelope (AKE); Static vs Kinetic; (climate) responsive, active, intelligent, (climatic) adaptive, smart, interactive, (high) performa-tive, kinetic, dynamic; Architectural aesthetics; Solar responsive, air-flow responsive;
Loonen et al.	2013	State of the art Climate Adaptive Building Shells (CABS)	Systematic	What Where How When	Relevant physics; Time scale; Scale of adaptation; Control type; Typology
Loonen et al.	2015	Classification approaches for adaptive façades	Systematic	What Where Why How When	Unified and systematic characterization; Façade classification; Responsive function; Operation: intrinsic, extrinsic; Response time; Spatial scale; Visibility; Adaptability; Dynamic exterior shading and louver façades; PCM glazing; BIPV double-skin
Luible et al.	2015	Common CABS research topics	Mixed	What	PV; Advanced materials; Façade glazing; Façade shad-ing; Control systems; Façade functions
McEvoy & Correll	2015	Materials that couple sensing, actuation, computation, and communication	Technological	What How	Sensing; Actuation; Multifunctional materials; Robotic materials; Shape-changing materials

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INNOVATIVE TECHNOLOGIES FOR THE BUILDING ENVELOPE					
Author	**Year**	**Topic**	**Approach**	**Answers to Ws**	**Terminology**
Vlachokostas & Madamopoulos	2015	Daylighting technology in high-rise commercial buildings	Technological	What Where How	Liquid filled prismatic louver (LFPL);
Badarnah	2016	Light management: lessons from nature	Systematic Biomimetic	Why How	Biomimetic design process; morphological means
Jayathissa et al.	2016	LCA of dynamic BIPV	Technological Life Cycle	What How When	Building-integrated photovoltaic system (BIPV); Adaptive solar façade (ASF); Actuator
Mao et al.	2016	3D Printed Reversible Shape Changing Components	Technological	What Where How	Stimuli responsive materials; Reversibly actuating components; Shape changing components; Shape memory polymers; Hydrogels; 3D printed components;
Persiani et al.	2016a	Autoreactive architectural façades	Systematic Biomimetic	How	Unpowered kinetic building skins; Adaptive systems: responsive, reactive, interactive, autoreactive; Motion parameters: System type, geometry, energy
Persiani et al.	2016b	Adaptive materials and autoreactive building skins (ABS)	Biomimetic Technological	What Where How	Type of energy in the environment: radiant, potential, kinetic; adaptivity in materials: SMP, SCP, TEM, TB, TBM, SCP, SMP, SMA, SMF, SMC, SM-BS, BM, Aps, SAPs
Sachin	2016	Dynamic Adaptive Building Envelopes (DABE): state of the art technology	Technological	What How	Methods of actuation: motor based, hydraulic actuators, pneumatic actuators, material based; Robotic materials; Smart glass
Aresta	2017	Auto-reactive strategies. Materials for innovative façade components	Technological	What Where How	Innovative; Adaptive; Passive; auto-reactive systems; input-Energy and output-Stategy
Badarnah	2017	Environmental adaptation in buidling envelope design	Systematic Biomimetic	Why How	Environmental adaptation; Adaptation means;
Bridgens et al.	2017	Wood based responsive building skins	Technological Life Cycle	What Where When	Wood based responsive; Hygromorphic materials; responsiveness; Reactivity; Actuation capacity; Durability; Sustainability, Aesthetics; Weathering
Clifford et al.	2017	Application of shape-memory polymers to climate adaptive building façades	Technological	What Where How	Shape-memory polymers; Climate adaptive building façades; Dynamic materials; Smart materials; smart tiles
Curpek & Hraska	2017	Ventilation units with PCM for double-skin BiPV façades	Technological	What Where How	PCM; double-skin BiPV façades

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INNOVATIVE TECHNOLOGIES FOR THE BUILDING ENVELOPE					
Author	**Year**	**Topic**	**Approach**	**Answers to Ws**	**Terminology**
Koláček et al.	2017	Thermal Properties of a PCM Window Panel	Technological	What Where How	PCM
Konis & Selkowitz	2017	Advancing façade performance	Technological	What Where How	IOT-based sensor network: dynamic façade, sensor, controllable lighting, user input
Maywald	2017	Texlon ETFE green building factsheets – product data, LEED, BREEAM and DGNB	Technological Life Cycle	What Where When	ETFE foils; ETFE cladding system; EPD; Building certification systems
Molter et. al.	2017	Autoreactive components in double skin façades	Technological	What Where How	Autoreactive components; double skin façades; Adaptive building envelope; closed cavity
Olivieri et al.	2017	Development of PCM-enhanced mortars for thermally activated building components	Technological	What Where How	PCM; Thermal energy storage (TES); Thermally activated building systems (TABS); Radiant wall
Prieto et al.	2017	Solar cool façades, review of solar cooling integrated façade concepts	Technological	What Where How	Solar cooling technologies; integration; high-performance, intelligent, adaptive façades
Ribeiro Silveira et al.	2017	adaptive thin glass façade panels	Technological	What Where	Chemically strengthened Thin glass; Adaptive panels; Lightweight façade; Kinetic façade

TABLE 4 Overview of the Academic Literature