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To whom it may concern,

Hereby I present the Scientific Report related to my Short Term Scientific Mission entitled STATE OF THE ART AND RESEARCH ABOUT ADAPTIVE FACADES that I concluded within COST action TU1403 Adaptive Facades.

The host institution was TU Delft / Faculty of Architecture and the Built Environment and the host responsible person was Dr.-Ing. Tillmann Klein, Associate Professor and Head Facade Research Group.

My mission was developed, as planned, from 9th June to 27th June, 2015.

I take part in this COST Action 1403 as a member of Working Group 1. The main objective of my mission was to make progress in the tasks of the working group with the help and collaboration of the Facade Research Group from TU Delft. I focused in the analysis of existing research about adaptive envelopes to achieve a robust common base of knowledge and this work was expressed in the resulting article I wrote in collaboration with other members of the COST action for Energy Forum 2015.

I attach a copy of the finished article.

My stay was also very productive because it was coincident with The Future Envelope conferences and the Facade Research Group meeting where I could learn about the word methodologies and research topics developed by the group members.

As a proof of the above mentioned I sign this report

In Donostia-San Sebastian, the 21st of July of 2015

José Miguel Rico Martínez

Design for façade adaptability – Towards a unified and systematic characterization

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Abstract

Adaptive facades provide opportunities for significant reductions in building energy use and CO_2 emissions, while at the same time having a positive impact on the quality of the indoor environment. Many different types of adaptive façade concepts (materials, components and systems) have already been developed, and an increase in emerging, innovative solutions is expected for the near future. The goal of this paper is to contribute to these developments by describing activities in EU COST Action TU1403 aiming at the classification of adaptive façade concepts. We present an analysis of existing classification approaches to identify requirements and challenges that are faced in this process. Based on an analysis of strong points in these approaches, we propose a new matrix that can be used to characterize adaptive façade concepts in a comprehensive way. The elements of this matrix are explained with the use of three case studies: dynamic exterior shading facades, glazing with phase change materials and BIPV double-skin facades. We conclude the paper by providing directions for future extension of the characterization matrix and an outline of planned follow-up research activities.

Keywords: Adaptive facade, Responsive facade, Facade classification, Facade performance, Facade characterization, Building envelope.

1. Introduction

Reductions in building energy consumption and carbon dioxide emissions are two of the most important challenges facing the building industry. These must be addressed in a cost effective manner and without compromising occupant comfort and well-being. Building envelopes are positioned at the interface between inside and outside, they have a dominant impact on a building's energy balance and can therefore play a large role in making the transition towards sustainable, energy-neutral buildings [1,2].

Until recently, the main focus in building envelope design and development was on structural, passive and robust performance aspects [3]. Nowadays, however, it is increasingly recognized that more flexible behaviour of the façade is desirable, with keywords shifting to: responsive, adaptive or dynamic [4–6].

This next generation of facades (or building envelopes) consists of multifunctional and highly adaptive systems, where the physical separator between the interior and exterior environment (i.e. the building envelope) is able to change its functions, features or behaviour over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance (Figure 1). Adaptive facades can provide controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading or humidity control. Moreover in the context of nearly Zero Energy Buildings (nZEB) these facades also have to collect and convert available surrounding energy (mainly solar) in an adaptive way, in order to correspond as far as it can to building energy needs (self consumption) [7]. They and are thus considered as a viable alternative for achieving low-energy building operation with high indoor environmental quality.

Research and development activities, as well as practical application of adaptive façade components and systems are growing [8]. There is a critical mass of European knowledge, expertise, resources, and skills in the fields relevant to adaptive facades. However, the research efforts cover multidisciplinary topics and the wide range of novel technologies are scattered across several R&D centres in Europe.

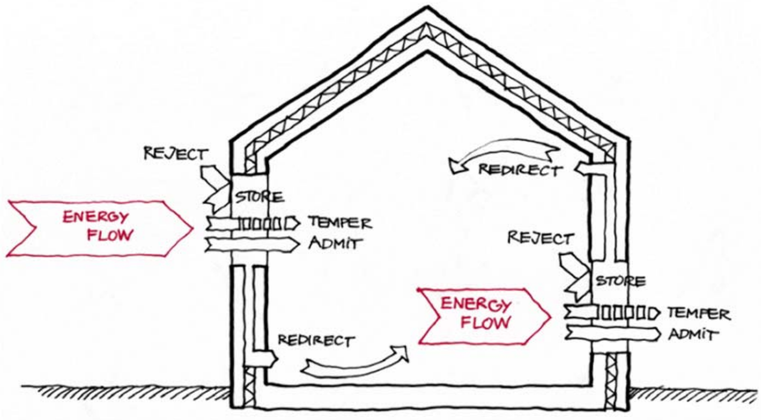

Figure 1. Illustration of the dynamic energy flows and interactions in buildings with adaptive/responsive facades (from: IEA EBC Annex 44, adapted by Fernández Solla [9]*). The energy flows from outside to inside and vice versa can actively be influenced by the adaptive façade technologies (reject, store, temper, admit, redirect, etc.).*

As a result, there is currently a lack of (i) standardized procedures, (ii) design support tools, and (iii) methods for assessing the operational performance and occupant interactions of buildings with adaptive building envelope components. This is a barrier to the widespread adoption of and development of adaptive facades.

1.1 Motivation for increased flexibility and adaptability

The building envelope is at the junction of multiple functions to be performed, multiple factors to which it is exposed and numerous stakeholders in the building process. It must ensure the stability and mechanical strength, health and safety of occupants through the materials composing it (emission of pollutants and fire resistance), contribute to a proper levels of acoustic, visual and thermal comfort and ensure a regulation of heat (radiation, conduction) and mass (vapor, air) transfer. Moreover, in urban areas, facades are often the largest potential surface for integration of renewable energy generation components (solar PV, thermal, piezo-electric, etc.). Facing the challenges of decarbonization for the building sector in the EU (target of 80% for 2050), the building envelope has to integrate active functions in term of energy production (collect, convert, store, distribute). However, the current standards and codes impose, from an energy viewpoint, a single solution direction that covers precisely a high air tightness and high thermal resistance of the envelope.

Multi-functional and adaptive building envelopes can provide step-change improvement of the energy efficiency, sustainability, comfort for the occupants, and economic value for the building sector, furthermore they represent a considerable contribution to meeting the EU 2020 and 2050 targets.

Despite the investments in many EU countries on building envelope-related research, the research programs across EU states are sometimes disjointed. Borrowing a set of terms from the discipline of biology now commonplace in architectural design, there is a need to articulate a conceptual paradigm, working vocabulary for the development of high-performance building skins that are smart, intelligent, interactive and responsive, pooling together the knowledge, technologies and research from across European countries and beyond.

1.2 COST Action TU 1403 – Adaptive Facades Network

Given the size of this challenge and its importance to achieving sustainability targets in the built environment, in 2014, the Adaptive Façade Network was commissioned in the framework of EU COST (European Cooperation in Science and Technology) [10]. The main aim of this COST Action is to harmonize, share and disseminate technological knowledge on adaptive facades at a European level [11]. By harnessing this knowledge, it will contribute to the generation of new ideas and concepts at a fundamental and product/system development level.

The activities in the COST Action are organized in four Working Groups:

- WG1: Adaptive technologies and products

- WG2: Component performance and characterization methods
- WG3: Whole building integration and whole-life evaluation methods of adaptive facades
- WG4: Dissemination and future research.

1.3 Paper objectives

The aim of this paper is to present the first developments and project findings integrated in the work developed by Working Group 1. In particular the paper aims at providing an overview of concepts and classification strategies for adaptive facades. An analysis of the approaches available in literature leads to the development of a new classification matrix as a common framework of understanding for describing adaptive building envelope systems. Three case studies are discussed to illustrate how the classification approach can be used.

2. Overview of previous classification approaches

Ever since there has been an interest in design and development of adaptive building materials and dynamic façade systems, there have also been efforts to classify the different concepts into sub-groups with shared characteristics. Several comprehensive review papers have recently been published on different categories of adaptive façade concepts, such as adaptive glazing [12,13], phase change materials [14], solar facades [15] and daylighting systems [16]. Whereas these publications mostly serve as overview or database of solutions [17], the function of a classification scheme/approach is deeper, as it tries to identify relationships among different concepts, and thereby aims at increased understanding of this multi-disciplinary field. By doing this, the idea is that classification helps in detecting patterns and identifying unexplored concepts, and that it therefore may ease the development of high-potential, innovative adaptive façade components.

Table 1 presents an overview of different classification schemes for adaptive facades, as they have been proposed in literature. The attempted bird's-eye view shows us a general pattern that is present in all approaches. In each classification, there are three main stages taken into consideration by different researchers, although the stages are differently named, thus the generalization is difficult.

The first stage is a phase of **collecting the information** about the environment (sensing, feeling). The second stage is the phase of **processing the acquired information** (computing, thinking, extrinsic vs. intrinsic control types, etc.), and the final one, of **taking the physical actions** in response to the status of the outside and inside environment (kineticism, actuating, folding, sliding, expanding, transforming, etc.).

Despite the presence of these common elements, we can also observe a wide range of categories and terminology. For example, the overview by Fox and Yeh [18] distinguishes only two groups, and has a strong emphasis on material aspects. The schemes by Addington and Schodek [19] and Ramzy and Fayed [20] on the other hand, can only be used for facades with kinetic components. Compared to others, the overviews by Ochoa and Capeluto [21], IEA Annex 44 [22] and Loonen et al., [8] tend to break the field down into many smaller sub-groups, with a primary focus on the system and component-level. The analysis in Table 1 further clearly shows the absence of agreement in terms of terminology and a generally-accepted definition for adaptive facades and the typical elements that such a definition should contain.

One of the goals of COST Action TU1403 is to harmonize the existing developments in adaptive façade research, including the incoherence of various classification approaches. To overcome the shortcomings of existing classifications, it is likely that this project will lead to the development of a new classification approach, taking the material presented in this section of the paper as a starting point. As much as possible, this approach will build upon previous developments, by taking the strong elements of existing approaches as a basis. This task should further address the following challenges:

- The classification scheme has to be future-proof. It should accommodate past achievements (materials and components) but certainly also be open to include future developments.
- The classification scheme should be generic, but at the same time be specific enough, with a level-of-detail that can stimulate the development of novel adaptive façade technologies.

- The classification scheme should not only include descriptive information but also cover quantitative system/material parameters and information about *performance.* It is noted that such data is not always easy to obtain.

Table 1. Overview of classification approaches for adaptive facades

[19] Addington and Schodek, 2005

Kinetic architecture: buildings, or building components, with variable location or mobility and/or variable geometry or movement

Ways	Folding	Sliding	Expanding	Transforming		
Means	Pneumatic	Chemical	Magnetic	Natural	Mechanical	
Control type	Internal	Direct	In-direct	Responsive in-direct	Ubiquitous, Responsive In-Direct Control	Heuristic, Responsive In-Direct Control

[18] Fox and Yeh, 1999

Smart materials: materials with properties that are changeable and thus responsive to transient needs

Type	**Examples**
Type 1: Property changing - Intrinsic response variation of material to specific internal or external stimuli	Color-changing, phase-changing, conducting polymers, rheological-property changing, liquid crystal technologies,
Type 2: Energy exchanging - Responses can be computationally controlled or enhanced	Light-emitting materials, photovoltaic materials, thermoelectric materials, piezoelectric materials, shape memory materials

[21] Ochoa and. Capeluto, 2008

Active features: the elements through which buildings self-adjust to changes initiated by their internal or external environments

	Class	**Design variable**	**Common values**
Sensor / input elements	Sensors	light, temperature, glare, solar radiation	internal/external
	User interfaces	switches/thermostats	On/off, variable control
Control processing elements	Individual control	Light controls	
		Shading controls	Always on, fixed slat angle
		Thermal comfort	Cooling on if temperature higher than…
		Ventilation controls	Open air inlet/window. Fan operation
		Energy controls	Grid-connected only
	Schedules		For non-sensor operations
	BMS		"Electronic brain"
	Synchronized controls		One element action turns on/off another
	Passive building		Static elements fulfil all functions
	Users only		Users perform operative routines
Actuating elements	Daylighting systems	Sun shading elements	Opaque/Light transmitting
		Daylight redirection elements	Fixed, external
	Fenestration	Glazing elements	Double glazing clear, low-e
	Ventilation systems	Windows, fans	Different combinations
	Cooling and heating		HVAC systems

[22] IEA ECBCS Annex 44, 2009.

Responsive Building Elements: building construction elements which are actively used for transfer and storage of heat, light, water and air. They assist to maintain an appropriate balance between optimum interior conditions and energy performance by reacting in a controlled and holistic manner to outdoor and indoor environment changes and to occupants requirements

Building technological system and Building Element	**Action performed**	**Function**	**Physical behaviour**	**Connection with HVAC**
Envelope: Wall, roof, ceiling, fenestration	Reduction of heat loads	Reject	Heat flux	Air
Superstructure: Column, Beam, wall, floor	Reduction of cooling loads	Store	Thermal storage	Water
Substructure: Piles, foundations beams	Heating	Admit	Transparency	
Underground: Earth to air heat exchanger	Cooling	Temper	Permeability	
Render and finishes: Partition wall, floor, ceiling	Energy conversion	Redirect		
	Thermal energy storage	Transform		
	Ventilation			
	Daylight			

[20] Ramzy, H. Fayed, 2011

Kinetic architecture: a design concept in contemporary architecture, which explores the physical transformation of a building with the objective to redefine traditional applications of motion through technological innovation.

	Kineticism	**Control technique**	**System configuration**	**Control limit**
Skin units systems	Limited	Direct or Responsive	Embedded	Minor
Retractable elements	Medium	Internal or Direct	Embedded	Medium
Revolving buildings	Major	Direct or Responsive	Dynamic	Significant
Biomechanical systems	Variable	Responsive Indirect	Dynamic or Embedded	Variable

[23] Wang et al., 2012

Acclimated Kinetic Envelope: The term "acclimated" is from biology and refers to a process in an individual organism adjusting to a gradual change in its environment (such as a change in temperature, humidity and etc.) through its morphological, behavioral, physical changes. The term kinetic is associated to motion, and also indicates an organism's response to a particular kind of stimulus in biology.

Climatic sources	Solar responsive	Solar heat
		Solar light and heat
		Solar electricity
	Air-flow responsive	Natural ventilation
		Wind electricity

[8] Loonen, et al., 2013

Climate adaptive building shell: A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.

Relevant physics	Thermal	Optical	Air flow	Electrical	
Time scales	Seconds	Minutes	Hours	Diurnal	Seasons
Scale of adaptation	Macro	Micro			
Control type	Extrinsic	Intrinsic			
Typology	Built examples	Subsystems and components	Full-scale prototypes	Reduced-scale prototypes	

3. Basis for systematic characterization of adaptive envelopes

The performance of a building envelope is complex as it is, but by introducing adaptivity we move to a further degree of complexity and, therefore, agreement on the principles and concepts that must be considered becomes crucial. Taking into account the findings described in the previous section we can summarize eight basic concepts that make it possible to thoroughly describe any example of envelope adaptivity (Table 2).

Table 2. Matrix of descriptive characterization concepts for envelope adaptivity.

Goal / purpose	Responsive function	Operation	Technologies (materials & systems)	Response time	Spatial scale	Visibility	Degree of adaptability
Thermal comfort	Prevent, Reject, Admit or Modulate (Store, Distribute) solar gains, and conductive, convective and long-wave radiant heat flux	Intrinsic Extrinsic	Shading Insulation Switchable glazing PCM Solar tubes BIPV and solar thermal systems Shape memory alloys Façade openings Kinetic systems Radiant glazing …	Seconds Minutes Hours Day-night Seasons Years Decades	Building material Façade element Wall Fenestration Roof Whole building	No Low High	On-off Gradual
Indoor air quality	Controlled porosity for exchange and filtering of outside air						
Visual performance (illuminance, glare, view)	Prevent, Reject, Admit or Redirect visible light						
Acoustic quality	Prevent, Reject, Admit or Redirect sound pressure						
Energy generation	Collect and convert wind energy and sunlight into electricity and thermal energy						
Personal control	User interaction and adaptation to individual needs						

The characterization starts by identifying the different **goals / purposes** an adaptive façade can fulfill. Each adaptive façade should strive at achieving one or several of these goals, while balancing this with overall energy use, CO_2 emissions and life cycle cost. These goals can be expressed with the use of performance indicators, and are often based on building codes or standards. Directly associated with these goals are the **responsive functions** of the façade. Depending on the physical domain, the source of energy (underlined) can be managed in a controllable way. While *prevention* aims to reduce the energy transfer through the envelope creating some kind of barrier, *Admission* allows and *rejection* avoids it. *Collection-Conversion-Modulation-Storage-Distribution* refers to an energy management model at which energy can be accumulated and circulated in the appropriate moment and direction depending on ambient conditions.

For classifying the way the adaptive façade components are controlled/**operated**, we choose the same terminology as in Loonen et al. [8]. *Intrinsic control* implies self-adjusting since the adaptive behaviour is automatically triggered by environmental stimuli which allows for low-cost operation and maintenance. *Extrinsic control* implies first information retrieving and processing and then, actions to be taken. This allows for feedback and, thus, for artificial intelligence. We prefer these terms instead of passive/active, to avoid confusion with the passive house approach (highly insulated, airtight envelopes), and *active* connotations regarding façade integration of PV modules or HVAC systems. It is mentioned, though, that the integration with the control of other systems in buildings, such as heating, cooling, ventilation and lighting, is of great importance for achieving high-performance adaptive facades.

The items in the category **Technologies (materials & systems)** are not meant to be exhaustive, but aim to give an overview of the available system types. Buildings with adaptive facades can make use of one or more elements in this list. At the level of façade sub-systems and components, this matrix may actually be used to characterize one of the items mentioned in this list. Including additional stimuli or ambient parameters will enrich the matrix and lead to new ideas; we can, for instance, consider a system that takes advantage of different precipitation types for energy or service purposes.

Response time of a façade says something about the temporal scale at which the actions of the adaptive façade effectively take place. Most commonly, this happens in the range of minutes to hours. However, some façade types, e.g. wind- or daylight responsive systems are able to change their configuration to changes that happen in the order of seconds. On the other hand, some façade types are purposefully designed to be flexible over seasons [24] or with respect to functional changes of a building (e.g. an office building that later can be refurbished into apartments) [25]. We must notice that in some cases the speed at which the envelope is capable to respond facing changes in boundary conditions depends on the implemented technology and in some others the facade is sensitive to a time-scale which is decided by designers (real time, night-day, season, weekday-weekend, etc).

The **spatial scale** is used to refer to the size of the façade system. At the smallest scale, the change happens with respect to the molecular structure of the building material, resulting in a change of thermophysical or optical properties. Via the level of individual building envelope components, this ranges to the whole-building level, where the appearance of the building itself is affected or its main elements are rearranged.

Visibility of adaption affects the appearance of architecture, which is an ancestral function of the envelope: it defines the exterior image of the building itself and also the interior appearance to a large extent. Some materials can change their properties producing no change in their appearance and some components are just hidden or not visible and therefore their adaptive behaviour does not carry any aesthetic consequence. But in many cases adaptivity becomes an important feature of architectural projects and is utilized as a significant composition resource. Besides, the visibility of adaptation can affect the user’s experience of the weather and therefore have subjective effects [26,27].

Finally, **degree of adaptivity** expresses to which extent the envelope can accommodate to changing boundary conditions. Non-adaptive facades provide fixed functions or operating configuration. The on-off operation type allows for a low degree of adaptivity and when we talk about gradual adaptation we need to determine the range of values the element can provide for a given property/function; the width and steps of this range will inform about its degree of adaptivity. The spatial scale is also related to the degree of adaptivity as the size of the building component allows for having different performances at different positions of the envelope.

4. Case studies

To clarify the meaning of the concepts introduced in section 3, we use this section to demonstrate its application to well-known adaptive facade technologies: Dynamic exterior shading, PCM glazing and double-skin façades with integrated photovoltaics.

4.1 Dynamic exterior shading and louver facades

Solar shading and regulation of façade transmission is one of the most important features of adaptive façade systems. By controlling the **admission of solar gains**, it has a direct impact on the energy balance of a building, trying to benefit from **passive solar energy** while **avoiding indoor overheating**. In addition, shading systems determine the access of **natural daylight illuminance, prevent glare and enable views to outside**. The dynamic aspect allows designers to respond to the variability of intensity and direction of sunlight, thereby bypassing some of the inherent compromises that need to be made when deciding the optimal window-to-wall ratio of conventional facades [28].

Although switchable glazing solutions are definitely gaining popularity, the most common way of exterior solar shading is via mechanical louvers, shutters, screens or blinds. An iconic example where the mechanical façade system also serves a distinctive architectural function with high **visibility** are the Oval Offices in Cologne, designed by Sauerbruch and Hutton Architects, 2010 (Figure 2)

Figure 2. The Oval Offices in Cologne (arch. Sauerbruch and Hutton, 2010) The vertical axis glazed sun louvers serve the purpose of light regulation and, simultaneously, perform as outstanding architectural façade element. (photo by M. Brzezicki)

Almost all types of dynamic exterior façade systems are operated in the **extrinsic** way. By integrating the shading elements with a network of sensors and the building energy management system (BEMS), the most efficient mode of operation can be ensured. Frequently, some sort of **personal control** is included to overrule the automated behavior of the facade; this is also the case for the Oval Offices in Cologne.

The facade regulation can take a form of (i) a binary action (transparent vs. non-transparent, **on-off**) usually performed by the mechanical system of louvers, rollers and sunshades, or (ii) the **gradual** regulation of light transmission usually performed by the physical system through partially opened systems or semi-transparent/translucent elements.

On days with intermittent clouds, the exterior daylight illuminance can fluctuate rapidly. For effective daylight management, it is important that the shading system can synchronize with these swift variations in the order of **seconds.**

4.2 PCM glazing

Phase Change Materials (PCMs) are materials that are able to vary their specific heat capacity at room temperature. This feature is achieved by storing the energy in the form of latent heat in the material, inducing a phase change (solid to liquid and vice versa). A such, little temperature variation is measured in the material during the phase change [29]. PCMs are used as energy efficiency measures in buildings by attenuating temperature fluctuations inside to r**educe heating and cooling loads**. Some PCMs are transparent in the liquid phase and translucent in the solid phase (paraffin waxes), therefore they can also be used in as **fenestration** elements [30,31].

PCM window systems are used to obtain enhanced utilization of solar gains [32]. The combined shading and energy buffering effects also have a positive influence of window surface temperature and can therefore improve **thermal comfort** conditions in both summer and winter conditions [30]. As a more indirect effect, PCM windows also influence **visual performance**.

The **visible** adaptivity of PCM windows happens as an **intrinsic** feature of the material; no electronics or movable components are needed. It is possible, though, to select PCM materials with different transition temperatures to meet the needs of specific climatic conditions or building functions. However, its operation cannot be influenced by the occupants. To make optimal use of the latent heat storage capacity, the idea is that melting and solidification **gradually** takes place on a **day-night** cycle. Achieving this requires careful attention during the design phase.

4.3 BIPV double-skin façade

Building envelopes have a significant potential to harvest and exploit environmental energetic resources. Double-skin facades with building-integrated photovoltaics (**BIPV**) systems aim at simultaneous optimization of both **electricity generation** and **heat production** (or recovery). Within the French RESSOURCES project, BIPV double-skin facades with different shapes, colours, and orientations (**façade** and **roof**) have been developed (Figure 3) [33]. Such facades are adaptable with respect to the **seasons**. In winter, a mechanically ventilated cavity (**extrinsic** and **gradual** control) can be used for heat recovery, pre-heating or coupling with a heat pump. In summer, the solar-driven ventilation process serves for natural cooling of the PV wall, as well as ventilative **cooling** of indoor spaces [34]. The concepts of active and adaptive BIPV envelope components demonstrate that it can be possible to combine **highly-visible** aesthetic and technological innovations

Figure 3. Double-skin prototype for detached houses (ETNA Test house – EDF R&D) - Pleated façade prototype for office buildings (HBS-Technal)

5. Conclusion and outlook

Adaptive facades are identified as a promising technological solutions for meeting many of the sustainability targets of the 21st century. To stimulate ongoing developments and guide new initiatives into directions with high potential, there is a need for systematic analysis of past achievements in the form of a comprehensive classification scheme. As part of ongoing developments in EU COST Action TU1403, this paper has presented an overview of the challenges and requirements for such a classification. We have introduced an outline of a new approach that aims to combine the strong elements of already existing classification schemes, and demonstrated this with three examples. In follow-up activities we will use this classification scheme to characterize a wide range of state-of-the-art adaptive building envelope materials and systems. Doing this will likely lead to further extension and/or refinement of the classification matrix. Other next steps will include finding ways of presenting it in a graphical format that is more intuitive to understand. In addition, we intend to complement the table as much as possible with material/system parameters and quantitative information on their performance.

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