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Review of current status, requirements and opportunities for building performance simulation of adaptive facades[†]

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Adaptive building envelope systems have the potential of reducing greenhouse gas emissions and improving the energy flexibility of buildings, while maintaining high levels of indoor environmental quality. The development of such innovative materials and technologies, as well as their real-world implementation, can be enhanced with the use of building performance simulation (BPS). Performance prediction of adaptive facades can, however, be a challenging task and the information on this topic is scarce and fragmented. The main contribution of this review article is to bring together and analyse the existing information in this field. In the first part, the unique requirements for successful modelling and simulation of adaptive facades are discussed. In the second part, the capabilities of five widely used BPS tools are reviewed, in terms of their ability to model energy and occupant comfort performance of adaptive facades. Finally, it discusses various ongoing trends and research needs in this field.

Keywords: building performance simulation; software review; adaptive building envelope; responsive building elements; control strategies

1. Introduction

To meet the sustainability targets that are set for the building sector, there is a need for continuing the development of new building concepts, technologies and materials that can further improve the energy efficiency of buildings, while simultaneously enhancing the indoor environmental comfort of building occupants. The building envelope, or building facade, plays a key role in this process. In particular, the technologies that are able to, actively and selectively, manage the energy and mass transfer between the building and its external environment are considered to be of crucial relevance (IEA 2013; Perino and Serra 2015). These so-called adaptive building envelopes have the ability to (i) significantly reduce the energy use of buildings (Perino 2008), while (ii) improving the level of indoor environmental quality (Luiblé 2015), and (iii) having a positive impact on the match between on-site harvested renewable energy and building energy use (Reynders, Nuytten, and Saelens 2013).

The unique feature of adaptive building envelopes is the capability to adjust their thermo-optical properties in a reversible way to transient boundary conditions (either external, such as climate, or internal, such as occupants' requirements), in order to respond to changing priorities (i.e. minimizing the building energy use, maximizing

the use of natural light, etc.). A state-of-the-art overview of various adaptive building envelope systems and components is presented in Loonen et al. (2013). Among the wide range of technology options, switchable glazing (Baetens, Jelle, and Gustavsen 2010), movable solar shading (Nielsen, Svendsen, and Jensen 2011), wall-integrated phase change materials (PCMs) (Kuznik et al. 2011), dynamic insulation (Kimber, Clark, and Schaefer 2014) and multifunctional facades (Favoino et al. 2014) are identified as the most promising adaptive building envelope systems. However, studies show that there is ample scope for further improvements (Favoino, Overend, and Jin 2015; Loonen et al. 2013).

Successful design of adaptive facades is a challenging task. In fact, they present a large technical potential, as demonstrated in scientific publications and testing reports, but low real-world uptake. This is partly due to a lack of thorough understanding of the benefits and possible risks, and the inability to measure them in a reliable way.

Adaptive building envelopes are complex systems that typically influence multiple physical domains simultaneously (thermal, luminous, air quality, etc.). Unlike most heating, ventilation and air-conditioning (HVAC)-dominated buildings, the performance of buildings with adaptive facades is to a very large extent determined

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by local climatic conditions and interactions with occupants and the other building systems. Traditional characterization methods for building envelopes, such as *U-value* and *g-value*, are based on static assumptions. Therefore, due to the intrinsic time-varying behaviour of adaptive facades, these conventional metrics provide limited and potentially misleading information for these inherently dynamic systems. As will be discussed in the paragraphs that follow, a more accurate and credible evaluation would instead determine their performance in terms of more comprehensive, whole-building performance indicators, such as total primary energy use and/or indoor environmental quality metrics.

Building performance simulation (BPS) has the potential to provide this type of information to several stakeholders, including building designers, material scientists, sustainable building consultants, control engineers and building services professionals (Clarke and Hensen 2015). The potential of the integration of modelling and simulation activities for performance analysis of adaptive facades can be illustrated in a number of different possible uses in the design and operation of buildings:

- Informed decision-making to support the design process of buildings with specific adaptive building envelope components, in particular when an optimal performance is required across occupant comfort, economic and environmental aspects;
- Prediction of energy-saving potential compared to a baseline design as part of green building certification schemes such as LEED and BREEAM;
- Virtual rapid prototyping to evaluate different future-oriented systems/materials and identifying promising alternatives for further refinement and product development;
- Exploration of high-potential control strategies that maximize the performance of adaptive building envelopes during operation;
- HVAC system sizing and fine-tuning of the interaction between adaptive building envelope and other building services;
- Virtual testing of the robustness of adaptive facade systems with respect to occupant behaviour and variable weather influences.

For these reasons, modelling and simulation can bring insights into the mutual influence between design and performance aspects of adaptive building envelopes, and can therefore strongly contribute to their spread into the building construction market, as well as to the development of innovative technologies. However, as we will demonstrate in this article, simulation of adaptive facades can be significantly more complex than performance prediction of conventional, static facades, because existing simulation tools were not originally developed for this purpose. Designers, engineers and researchers who plan to use BPS

for analysing adaptive facades are faced with a number of challenges and should develop their simulation strategy accordingly. The currently available information about modelling approaches and issues regarding simulation of adaptive facades is fragmented. Simulation users, therefore, have limited guidance when it comes to factors such as software selection, availability of models for specific adaptive technologies, best-practice examples and important points of attention (such as modelling assumptions and strategies).

This paper intends to provide researchers and designers, who are approaching the simulation of adaptive building envelope systems, with a critical overview of existing information, in order to enable them to choose the most suitable tool/method according to their needs and resources. This work was partly conducted in the Framework of European COST Action TU1403 – Adaptive Facades Network, within the Task group on BPS of adaptive facades (www.adaptivefacade.eu). The main aim of this Task group and of the work reported in this article is threefold: (i) to describe the current capabilities of BPS tools, (ii) to describe their current limitations and (iii) to specify the requirements of novel simulation strategies suitable for adaptive building envelope systems. In Section 2, the general requirements and main challenges related to whole building energy simulation of adaptive building envelope systems are described. Following, Section 3 analyses the opportunities and limitations of state-of-the-art simulation software at modelling adaptive building facades, based on their underlying assumptions and modelling methods. In Section 4, we provide a detailed overview of the capabilities to model adaptive facades in five of the most widely-used BPS tools, including an overview of simplified simulation strategies and workarounds. Finally, Section 5 concludes the paper by presenting ongoing trends and research needs that are expected to move modelling and simulation of adaptive building envelopes forward in the coming years.

2. Challenges for performance prediction of adaptive building envelopes

Modelling and simulation of adaptive building envelopes have to accurately represent a sequence of time-varying building envelope system states (or properties), instead of a static representation of the building enclosure. Moreover, for effective performance prediction of adaptive building envelope systems, it is essential to simultaneously consider multiple levels, in terms of (i) spatial scales, (ii) time resolutions, and (iii) physical domains. Compared to simulation-based analysis of conventional, static facades, two major additional requirements for performance prediction of adaptive systems are identified:

Modelling time-varying facade properties: facade specifications (i.e. material properties or position of components)

need to be changeable during simulation run-time to properly account for transient heat transfer and energy storage effects in building constructions (Loonen, Hoes, and Hensen 2014). Many state-of-the-art BPS tools have restricted functionalities for accomplishing this feature. Not only these limitations, but also the various opportunities are further discussed in Section 4, together with some simplified simulation approaches used to overcome specific software constraints.

Modelling the dynamic operation of facade adaptation: the dynamic interactions in adaptive building envelope systems give rise to a strong mutual dependence between design and control aspects (Loonen et al. 2013). The performance of adaptive systems fully depends on the scheduling strategy (i.e. control logic) for facade adaptation during operation. Moloney (2011) describes it as: “The design outcome in a project with kinetic facades is a *process*, rather than a static object or artifact”. Thus, to identify the characteristics of high-performance adaptive building envelope systems, it requires not only design considerations (i.e. facade system design parameters), but also insights into adequate automated and occupant-driven operation strategies of the dynamic facade. Moreover, effective design and operation of a dynamic facade system depend also on the integration with operations of the other building services. For example, limited lighting energy savings could be achieved if the operation of dynamic solar shading is not integrated with a lighting dimming system. Similarly, the integration with HVAC, and renewable energy systems needs to be carefully considered. To explore such synergetic effects, it is important to take this integration into account in the simulation strategy.

3. Requirements and limitations of current BPS software

A large number of software tools are available for predicting the energy and comfort performance of buildings.¹ Each program has unique features in terms of modelling resolution, solution algorithms, intended target audience, modelling options, ease of use vs. flexibility, etc. The simulation tools with most powerful modelling capabilities, and which have undergone most rigorous validation studies (e.g. EnergyPlus, ESP-r, ICE, IES VE and TRN-SYS), are all legacy software programs (Crawley et al. 2008). Although these tools have active development communities, and receive regular updates and extension of modelling capabilities, their underlying concepts and basic software architecture do not change. Most tools stem from a time when adaptability of building components was not a primary consideration (Ayres and Stamper 1995; Oh and Haberl 2015). Consequently, the building shape and material properties are usually not changeable during simulation run-time in these tools, which restricts the options for modelling adaptive building envelope systems. The

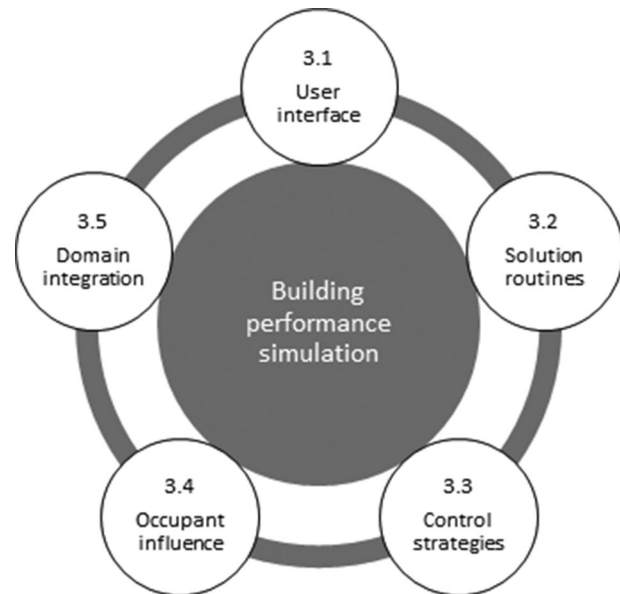


Figure 1. Different modelling aspects playing a role in performance evaluation of adaptive building envelope systems.

requirements and limitations of existing BPS tools can be grouped into five aspects as shown in Figure 1, based on their characteristics and underlying assumptions.

3.1. User interface

All modern BPS tools possess a graphical user interface (GUI) as a front-end for communication with simulation users. In these programs, the input for constructions and material properties is normally given in the form of scalar values. These parameters are either directly entered by the user, or imported from pre-configured databases. The same static representation is implemented for the size, geometry and orientation of the various surfaces that together form the building envelope. In the most common approach, this information is then processed once, prior to the actual simulation run, and is not updated further during the simulation. Users of the simulation tools have limited flexibility to extend the functionality for modelling adaptive building envelopes through the non-modifiable user interface and the restricted access to the source code of (proprietary) simulation tools. This is especially the case in the simulation tools that are geared towards the needs of architects (Attia et al. 2012).

Some exceptions to this rule also exist, in which two types of modelling features can be distinguished: (i) application-oriented and (ii) general-purpose features (Table 1). *Application-oriented* indicates that the modelling capability was implemented in the software with a specific adaptive building envelope technology in mind and is labelled in the software as such. The adaptive mechanism and how it is triggered are, therefore, already embedded in the specific model, and users can activate it easily

Table 1. GUI modelling capabilities for adaptive building envelope technologies, pros (+) and cons (-).

Modelling capability	Features
Application-oriented	(+) Easy to use, robust (-) Restricted flexibility, limited number of options
General-purpose	(+) Offers more flexibility (-) Requires a high level of expertise and more input data from the BPS user

by means of the GUI, but are limited to the presets available. The *general-purpose* features, on the other hand, are not restricted to a specific technology, but offer flexibility for user-defined combinations of adaptive thermo-physical property variations and/or triggering mechanisms. This higher abstraction level affords more freedom for exploring innovative adaptive building envelope systems, although it requires the BPS user to define and code the control mechanism that triggers adaptation in the building element.

3.2. Solution routines for transient heat conduction through building elements

Many of the widely used BPS tools adopt response factor techniques (e.g. Thermal Response Factors [TRF] or Conduction Transfer Functions [CTF]) to solve the differential equations governing the heat transfer phenomena through opaque building elements (Spitler 2011). These methods are optimized for computational efficiency, but by virtue of their design, they can only work with time-invariant thermo-physical properties (i.e. density, specific heat capacity, and thermal conductivity) (Clarke 2001). This is because the coefficients that are used in the equations are constant and determined only once for each building envelope element at the beginning of the simulation. As such, response factor methods do not permit variations in thermo-physical material properties during simulation run-time (Delcroix et al. 2012; Pedersen 2007).

Other simulation tools use finite difference or finite volume methods for modelling transient conduction. These numerical methods adopt an iterative procedure, thereby allowing for updates of the matrix coefficients that describe heat transfer, as time steps of the simulation proceed. This makes the simulation of variable thermo-physical properties possible.

The models for calculating energy gains/losses through transparent portions of the building envelope, on the other hand, do not normally include thermal storage effects (Freire et al. 2011), so that it is easier to take dynamically changing window properties into account in the simulation, also in BPS tools adopting response factor techniques. A similar approach can be chosen for so-called massless layers (i.e. constructions with no or very low thermal

capacity), which only affect thermal resistance, but do not influence the storage term in the heat balance equations.

3.3. Control strategies

Control strategies in BPS models provide the link between sensed variables and actuator actions by means of a certain control logic. This feature is mostly used for the control of HVAC systems, but other opportunities also exist. The (non-)availability of actuator options is what in the end determines the types of adaptive facade technologies that can be modelled in a simulation tool. Figure 2 illustrates the general architecture for the control of building systems (including adaptive building envelope systems) in BPS tools, which can be divided into (i) sensors level (climatic boundary conditions, building internal boundary conditions and occupant preferences); (ii) control logic level and (iii) actuators level, that is, any building component that can be controlled (including HVAC, artificial lighting and adaptive building envelope systems).

The control of adaptive building envelopes can be subdivided into (i) *intrinsic* and (ii) *extrinsic* concepts (Loonen et al. 2013). The term *intrinsic* indicates that the adaptive mechanism is automatically triggered by a stimulus (surface temperature, solar radiation, etc.). This intelligence is chemically embedded in the material and the switching mechanism is activated by a variation in its internal energy. This kind of control (dashed arrows in Figure 2) is also referred to as “direct” or “open-loop” control and the material is said to be “smart” (e.g. thermochromic, photochromic and PCMs), as no intervention from an external system/user is required. In contrast, *extrinsic* refers to the presence of an external decision-making component that is able to trigger the adaptive mechanisms according to a feedback rule (continuous arrows in Figure 2). This is the so-called feedback or closed-loop control type, and in this case, the adaptive system, which includes the adaptive building envelope component and the controlling system, is often referred to as “intelligent” (electro-chromic glazing, movable shading devices, kinetic facades, etc.). Hence, intelligent systems require a control management system in order to respond in an adaptive manner, consisting of sensors, processors and actuators.

The control options for adaptive building envelope systems available in BPS tools can be classified into four groups: (i) hard-coded intrinsic, (ii) hard-coded extrinsic, (iii) time-scheduled and (iv) script-based.

Hard-coded intrinsic control refers to control options for *application-oriented* modelling capabilities which are already implemented into the software and accessible through the GUI. This is the case, for example, for the actuation of thermo-optical properties of a fenestration system based on temperature (i.e. thermochromic windows), or for phase-changing materials, modelled via temperature-based changes in specific heat capacity.

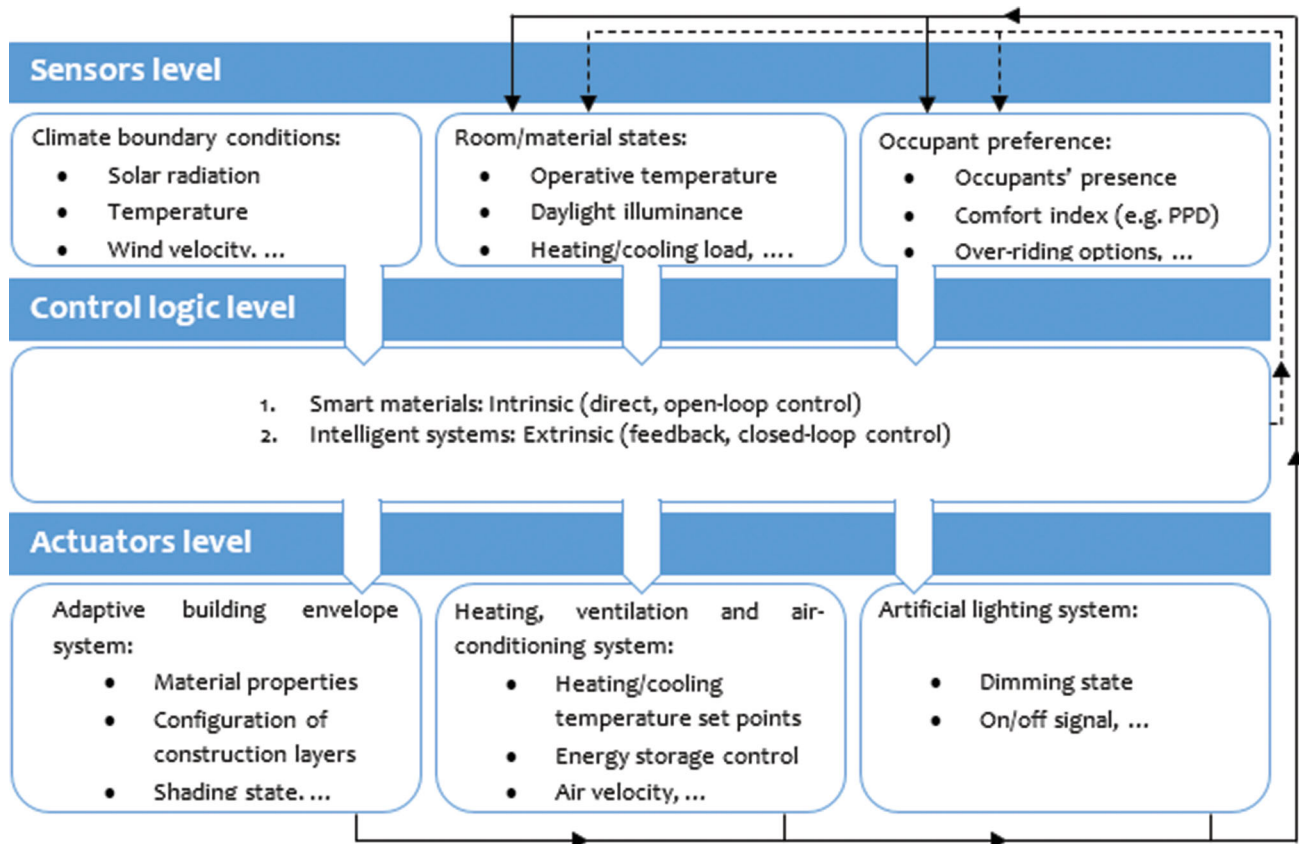


Figure 2. Control architecture for building systems, including building services and adaptive facades: the continuous line represents active, closed-loop, control; the dashed line represents passive, open-loop, control.

Hard-coded extrinsic control, on the other hand, can usually be chosen from a limited number of fixed presets. These typically include if-then-else statements where the user can select (i) sensor types (e.g. incident solar radiation, room temperature, heating or cooling demand, etc., or combinations thereof) and (ii) control thresholds to actuate a specific adaptive technology.

Time-scheduled control shares many characteristics with hard-coded extrinsic control systems, but is different in the sense that control actions are predetermined as a function of time, instead of being based on boundary conditions or simulation state variables.

Finally, more advanced intrinsic and extrinsic adaptive systems control options can be evaluated if a script-based control can directly be coded by the user in the simulation tool. Script-based control, referring to the ability to change the state of the building envelope during simulation run-time, gives the possibility to test a specific control approach, replicating and extending the hard-coded direct or feedback preset options. The fundamental steps of modelling a script-based control are (i) selecting from a list of available sensors (i.e. simulation state variables or boundary conditions); (ii) selecting from a list of possible actuators (chosen according to the specific adaptive technology/concept that needs to be simulated) and (iii) coding a control algorithm, which translates sensor

signals into actions, by means of simple algebraic and Boolean operators.

3.4. Occupant influence

In contrast to conventional, static facades, adaptive building envelope systems can have an interdependent relationship with building occupants. For some applications, the simulation model needs to be able to evaluate not only how the adaptive building element affects occupant comfort conditions, but also how individual occupants may want to control a specific adaptive building envelope technology (Haldi and Robinson 2010) (Figure 2). This capability requires behavioural models that describe the interaction of building occupants with adaptive building envelope systems (Gunay, O'Brien, and Beausoleil-Morrison 2013; Haldi and Robinson 2010; Hoes et al. 2009). For example, different deterministic and probabilistic models are available for occupants' operation of blinds (Reinhart 2004) and window openings (Fabi et al. 2012). The development of occupant behaviour models for integration in BPS tools is an active field of research, coordinated at an international level via IEA ECB Annex 66 (<http://www.annex66.org/>). Until now, such occupant interactions can only be implemented via script-based control approaches (Section 3.3), but efforts to integrate

them more seamlessly into BPS tools are ongoing (Hong et al. 2015). The available information on the interaction of people with more advanced adaptive facade technologies is, however, still scarce (Bakker et al. 2014).

3.5. Multi-domain integration and physical interactions

The influence of the building envelope on the indoor environment can be evaluated in different physical domains: for example, thermal, visual and mass-flow (air and/or moisture). Moreover, to ensure adequate levels of occupant comfort, there is a need to synchronize the actions of adaptive facades with the operation of building services. Because these multi-domain influences can be mutually interrelated, there may be a need to solve the differential equations that describe the relevant physical phenomena in a coupled way. Matching the required physical interactions of a specific adaptive facade technology with the capabilities of a BPS tool to assess the performance across these multiple domains is, therefore, an important requirement for selecting suitable simulation strategies.

The focus of this paper is on the use of BPS tools to evaluate comprehensive building energy use and occupant comfort indicators. Most of these BPS tools are able to integrate thermal, airflow and building services (HVAC) domains, such as ESP-r and TRNSYS (Figure 3). A limited subset of them also integrates daylight models² (and therefore artificial lighting models as well), such as EnergyPlus, IDA ICE and IES VE (Figure 3).

Whenever a BPS tool presents restricted cross-domain modelling capabilities, the exchange of information between different BPS tools across different domains can be managed (i) before the simulation (data and process model integration) or (ii) during simulation run-time (data and process model co-operation) (Hensen et al. 2004), also

called co-simulation (Trcka, Hensen, and Wetter 2009) (cf. Section 5.3).

4. Capabilities of various building energy simulation software tools

The previous section has introduced several challenges and limitations, but at the same time also highlighted numerous opportunities for effective performance prediction of buildings with adaptive facades, based on BPS tool characteristics and underlying modelling assumptions. The main aim of this section is to develop these capabilities further by reviewing the specific adaptive envelope modelling capabilities of five widely used BPS tools in more detail.

It should be noted, however, that simulation users have also developed various approaches to partially overcome or bypass the aforementioned limitations for modelling adaptive facade behaviour in the simulation tool of their choice. The principles and possible pitfalls of such simplified approaches are described first (Section 4.1), before presenting the methodology (Section 4.2) and results of the review of application-oriented and general-purpose modelling features (Sections 4.3 and 4.4, respectively), and control options (Section 4.5).

4.1. Simplified simulation strategies and workarounds

Building performance simulation is a field where modelling features, almost by definition, lag behind the newest breakthrough technological developments and most creative design proposals. Workaround simulation strategies, therefore, have a long tradition in this field (Brahme et al. 2009), and can be used for various legitimate reasons such as the complete absence of existing models for certain adaptive building envelope technologies; a lack of user expertise/experience; limited project resources (time and money) to move towards more complex models and the absence of advanced control options for determining the optimal dynamic building envelope properties. In many of these cases, the ability to reuse validated, high-resolution models is an important argument in favour of using existing software instead of the development of custom-made simulation code from scratch (Wetter 2011a), such as the approach taken by Liu, Wittchen, and Heiselberg (2014). A main drawback of using workarounds is that they tend to rely on approximations or simplifications that might infringe the physics of model representations and, consequently, also put the credibility of simulation outcomes at risk.

Arguably, the simplest approach for representing an adaptive building envelope system is by subdividing the simulation period (e.g. one year) into several simulation runs with shorter periods (seasons, months, weeks, etc.), each with distinct building properties (Favoino, Jin, and Overend 2014; Hoes et al. 2011; Joe et al. 2013; Kasinalis et al. 2014; Loonen, Trčka, and Hensen 2011)

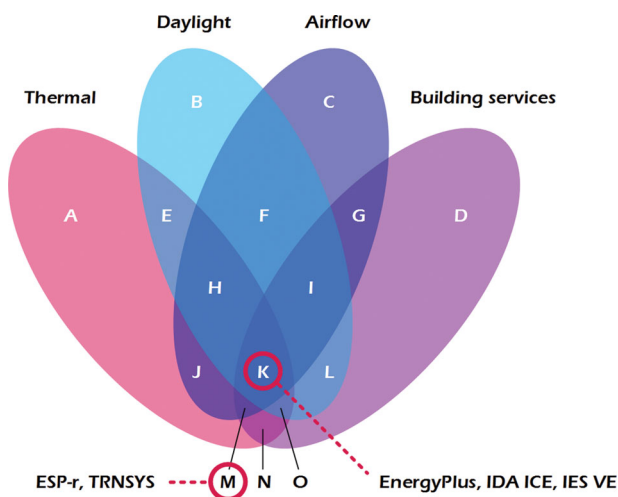


Figure 3. Multi-domain integration required to model adaptive building facades in different BPS tools.

(Figure 4(a)). This discrete approach works well for facade systems with long adaptation cycles (e.g. seasonal), but it cannot accurately model short-term adaptive building envelope dynamics. This is due to shortcomings in the initialization of equations at the start of each simulation run, where the end states of one simulation (i.e. surface and construction node temperatures) are different from the starting conditions of the subsequent simulation.

An alternative approach uses separate models for the whole simulation period, each with static properties that represent different states of the adaptive building envelope system. At a post-processing stage, the results of these independent simulation models are combined in a single representation of the performance of the building, according to a certain control strategy for the adaptive facade (Figure 4(b)). This modelling approach can have the advantage of (i) mimicking more advanced building operation controls and/or (ii) simulating adaptive building envelope technologies and materials for which a model does not exist yet. Specifically, even though such a modelling method is well able to capture switching of instantaneous solar gains, for example, due to changing window-to-wall ratio (Goia and Cascone 2014) or glazing properties (DeForest et al. 2013), it fails to account for the effect of delayed thermal response due to the capacitance of building components (i.e. slabs, walls and internal partitions). Therefore, in cases where thermal mass is involved in adaptive building envelope operations, the use of these approximate models would probably lead to significant errors in the results, because they do not correctly handle transient thermal energy storage effects (Erickson 2013). These inaccuracies may eventually compromise decision-making based on simulation outcomes, but little information about this issue is reported in the literature.

4.2. Overview of capabilities – methodology

A review of the opportunities for modelling adaptive building envelope systems in state-of-the-art BPS tools was conducted to compile an overview of the current capabilities and existing development needs. Based on literature review (Attia et al. 2012; Crawley et al. 2008) and first-hand

experience, five simulation tools (presented in Table 2) were selected on the basis of the following criteria:

- Extensive building envelope modelling capabilities, as identified by Crawley et al. (2008);
- Subject to active development by their development team or user community;
- Thorough validation through compliance with ANSI/ASHRAE Standard 140 (BESTEST) and other quality assurance procedures;
- Use in both research and consulting engineering practice;
- International user base.

The analysis of capabilities is based on the information in user manuals, software tutorials, release notes and contextual help facilities of the BPS tools, as well as communication with their development teams. Furthermore, scientific articles, dissertations and the information exchange in mailing lists were used to gather input. The review outcomes are divided into (i) application-oriented, (ii) general-purpose and (iii) control capabilities for each software, following the descriptions in Sections 3.1 and 3.3.

The review is also presented in a tabular fashion (Tables 4, 5 and 6): the notation used is indicated in Table 3 and includes required and available relevant physical domains (T: thermal, V: visual, A: airflow), type of control (represented by the cell colour), control options related to a specific technology (only for Table 6, indicating the modelling options for which this control is available) and level of expertise required (in the form of a superscript for knowledgeable users and expert users). “Knowledgeable user” refers to the need to develop custom-made scripts within the software interface. “Expert user” requires an even higher level of proficiency as it indicates that either creative modelling approaches have to be used, that the features are not documented, or that small source code modifications are necessary. The ability to include code modifications is only possible in tools that allow access to its source code (Table 2). Such interventions can be onerous, but are sometimes the only option to support

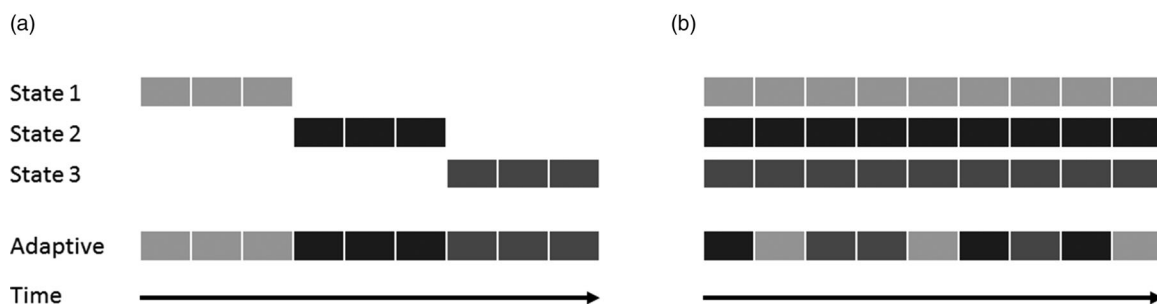


Figure 4. Schematic representation of workaround strategies for modelling the performance of adaptive facades. Case A represents the discrete approach that combines a number of short-term simulations. Case B represents the approach that assembles the results of simulations with static facades during post-processing.

Table 2. Characteristics of whole building energy simulation tools with respect to performance prediction of adaptive building envelope systems.

	Conduction solution method	User Interface ^a	Source code access and modification	Control simulation capabilities	Physical domain integration
EnergyPlus v8.3	CTF, Finite difference ^b	IDF editor, DesignBuilder, Comfen, OpenStudio, Simergy, Sefaira, DIVA, AECOSim	X	Presets, Time-scheduled, Energy Management System (EMS)	Thermal, visual, airflow
ESP-r	Finite volume	Graphic and text mode	X	Presets, time-scheduled	Thermal, airflow ^c
IDA ICE v4.7	Finite difference	Standard and advanced level	X	Presets, time-scheduled	Thermal, visual, airflow
IES v2015	Finite difference	IES VE, SketchUp and Revit plug-ins ^d		Presets, time-scheduled, formula profile (APpro)	Thermal, visual, airflow
TRNSYS v17.1	CTF ^e	TRNBuild, SketchUp plug-in	(X) ^f	Presets, time-scheduled, user-defined <i>equations</i> in Simulation Studio, W-editor (Type 79)	Thermal, airflow

^aOptions for modelling adaptive facades are significantly limited when the simulation engine is accessed through one of the third-party GUIs.

^bBy default, EnergyPlus uses the CTF method, but it was recently extended with a new finite difference scheme for conduction, to allow for modelling temperature- or time-dependent material properties (Pedersen 2007; Tabares-Velasco and Griffith 2012). The usage of this new approach has been large unexplored in the literature.

^cDaylight performance predictions with ESP-r are possible but are either limited to the restricted functionality of the *obsolete* daylight factor metric, or require setting up a co-simulation with the Radiance daylight simulation engine. Unlike the other daylight models in this overview, Radiance is not part of the host software (ESP-r), it is not seamlessly integrated in the simulation workflow and its use requires detailed operational knowledge of Radiance commands and algorithms. It is therefore not included in this overview.

^dAdditional modelling is needed in IES VE in order to perform a simulation, but some preliminary early-stage analysis could be performed via the plug-ins directly.

^eSimulation users can also choose to bypass the CTF approach by coupling TRNSYS Type 56 with finite element or finite difference schemes such as Type 260 or Type 399 (Kośny 2015).

^fExcluding dynamic building model Type 56.

Table 3. Legend for Tables 4 and 5.

	Expertise required	Control	Physical domain	
*	Knowledgeable user	Intrinsic	T	Thermal
**	Expert user	Extrinsic	V	Visual
			A	Airflow

modelling of innovative façade systems. Open-source simulation tools also enable calls to external software programs in a co-simulation framework, as is further discussed in Section 5.3.

4.3. Application-oriented capabilities

The software capabilities were assessed for 20 different adaptive facade technologies and corresponding application-oriented modelling features (Table 4); the main findings are discussed in this section.

Different types of switchable windows, including electrochromic glazing, are commercially available, and many research papers have been written about their application in buildings and architecture (Baetens, Jelle, and Gustavsen 2010). As a result of their presence in the market, options for modelling switchable glazing technologies are embedded in several simulation tools. All the software

tools analysed offer the possibility to control the properties of the fenestration system during simulation run-time. The differences between the various implementations are the number of possible window states (e.g. on/off versus gradual transitions) and the simulation state variables that can be used for the control of adaptation (e.g. room temperature, ambient temperature and incident radiation).

Thermotropic/chromic windows are slightly more complicated to simulate than other switchable window types because of their intrinsic control character; adaptation of the fenestration properties is directly triggered by window surface temperature instead of a control signal that is based on more general simulation variables. A provision for thermochromic window simulation was implemented in EnergyPlus (since v3.1, 2009) and ESP-r (Evans and Kelly 1996). The input of these models consists of sets of window properties at various temperatures. During the simulation, the thermochromic layer temperature of the previous time step is automatically fed into a window control algorithm, which then selects the window properties that best match with the given temperature. In IDA ICE and Trnsys, it is also possible to model thermotropic/chromic windows, but a significantly higher level of work and expertise is required from the user side (Section A.3 for IDA ICE and A.5 for TRNSYS).

Table 4. Overview of application-oriented features for modelling adaptive building envelope systems.

		#	Adaptive facade technology	Required domains	Energy Plus	ESP-r	IDA ICE	IES VE	TRNSYS Type 56
Transparent	Switchable glazing	4.1	Electro-chromic (EC), Liquid crystal, SPD	T-V	T-V	T	T-V	T-V	T*
		4.2	Photo-volta-chromic	T-V	T-V *	T*	T-V**		T*
		4.3	Independently tunable NIR-VIS EC	T-V					T**
		4.4	Thermo-tropic/chromic	T-V	T-V	T	T-V**		T*
		4.5	Photo-chromic	T-V	T-V*	T	T-V**	T-V*	T*
		4.6	Fluidglass	T-V					
	Shadings	4.7	Screens/roller shades	T-V	T-V	T	T-V	T-V	T
		4.8	Blinds with slat angle control	T-V	T-V	T	T-V		
		4.9	Bi-directional transmission control	T-V	T-V	T	T-V		T**
		4.10	Insulating shutters	T-V	T-V		T-V	T-V	
		4.11	Shading with dual-axis tracking	T-V					
		4.12	Phase change material	T-V			T-V		
	Opaque	4.13	Double skin facade	T-V-A	T-V-A*	T-A*	T-V-A*	T-V-A*	T-A*
4.14		Double skin facade	T-A	T-A*	T-A*	T-A*	T-A*	T-A*	
4.15		Trombe wall	T-A	T-A*	T-A*	T-A*	T-A*	T-A*	
4.16		Green roof	T	T	T			T**	
4.17		Green wall	T	T	T			T**	
4.18		Movable/switchable insulation	T	T		T			
4.19		Thermocollect	T						
4.20		Phase change material	T	T	T	T		T**	

Note: See Table 3 for legend.

Moveable internal and external solar shading is probably the most widely used adaptive building envelope function. In all simulation tools that were included in this study, it is available in various forms. The GUIs of EnergyPlus, IDA ICE and IES VE offer the possibility to give dynamic shading devices additional thermal resistance properties. This makes it possible to simulate the performance of *insulating solar shading systems* (Hashemi and Gage 2012). In such an implementation, dynamic thermal insulation and solar shading are coupled, so that their separate effects cannot be analysed. As the need for coupled analysis of thermal and daylight aspects gets increasingly recognized, the options for modelling more advanced optical facade systems in building energy simulation software are also expanding (Table 4). Recent additions in many tools include the possibility to control the slat angle of blind systems and the properties of light-redirecting complex fenestration systems.

Prediction models for wall-integrated PCMs are present in EnergyPlus (Tabares-Velasco, Christensen, and Bianchi 2012), ESP-r (Heim and Clarke 2004), IDA ICE (Plüss et al. 2014) and TRNSYS (Kuznik, Virgone, and Johannes 2010). These models influence heat transfer in constructions via either the “effective heat capacity” or the “additional heat source”/“enthalpy” method. The need to

implement PCM features led the developers of EnergyPlus to abandon the CTF approach and introduce a numerical finite difference conduction algorithm (Pedersen 2007). This new algorithm includes a temperature coefficient that allows variable thermal conductivity during the simulation (Tabares-Velasco and Griffith 2012). Only a few applications of this latter model were found in the literature. The performance of transparent/translucent PCM systems can only be modelled in IDA ICE (Plüss et al. 2014) or with the use of reduced-order building models (Goia, Perino, and Haase 2012).

The capability of simulating double-skin facades (either transparent or opaque, including Trombe walls and ventilated facades) is generally available in several whole building simulation tools (EnergyPlus, ESP-r, TRNSYS, IDA ICE and IES VE) (Hensen, Bartak, and Drkal 2002; Kim and Park 2011). Some BPS tools provide specific models for the simulation of double-skin facades from the GUI (e.g. multi-skin in EnergyPlus), although their accuracy depends on the choice and availability of calculation methods for cavity heat transfer in terms of the mode of ventilation (buoyancy driven and/or mechanical), the ventilation air path (from outdoor to indoor, outdoor to outdoor, etc.), the type of solar shading in the ventilated cavity (Kim and Park 2011) and the spatial discretization of the air

cavity (Mateus, Pinto, and Da Graça 2014). Additionally, it is generally possible to represent a multiple skin facade by coupling the thermal model with an airflow network, but additional modelling could be required in order to ensure reliability of the results (Favoino 2015).

EnergyPlus, ESP-r and TRNSYS support the simulation of *green walls and roofs*. The models account for (i) long-wave and short-wave radiative exchange within the plant canopy, (ii) plant canopy effects on convective heat transfer, (iii) evapotranspiration from the soil and plants and (iv) heat conduction and storage in the soil layer (Djedjig, Bozonnet, and Belarbi 2015; Sailor 2008). In the EnergyPlus model, it is possible to include material properties that change over time with fluctuations in plant growth and moisture content (Sailor and Bass 2014).

Finally, EnergyPlus (Jin, Favoino, and Overend 2015) and IDA ICE (Bionda, Menti, and Manz 2014) can simulate the performance of building envelopes with *moveable insulation*. A controllable layer can be applied to the interior or exterior side of an opaque facade element to temporarily increase its thermal resistance. These materials are massless, which means that no thermal energy can be stored in a moveable insulation layer.

The suitability of a model for evaluating the performance of a particular adaptive building envelope system depends to a large extent on the flexibility that the BPS tool offers in terms of the control strategies that are available. This is especially the case for the application-oriented modelling features with extrinsic controls that are discussed in this section. More attention to the implementation and availability of control options is given in a separate section (Section 4.5).

The review of application-oriented modelling options presented in this paper focuses on software capabilities. It is not intended to provide a comprehensive review of existing adaptive building envelope materials, technologies and systems. In fact, the tendency of BPS tools to lag behind the market availability of adaptive technologies limits the number of application-oriented modelling capabilities available in a specific BPS tool, compared to

what is technologically available. As such, there are many adaptive building envelope systems (either at prototype or at product stage), whose performance cannot be evaluated yet with the existing application-oriented simulation models. Some examples are included in Table 4 for illustration (i.e. 4.3 (Llordés et al. 2013), 4.6 (Ritter 2014), 4.11 (Rossi, Nagy, and Schlueter 2012), 4.12 (Goia, Perino, and Haase 2012), 4.19 (Burdajewicz, Korjenic, and Bednar 2011)).

Therefore, from a product development point-of-view, it is more desirable to allow for bottom-up or general-purpose approaches to simulate emerging or not-yet-existing adaptive building envelope materials and technologies (Loonen et al. 2014).

4.4. General-purpose modelling options

General-purpose modelling options offer more flexibility than application-oriented features. A review of available general-purpose adaptive features is presented in this section and the results are summarized in Table 5. The discussion that follows provides the principal outcomes of this review. A more extensive description of the capabilities of each simulation tool is provided in the appendix.

EnergyPlus: Of all software tools analysed, EnergyPlus has had the largest growth in adaptive facade modelling capabilities since it was developed. Most notably, these developments have been driven by the introduction of the EnergyPlus Runtime Language (ERL) (Ellis, Torcellini, and Crawley 2007). With ERL, users can implement energy management systems (EMS) of various kinds by linking sensors, control logic and actuators. Among the possible EMS actuators are various thermophysical building envelope material properties (Table 5). These actuators can be controlled with user-defined IF-ELSE statements during simulation run-time.

ESP-r: ESP-r is a simulation tool with an open-source environment aimed at the research community. Since its first version, various groups have contributed general-purpose functionalities for modelling adaptive facade technologies. The capabilities include (i) *thermo-physical property*

Table 5. Overview of general-purpose modelling features for adaptive building envelope systems.

#	Controllable property	Required domains	EnergyPlus	ESP-r	IDA ICE	IES VE	TRNSYS
5.1	Visible optical properties	T-V	T-V*	T	T-V*	T-V*	T*
5.2	Solar optical properties	T-V	T-V*	T	T-V*	T-V*	T*
5.3	Emissivity	T	T*				
5.4	Surface heat transfer coefficient	T	T*	T*	T*	T*	T*
5.5	Solar absorption	T	T*				
5.6	Conductivity	T	T*	T*	T**		T**
5.7	Density/specific heat capacity	T		T*	T**		
5.8	Facade geometry	T-V					
5.9	Site rotation	T-V	T-V**	T*			T*
5.10	Evaporation at surface	T		T*			

Note: See Table 3 for legend.

substitution mode (MacQueen 1997), (ii) transparent multilayer construction control, (iii) *special materials* (Evans and Kelly 1996), (iv) variable thermo-physical properties (Nakhi 1995) and (v) the use of roaming files to model rotating buildings with changeable orientation. Each of these models has unique characteristics as well as control restrictions, as described in the appendix and Section 4.5.

IDA ICE: Unlike most other simulation tools, IDA ICE works with symbolic equations instead of variable assignments (Sahlin 2004). This feature makes it relatively easy to upgrade existing modelling functionality, as was recently done for the finite-difference multilayer wall model (“fdwall”) that can now account for time-varying thermo-physical properties (“fdwalldyn”) (Bionda, Menti, and Manz 2014). Other adaptive features in IDA ICE can be activated by defining custom control macros, and selecting the advanced-level instead of standard user interface.

IES VE: IES VE is a commercial simulation tool with a closed software environment. The program gives limited flexibility for modelling adaptive facades beyond the application-oriented features that were discussed in Section 4.3. Nevertheless, using APro, the module for time-scheduling and profiles in IES VE, there are some opportunities to link user-selected sensor values with time-varying facade property actuators (Table 5).

TRNSYS: In TRNSYS, the multi-zone building model (TYPE 56) is one out of a large number of possible system components. The *variable window id* option and a controllable bidirectional scattering distribution function (BSDF) (Hiller and Schöttl 2014) are directly implemented in TYPE 56. All other adaptive features in TRNSYS can be activated by manipulating (i.e. switching on/off or modulating) the connections to and from the TYPE 56 building model, via so-called equations using either the graphical Simulation Studio or by editing text files. These functions include overhangs and wingwalls (TYPE 34), shading masks (TYPE 64), attached sunspaces (with or without movable thermal insulation) (TYPE 37), windows with variable insulation properties (TYPE 35) and photovoltaic modules (TYPES 94, 180 and 194). In addition, it is also possible to adjust the way that weather files and radiation processors are connected to model the effect of time-varying facade orientations (e.g. rotating buildings).

4.5. Control options

An overview of the control options, according to the definitions given in Section 3.3 (hard-coded intrinsic, hard-coded extrinsic, time-scheduled and script based), is provided in Table 6. The table provides different information for each of the four control options:

- hard-coded intrinsic: only available for application-oriented modelling capabilities, the reader is

redirected to Table 4 for the specific passive technologies;

- hard-coded extrinsic: only available for application-oriented modelling capabilities. The rows indicate the different sensor options, and the number indicates the particular adaptive facade technology in Table 4 to which the specific control can be applied;
- time scheduled: available for all hard-coded extrinsic application-oriented modelling capabilities;
- script based: available for all application-oriented modelling capabilities (indicated as T4) and partially for general purpose modelling capabilities (indicated as a number in row 6.19 referring to Table 5). Row 6.18 indicates the availability of sensor options.

The script-based control approaches include EMS (Energy-Plus), user-defined control macros (IDA ICE), APro (IES VE) and “equations” and W-editor (TRNSYS). This control approach can also be applied, differently for each BPS tool, to the other three control options (hard-coded intrinsic and extrinsic, as well as time scheduled). This is indicated with a shaded cell in Table 6.

Dynamic operation of building components is usually represented in BPS tools by means of hard-coded preset rules (6.2–6.16) or time-scheduled operations (6.17). These control options are related to application-oriented modelling capabilities, in which the control rule is often closely related to operating modes of the technology itself. The hard-coded preset control rules can be editable, if the specific technology allows for extrinsic control, by selecting from a limited number of sensor options in the GUI. Otherwise, if the specific technology modelled is a smart adaptive technology, that is, only intrinsic control is available, the preset control rule is fixed and cannot be edited (e.g. relationship between glazing thermo-optical properties and glass temperature for thermochromic glazing).

When adopting a general-purpose modelling approach, the user is required to explicitly model the way the adaptive mechanism is triggered by boundary conditions, by defining sensors, control algorithms (either intrinsic or extrinsic) and actuators, following the architecture represented in Figure 2. This can be done in the user interface of the specific BPS tool, by means of scripting and/or the use of graphical interfaces (Table 6, script-based control type). This approach, although requiring a higher level of user expertise, and more detailed information about how the adaptive building element/material is controlled, gives a higher level of flexibility for modelling innovative components with different and more advanced control strategies/algorithms.

Design performance evaluation of adaptive building envelope systems could require the need for calculating metrics that may not be directly available as outputs of the simulation tool. For example, double-skin facades can be evaluated and/or operated according to their dynamic

Table 6. Overview of control modelling features for adaptive building envelope systems, numbers in the table entries indicate the applicability of the control to a specific model (cf. Tables 4 and 5).

Control type	Boundary condition	#	Sensor	EnergyPlus	ESP-r	IDA ICE	IES VE	TRNSYS
Hard-coded intrinsic	Material state	6.1	NA	Cf. Table 4	Cf. Table 4	Cf. Table 4	Cf. Table 4	Cf. Table 4
Hard-coded extrinsic	Constant	6.2	Always on	All extrinsic	All extrinsic	All extrinsic		
		6.3	Always off	All extrinsic	All extrinsic	All extrinsic		
	Climate	6.4	Outdoor air temperature	4.1, 4.2, 4.7–10, 4.13–15, 4.18	4.1, 4.2, 4.7, 4.8, 4.9	4.13–4.15		
		6.5	Horizontal solar radiation	4.1, 4.2, 4.7–10				
		6.6	Perpendicular solar radiation	4.1, 4.2, 4.7–10	4.1, 4.2, 4.7, 4.8, 4.9	4.1, 4.2, 4.7–10	4.1, 4.2, 4.7, 4.10	
		6.7	Block beam solar radiation	4.1, 4.2, 4.7, 4.8				
		6.8	Day/night	4.18			4.10	
		6.9	Wind speed	4.13–15		4.1, 4.2, 4.7–10		
		Building states	6.10	Heating load	4.18			
	6.11		Cooling load	4.1, 4.2, 4.7–10, 4.18				
	6.12		Zone air temperature	4.1, 4.2, 4.7, 4.10, 4.13–15, 4.18	4.1, 4.2, 4.7, 4.8, 4.9, 5.6–7			
	6.13		Daylight level	4.1, 4.2, 4.7–4.10				
	Occupant	6.14	CO ₂ concentration	4.13, 4.14	4.13, 4.15			
		6.15	Occupants' presence	4.1, 4.2, 4.7–10, 4.13–15, 4.18				
6.16		Visual comfort (e.g. glare) Thermal comfort (e.g. PMV)	4.1, 4.2, 4.7–10 4.13–15					
Time scheduled	N/A	6.17	N/A	All extrinsic	All extrinsic	All extrinsic	All extrinsic	
Script-based	Sensor	6.18		Any output		Any output	Limited	Any output
		6.19	Actuator	T4, 5.1–6, 5.9		T4, 5.1–2, 5.4, 5.6–7	T4, 5.1–2, 5.4	T4, 5.1, 5.2, 5.4, 5.6, 5.9

insulation efficiency or preheating efficiency (Zanghirella, Perino, and Serra 2011). Allowing the user to make this intermediate step, by transforming simulation outputs into this type of custom performance metrics/control input, could enable a more efficient design process, while simultaneously allowing the evaluation of more advanced control strategies. This can be done by means of script-based control strategies.

5. Conclusions, trends and future perspectives

This paper has highlighted the potential of simulation-based analysis in various stages of design and development of buildings with adaptive building envelopes. The main requirements and challenges compared to performance prediction of conventional, static building envelopes were identified. On these bases, we have presented a comprehensive comparative overview of application-oriented, general-purpose and control capabilities for the modelling and simulation of adaptive building envelopes in state-of-the-art whole building performance simulation software. It should be emphasized that the simulation of adaptive facades tends to involve a high level of multi-domain interactions and corresponding reciprocal exchange with other energy systems in buildings. It is therefore important that users develop suitable simulation strategies, by carefully matching the performance evaluation objectives with the capabilities and limitations of the different models and simulation tools at hand.

Relative to the well-established position of BPS in performance-based building design, the application of modelling and simulation for adaptive building envelope assessment is still at an early stage of development, with many more aspects of this field that have yet to be explored. This review has focused on the more advanced and comprehensive subset of available simulation tools, which are not always considered to be user-friendly, or suitable for early-phase design explorations. Various different GUIs have recently been developed, aiming at an easier integration of the simulation engines behind these BPS tools with the building design process. Due to interface limitations arising from the trade-off between ease of use and modelling complexity, the number of options for modelling adaptive facades in these user-friendly GUIs ranges from very limited to none. Extending such options is a clear target for future work. This section concludes the article by discussing four parallel trends and future perspectives that have the potential to further improve the impact of simulation-based design, research and engineering of adaptive building envelopes.

5.1. Advanced design support opportunities

In both research and engineering practice, it is increasingly common to extend BPS studies with more advanced analysis techniques such as uncertainty propagation and

sensitivity analysis methods (Clarke and Hensen 2015). Although the number of reports on the application of this type of analysis in combination with adaptive facades is still limited, there is potential for considerable progress also in this domain. Sensitivity analysis methods can be useful to identify the envelope design variables that have the largest influence on relevant building performance indicators (Tian 2013). Uncertainty analysis methods can additionally be used to make better-informed decisions by gaining in-depth understanding of the robustness of a particular adaptive facade design option with respect to possible scenarios regarding, for example, weather conditions and occupant behaviour (Hopfe and Hensen 2011). Purposely developed approaches such as dynamic sensitivity analysis can be helpful to deal with the time-varying features of adaptive facade problem configurations (Loonen and Hensen 2013).

Computational optimization is a second example of advanced design support that can assist in the performance assessment and design selection of adaptive building envelopes, as well as support the development and virtual prototyping of innovative adaptive facade technologies. The coupling of optimization algorithms with BPS tools allows for structured design space explorations that can help designers to find the most promising design solutions among the many possible alternatives (Attia et al. 2013; Evins 2013). Due to the close interaction between design and operational aspects of adaptive building envelopes, setting up the optimization formulation is a challenging task that requires novel approaches and further research (Favoino, Overend, and Jin 2015b; Kasinalis et al. 2014).

5.2. Parametric and generative design tools

The work presented in this article has mostly focused on the use of BPS as a tool for performance analysis. Recently, however, there is a growing interest in the use of these tools for performance-based generative design and architectural form finding (Shi and Yang 2013). These applications, mostly driven by dedicated plug-ins that interface BPS programs with CAD tools such as Rhinoceros and Revit, can also have potential when applied to the design of adaptive, especially kinetic facades. Existing work in this field has mostly addressed daylight aspects and innovative solar shading solutions (González and Fiorito 2015; Sharaidin, Burry, and Salim 2012). Future research could extend the scope to other performance aspects, and focus more on the design opportunities that the introduction of adaptive building envelopes brings along.

5.3. Co-simulation

Co-simulation is a simulation strategy in which two or more simulators solve systems of coupled equations, by exchanging data during simulation run-time (Trcka,

Hensen, and Wetter 2009). This strategy could become particularly important for performance prediction of adaptive building envelope systems, as it promotes opportunities for (i) integrating the simulations over different interrelated physical domains using different coupled tools, (ii) evaluating emerging technologies for which models may not be directly available in the specific BPS tool used and (iii) assessing the potential of advanced control strategies of adaptive building envelope systems in specialized control-oriented software. The co-simulation functionality can be enabled by means of middleware software, such as BCVTB (Wetter 2011b). An alternative development relates to the functional mock-up interface, which promises to make the coupling between building simulation tools even more flexible and versatile (Nouidui, Wetter, and Zuo 2013).

5.4. Next-generation simulation tools

Whereas co-simulation tries to leverage and reuse the capabilities of existing simulation programs, there are also significant ongoing research efforts that aim at reconceiving BPS modelling approaches from the bottom-up. At the centre of these developments are the simulation libraries based on the Modelica modelling language (Wetter 2009). Within International Energy Agency (IEA) EBC Annex 60 *New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards*, these developments are coordinated at an international level. Modelica provides an equation-based, object-oriented approach that has the potential to make modelling and simulation of complex building systems faster and more flexible. In the context of adaptive facades, it allows for high-resolution multi-domain analysis, rapid extension of modelling capabilities, as well as smooth interactions with other building-integrated energy systems. However, the development of Modelica for building performance simulation has not yet reached a mature phase. More research is needed to improve, for example, the robustness of component models, the interface with design tools and simulation speed.

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Notes

1. The database of building energy analysis software maintained by the US Department of Energy currently consists of 453 different tools (US DOE 2015b).

2. Although ESP-r does offer some rudimentary daylight prediction options, this functionality is not included in the present paper, because unlike for other tools, the advanced daylight models are not part of the ESP-r distribution, but should rather be classified under co-simulation.

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Appendix

This appendix aims to provide a more comprehensive explanation of the general-purpose modelling capabilities and control options available in each of the BPS tools analysed. By means of this appendix, readers could investigate whether the specific BPS tool is suitable for their modelling purpose, if an application-oriented option is not available in the user interface already.

A.1. EnergyPlus

EnergyPlus is a modular whole building energy simulation program based on the best features and capabilities of BLAST and DOE-2.1, developed under the auspices of the US Department of Energy. Its modular structure was designed in order to integrate different simulation engines (building loads and systems) and models (i.e. heat and mass balance, thermal comfort, daylight, advanced fenestration, etc.). One of the main goals for developing this tool was to enhance the possibility of adding and validating new models. Thanks to this feature, different modelling capabilities have been included into EnergyPlus so far, which is reflected by the high number of releases from the first one (currently at version 8.3). This has enabled the implementation of application-oriented modelling capabilities for different technologies, which was presented in the previous section. Recently, ERL was added to EnergyPlus (Ellis, Torcellini, and Crawley 2007) in order to replicate a building EMS in the simulation tool. The system is based, as in the real world, on the same elements of an EMS (sensors, control logics/algorithms and actuators). Since the latest release of the EMS system (US DOE 2015a), new actuators were introduced that enable control of thermo-optical properties at the building envelope level. The available actuators are able to control different building envelope adaptive components and properties, such as window shading devices, slat angle of the shading device, surface heat transfer coefficients, material surface properties, surface construction state (material construction properties) and surface boundary conditions. Moreover, any schedulable action in EnergyPlus can be controlled by means of an actuator within the EMS. A control algorithm can be designed in the EMS by means of IF-ELSE statements and simple algebraic operations, adopting the ERL programming language. The control algorithm can be used to control any actuator, based on data from sensors (wherein any output of EnergyPlus can potentially be treated as such). For example, the surface construction state actuator can be used to simulate variable thermo-optical properties: different constructions can be created, characterized by different thermo-physical properties, to be used in sequence according to a user-defined control algorithm (Favoio, Overend, and Jin 2015b). However, the different constructions are required to have similar thermal capacity due to limitations of the solution routines for the transient conduction through the building envelope elements adopted in EnergyPlus (US DOE 2015a). The EMS can be used to simulate controllable building envelope properties, also of technologies for which a model is not available yet, or to implement more advanced control strategies which are not available in EnergyPlus as hard-coded presets. Moreover, the EMS could be used to overcome some limitation at integrating smart glazing control with the simulation of artificial lighting systems control (Favoio and Overend 2015). In fact it is not possible to simulate the control of the lighting systems for intermediate

states of the smart glazing, when using the application-oriented modelling approach.

Due to the relatively new development, few documented applications of the use of EMS to model adaptive building envelope systems are available in the literature. Moreover, little evidence was found in the literature about the reliability of the EMS modelling approach when applied to dynamic building envelope components. Although for the specific case of modelling smart glazing, negligible differences exist between the application-oriented model and the general-purpose one by means of the EMS modelling approach (Favoino et al. 2015).

A.2. ESP-r

ESP-r is a multi-domain research-oriented BPS tool with an active development community and a source code that is accessible and modifiable. Over the course of the years, several functionalities that can be used to model adaptive behaviour in the building shell have been implemented by various research groups. Nevertheless, the use of these capabilities has remained limited, possibly because the features are (i) not well documented or (ii) concealed somewhere in the distributed menu-structure of ESP-r. This section summarizes five of such features.

One of the control laws in ESP-r is called *thermo-physical property substitution mode*. It is the only strategy that is not used for controlling the operation of HVAC systems. Instead of this, this control strategy can replace the thermo-physical properties (λ , c_p , ρ) of a construction during the course of the simulation. In essence, this control works like any other control algorithm in ESP-r, in the way that actions are triggered based on “tests” applied to sensed variables during run-time (MacQueen 1997). Unfortunately, this feature does not allow for full flexibility since it only affects opaque wall elements and the only “sensor variable” is indoor air temperature.

The previous feature dealt with opaque construction elements only; however, ESP-r also has a similar functionality available for modelling the dynamic behaviour of windows, transparent multilayer construction control. This functionality can for example be used for performance prediction of switchable glazing technologies. Currently, it is possible to replace window properties (.tmc-files) based on time, temperature, solar radiation level or illuminance level. Restrictions are that no more than two window states are supported without the possibility for gradual transitions. Recently, the capabilities of ESP-r have been further extended with the implementation of two new facilities for modelling transparent facade systems. Both the complex fenestration constructions (Lomanowski and Wright 2012) and the advanced optics (Kuhn et al. 2011) module have powerful options for facade systems with dynamic fenestration properties.

In ESP-r, the *special materials* facility was introduced to model “active building elements” (Evans and Kelly 1996). This universal functionality may be applied to any node within a multilayer construction. The *special material* subroutines can actively modify the matrix coefficients of these specific nodes at every time step. By doing this, it directly changes basic thermo-physical or optical properties and/or the associated energy flows at the equation level, based on the respective physical relationships. Currently, the following special materials are implemented: building-integrated photovoltaics, ducted wind turbines, solar thermal collectors, thermochromic glazing, evaporating surfaces and PCMs. It is possible to add new user-defined special materials; however, this may require time-intensive programming work.

ESP-r offers the unique possibility to use *roaming files*. This facility is used to change the location of a building as a function

of time, and was originally intended to be used for cruise ships. Because this roaming file not only includes coordinates but also orientation of the zone, it is very well suited for the simulation of rotating buildings.

Nakhi (1995) introduced variable thermo-physical properties in ESP-r with the aim to model heat transfer in building slabs in a more accurate way. The model takes into account that the properties of most construction materials are not constant, but change as a function of temperature and/or moisture content. This dependency is implemented via transient thermo-physical material properties (λ , c_p , ρ) that are linear or polynomial functions of layer temperature or moisture content. The same functionality can be used to model certain types of adaptive building envelopes.

A.3. IDA ICE

IDA Indoor Climate and Energy (IDA ICE) is a flexible, whole-building performance simulation tool that is mostly used in Nordic and Central European countries. It covers multiple physical domains, including models for building envelope heat transfer, flow networks, daylight illuminance and energy systems analyses. IDA ICE works with symbolic equations instead of variable assignments (as most other BPS tools do), and therefore, it is relatively easy to extend the existing modelling functionality. For example, the finite-difference multilayer wall model “fdwall” was recently extended with a new model “fdwalldyn” that allows for time-varying thermo-physical properties. The tool has both a standard and advanced-level interface. This enables a separation of concerns where expert users can implement adaptive features and control strategies directly into the mathematical model using the latter approach. Especially the possibility to define custom *control macros* is a useful feature in the context of adaptive facades, as it enables simulation users to control the operation of various building systems, facade actuators included.

A.4. IES VE

Integrated Environment Solutions Virtual Environment is a consultancy-oriented software, integrating different calculation modules in a comprehensive user interface. It integrates tools for thermal, airflow and daylight analysis, computational fluid dynamics (CFD), value engineering, cost planning, life cycle and occupant safety analysis. This modularity allows to integrate building performance analysis in multiple domains (i.e. thermal, airflow and daylight). The daylight analysis can only be used in the thermal module to evaluate the effect of dimmable artificial lights, but not to control shading devices or smart glazing technologies, while the CFD module can only use the results from the thermal analysis as boundary conditions and not vice versa.

IES VE is a commercial program. Its code is not accessible and the user cannot add any additional simulation modules to enhance either application-oriented or general-purpose modelling capabilities. This limits the application of IES VE to application-oriented models already included in the software and to some alternative approaches described in Section 4.3 or approximate solutions such as for PCMs (Kendrick and Walliman 2007).

Despite the limitations, a useful feature is found in the time-schedule module APpro. It enables the simulation of rule-based control of a building system and of the adaptive building envelopes available (shading devices, cavity ventilation, electrochromic glazing, etc.), even though it is limited by the availability of sensors. In fact only some of the software inputs and outputs can be used (cf. Table 6).

4.5. TRNSYS

The approach that TRNSYS takes towards managing complexity in the built environment is characterized by breaking down the problems into a series of smaller components. One of these components is a multi-zone building model – TYPE 56 – that can be connected to a large number of other components, including weather data, HVAC systems, occupancy schedules, controllers, output functions, thermal energy storage, renewable (solar) energy systems, etc. This particular configuration allows the user to set up and manipulate the connections between the building and various other subsystems/components in the simulation environment.

TRNSYS TYPE 56 offers the possibility to change the thermal and optical window properties during run-time with a function called *variable window ID*. Additionally, it is also possible to control the ratio of window/frame area, which influences the degree of transparent facade elements. In the near future, TRNSYS will be extended with a bidirectional scattering distribution function (BSDF) that can be changed at every time step of the simulation (Hiller and Schöttl 2014). All the other adaptive mechanisms in TRNSYS are not found in the (non-modifiable) building model itself, but in the connections with other components. Using *equations* in TRNSYS enables the application of Boolean logic and algebraic manipulations to almost all state variables in the simulation. This flow of information can then be used to drive a control algorithm that is able to dynamically “switch on”, “switch off” or modulate, for example, overhangs and wingwalls (TYPE 34), shading masks (TYPE 64), attached sunspaces (with or without movable thermal insulation) (TYPE

37), windows with variable insulation properties (TYPE 35) and photovoltaic modules (TYPES 94, 180 and 194). In addition, it is also possible to adjust the connections with weather files and radiation processors. In this way, the effects of changing orientations (e.g. rotating buildings) can be mimicked. Even more control flexibility can be achieved by connecting TRNSYS models to the W-editor (Type 79) (Keilholz et al. 2009). Type 79 makes use of W, a simple programming language that can influence the connection between the inputs and outputs of TRNSYS components at every iteration of the simulation.

The standard TRNSYS distribution already comes with an extensive library of components. Yet, one of the distinct benefits of TRNSYS’ modular structure is the fact that it allows users to add content by introducing new components (McDowell et al. 2004). With some coding efforts, it is possible to encapsulate the desired adaptive behaviour in a new TRNSYS TYPE, which can then be linked to the building model. Due to constraints in TRNSYS’ CTF method, coupling of these new TYPES with the building envelope model works in a rather indirect way via the so-called slab-on-grade approach. In TRNSYS it is not possible to substitute building shell constructions/properties during simulation run-time. Instead, developers can impose the desired behaviour by overwriting the inside surface layer temperatures of adjacent zones and the respective heat transfer coefficients. With respect to adaptive facades, Kuznik et al. (2010) and Claros-Marfil et al. (2014) recently demonstrated this approach for a new PCM wallboard TYPE, and Djedjig et al. (2015) developed a model for green walls.