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

Roel C.G.M. Loonen[A#], Fabio Favoino[B#], Jan L.M. Hensen[A], Mauro Overend[B].

[A] Building Physics and Services, Eindhoven University of Technology, Postbus 513 5600 MB, Eindhoven, the Netherlands.

[B] Glass and Façade Technology research group, University of Cambridge, Trumpington Street, CB2 1PZ, Cambridge, UK.

[#] These authors contributed equally to this work

Abstract

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. 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 analyze the existing information in this field. In the first part, the unique requirements for successful modeling and simulation of adaptive facades are discussed. In the second part, the capabilities of five widely-used building performance simulation 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 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 (Luible 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 (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 (e.g. thermal, luminous, air quality, etc.). Unlike most HVAC-dominated buildings, the performance of buildings with adaptive facades is to a very large extent determined by local climatic conditions and interactions with occupants and the other building systems. Traditional characterisation methods for building envelopes, such as *U-value* and *g-value*, are based on static assumptions. Therefore, due to the intrinsic time-varying behavior 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 modeling 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 maximise 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 behavior and variable weather influences.

For these reasons, modeling 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 analyzing adaptive facades are faced with a number of challenges and should develop their simulation strategy accordingly. The currently available information about modeling 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 building performance simulation 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 analyzes the opportunities and limitations of state-of-the-art simulation software at modelling adaptive building facades, based on their underlying assumptions and modeling methods. In section 4, we provide a detailed overview of the capabilities to model adaptive facades in five of the most widely-used building performance simulation 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 modeling and simulation of adaptive building envelopes forward in the coming years.

2 Challenges for performance prediction of adaptive building envelopes

Modeling and simulation of adaptive building envelopes has 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:

Modeling 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. 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;

Modeling 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 depends 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 heating, ventilation and air-conditioning (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 modeling resolution, solution algorithms, intended target audience, modeling options, ease-of-use vs. flexibility, etc. The simulation tools with most powerful modeling capabilities, and which have undergone most rigorous validation studies (e.g. EnergyPlus, ESP-r, IDA ICE, IES VE, TRNSYS), are all legacy software programs (Crawley et al. 2008). Although these tools have active development communities, and receive regular updates and extension of modeling 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 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.

---

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

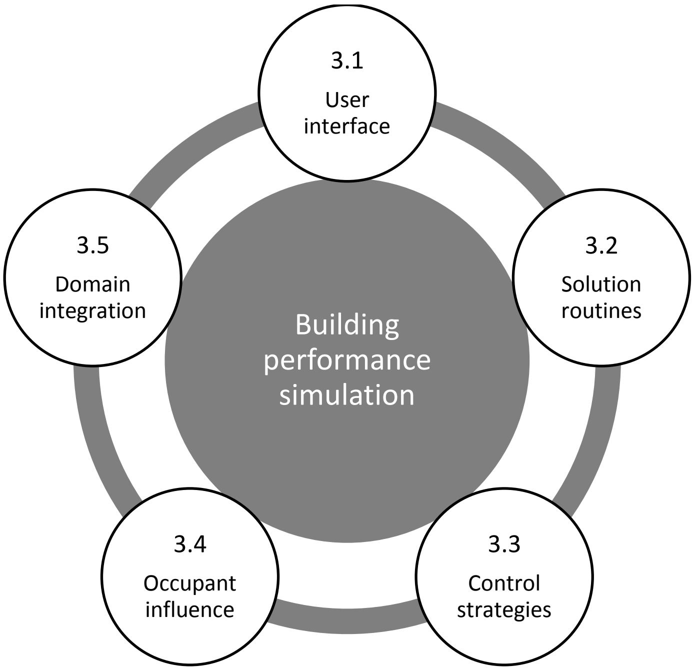

Figure 1. Different modeling aspects playing a role in performance evaluation of adaptive building envelope systems.

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 modeling features can be distinguished: (i) application-oriented and (ii) general-purpose features (Table 1). A*pplication-oriented* indicates that the modeling capability was implemented in the software with a specific adaptive building envelope technology in mind and is labeled 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 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.

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

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 optimised 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, 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 modeling 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 easier to take dynamically changing window properties into account in the simulation, also in BPS tools adopting response factors 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 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 modeled 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, occupant preferences); (ii) control logic level; (iii) actuators level, i.e. any building component that can be controlled (including HVAC, artificial lighting and adaptive building envelope systems).

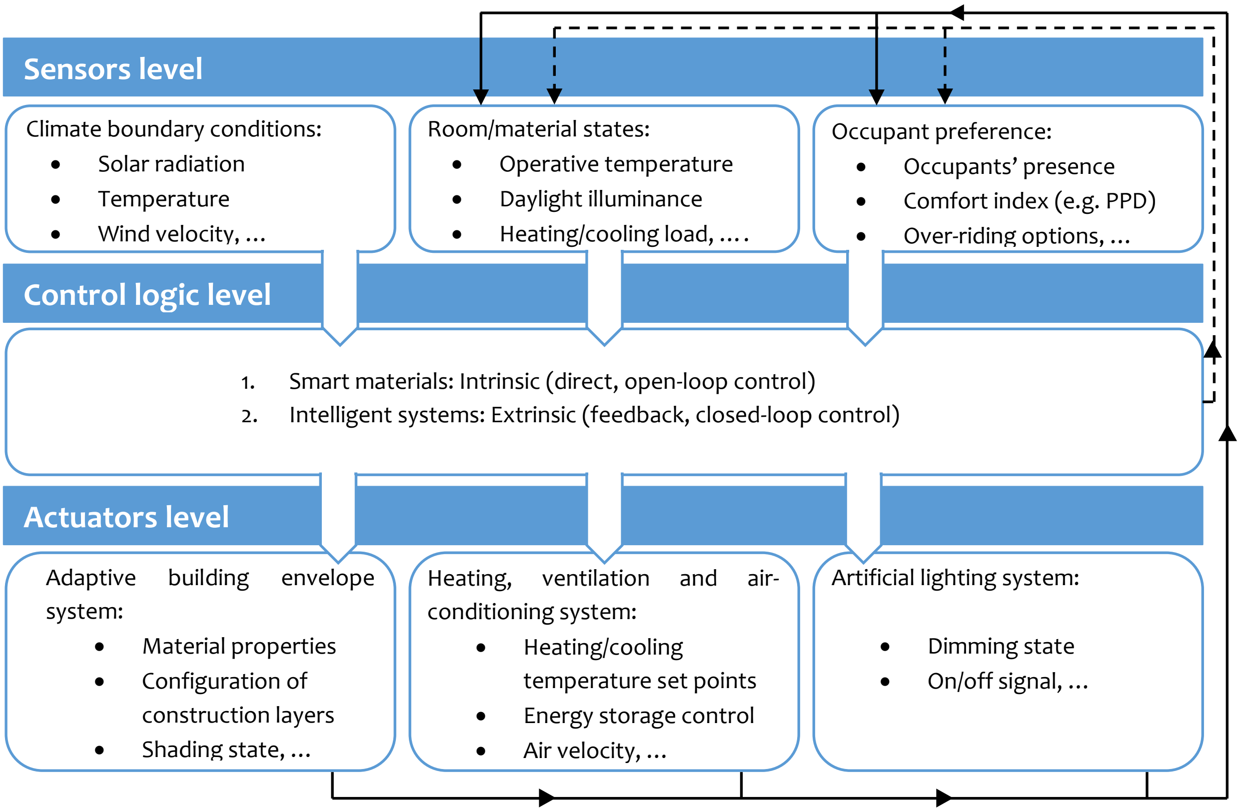

Figure 2. Control architecture for building systems, including building services and adaptive facades: the continuous line represents active, closed-loop, control; the dashed line represents passive, open-loop, control.

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 (e.g. 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. thermo-chromic, photo-chromic, phase change materials), 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" (e.g. 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. thermo-chromic windows), or for phase-changing materials, modeled via temperature-based changes in specific heat capacity.

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 pre-determined 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); (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 behavioral models that describe the interaction of building occupants with adaptive building envelope systems (Haldi and Robinson 2010; Hoes et al. 2009; Gunay et al. 2013). 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 behavior models for integration in BPS tools is an active field of research, coordinated at an international level via IEA ECB Annex 66 (Yan et al. 2015). 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: e.g. thermal, visual and mass-flow (air and/or moisture). Moreover, to ensure adequate levels of occupant comfort, there is a need to synchronise 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, TRNSYS (Figure 3). A limited subset of them also integrates daylight models[2] (and therefore artificial lighting models as well), such as EnergyPlus, IDA ICE, 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).

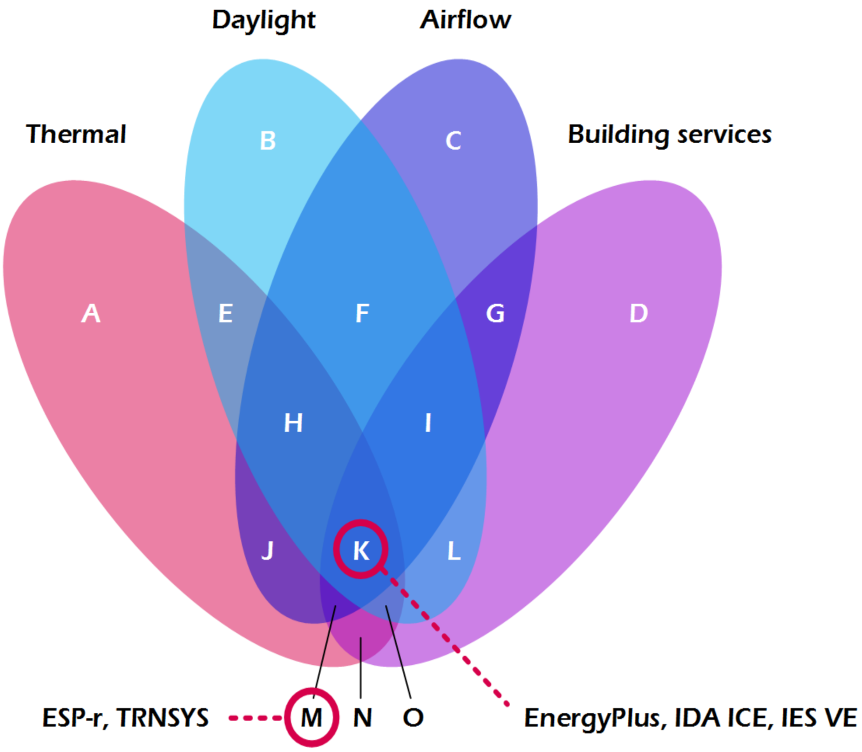

Figure 3. Multi-domain integration required to model adaptive building facades in different BPS tools .

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

---

[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.

main aim of this section is to develop these capabilities further by reviewing the specific adaptive envelope modeling 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 modeling adaptive facade behavior 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 modeling 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 modeling 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, money) to move towards more complex models; 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 et al. (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 (e.g. seasons, months, weeks, etc.), each with distinct building properties (Kasinalis et al. 2014; Favoino, Jin, and Overend 2014; Joe et al. 2013; Hoes et al. 2011; Loonen, Trčka, and Hensen 2011) (Figure 4a). 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. surfaces and construction nodes 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 4b). 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 modeling method is well able to capture switching of instantaneous solar gains, e.g. 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 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 literature.

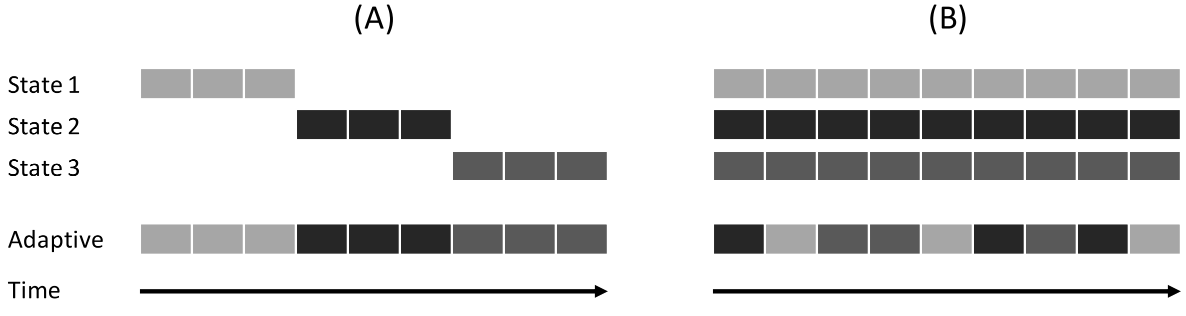

Figure 4. Schematic representation of workaround strategies for modeling the performance of adaptive facades. Case A represents the discrete approach that combines a number of short term simulations. Case B represents the approach that assembles the results of simulations with static facades during post-processing.

4.2 Overview of capabilities – methodology

A review of the opportunities for modeling 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 (Crawley et al. 2008; Attia et al. 2012) and first-hand experience, five simulation tools (presented in Table 2) were selected on the basis of the following criteria:

- Extensive building envelope modeling 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.

Table 2. Characteristics of whole Building Energy Simulation tools with respect to performance prediction of adaptive building envelope systems.

	Conduction solution method	**User Interface**[3]	**Source code access and modification**	**Control simulation capabilities**	**Physical domain integration**
EnergyPlus v8.3	CTF, Finite difference[4]	IDF editor, DesignBuilder, Comfen, OpenStudio, Simergy, Sefaira, DIVA, AECOsim	X	Presets, Time-scheduled, Energy Management System	Thermal, Visual, Airflow
ESP-r	Finite volume	Graphic and text mode	X	Presets, Time-scheduled	Thermal, Airflow[5]
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[6]		Presets, Time-scheduled, Formula profile (APpro)	Thermal, Visual,

---

[3] Options for modeling adaptive facades are significantly limited when the simulation engine is accessed through one of the third-party GUIs

[4] By 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 literature.

[5] Daylight 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.

					Airflow
TRNSYS v17.1	CTF[7]	TRNBuild, SketchUp plug-in	(X)[8]	Presets, Time-scheduled, user-defined *equations* in Simulation Studio, W-editor (Type 79)	Thermal, Airflow

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, 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 color), control options related to a specific technology (only for Table 6, indicating the modelling options for which this control is available), 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 modeling 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 modeling 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.

---

[6] Additional 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.

[7] Simulation 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 (Kosny, 2015)

[8] Excluding 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

4.3 Application-oriented capabilities

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

Table 4. Overview of application-oriented features for modeling adaptive building envelope systems. See Table 3 for legend.

		#	Adaptive facade technology	Required Domains	Energy Plus	ESP-r	IDA ICE	IES VE	TRNSYS
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	T
		4.11	Shading with dual-axis tracking	T-V					
		4.12	Phase change material	T-V			T-V		
		4.13	Double skin facade	T-V-A	T-V-A*	T-A*	T-V-A*	T-V-A*	T-A*
Opaque		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**

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 modeling switchable glazing technologies are embedded in several simulation tools. All the software tools analyzed offer the possibility to control 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 control of adaptation (e.g. room temperature, ambient temperature, incident radiation).

Thermo-tropic/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 thermo-tropic/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).

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 analyzed. As the need for coupled analysis of thermal and daylight aspects gets increasingly recognised, the options for modeling 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 *phase change materials* (PCM) 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 literature. The performance of transparent/translucent PCM systems can only be modeled 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, 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 (Sailor 2008; Djedjig, Bozonnet, and Belarbi

2015). 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 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 modeling options

General-purpose modeling 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 summarised 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 Appendix A.

Table 5. Overview of general-purpose modeling features for adaptive building envelope systems. See Table 3 for legend.

#	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*			

EnergyPlus Of all software tools analyzed, EnergyPlus has had the largest growth in adaptive facade modeling 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 modeling adaptive facade technologies. The capabilities include: (i) *thermo-physical property substitution mode* (MacQueen 1997), (ii) transparent multi-layer 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 Appendix A 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 modeling functionality, as was recently done for the finite-difference multi-layer wall model ("fdwall") that can now account for time-varying thermo-physical properties ("fdwalldyn") (Bionda, Menti, and Manz 2014). Other adaptive features in IDA ICA 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 modeling adaptive facades beyond the application-oriented features that were discussed in section 4.3. Nevertheless, using APpro, 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 bi-directional 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 the 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 sensors 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 (EnergyPlus), user-defined control macros (IDA ICE), APpro (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 the Table 6.

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

#	Control type	Boundary condition	Sensor	EnergyPlus	ESP-r	IDA ICE	IES VE	TRNSYS
6.1	**Hard-coded Intrinsic**	Material state	NA	Cf. Table 4	Cf. Table 4	Cf. Table 4	Cf. Table 4	Cf. Table 4
6.2	**Hard-coded Extrinsic**		Always on	All extrinsic	All extrinsic	All extrinsic		
6.3			Always off	All extrinsic	All extrinsic	All extrinsic		
6.4		Climate	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	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	4.10
6.9			Wind speed	4.13-15		4.1, 4.2, 4.7-10		
6.10		Building states	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				
6.14			CO_2 concentration	4.13, 4.14	4.13, 4.15			
6.15		Occupant	Occupants' presence	4.1, 4.2, 4.7-10, 4.13-15, 4.18				
6.16			Visual comfort (e.g. glare)	4.1, 4.2, 4.7-10				
			Thermal comfort (e.g. PMV, operative temperature)	4.13-15	4.1, 4.2, 4.7, 4.8, 4.9, 5.6-7			
6.17	**Time scheduled**	N/A	N/A	All extrinsic	All extrinsic	All extrinsic	All extrinsic	All extrinsic
6.18	**Script-based**		Sensor	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

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 insulation efficiency or pre-heating 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 modeling and simulation of adaptive building envelopes in state-of-the-art whole building performance simulation software. It should be emphasised that 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 modeling 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 modeling complexity, the number of options for modeling 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 e.g. weather conditions and occupant behavior (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 (Evins 2013; Attia et al. 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 2015; 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 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 specialised 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 (FMI), 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 modeling approaches from the bottom up. At the center of these developments are the simulation libraries based on the Modelica modeling 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 potential to make modeling 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 modeling 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 e.g. the robustness of component models, the interface with design tools, and simulation speed.

6 Acknowledgments

The authors would like to thank EU Cost Action TU1403 “Adaptive Facades Network” for providing excellent research networking. The Dutch authors acknowledge the support from RVO

EOSLT08016 project FACET. The British authors would like to acknowledge the support from EPSRC and project RG70518, funded by Wintech ltd.

7 References

Attia, S., Hamdy, M., O'Brien,W., and S. Carlucci. 2013. "Assessing Gaps and Needs for Integrating Building Performance Optimization Tools in Net Zero Energy Buildings Design." Energy & Buildings 60: 110–24. doi:10.1016/j.enbuild.2013.01.016.

Attia, S., Hensen, J.L.M., Beltrán, L., and A. De Herde. 2012. "Selection Criteria for Building Performance Simulation Tools: Contrasting Architects' and Engineers' Needs." Journal of Building Performance Simulation 5 (3): 155–69. doi:10.1080/19401493.2010.549573.

Ayres, JM, and E Stamper. 1995. "Historical Development of Building Energy Calculations." ASHRAE Transactions 101 (1): 841–49.

Baetens, R, B.P. Jelle, and A Gustavsen. 2010. "Properties, Requirements and Possibilities of Smart Windows for Dynamic Daylight and Solar Energy Control in Buildings: A State-of-the-Art Review." Solar Energy Materials and Solar Cells 94 (2): 87–105.

Bakker, L.G., E.C.M. Hoes-van Oeffelen, R.C.G.M. Loonen, and J.L.M. Hensen. 2014. "User Satisfaction and Interaction with Automated Dynamic Facades: A Pilot Study." Building and Environment 78 (August): 44–52. doi:10.1016/j.rser.2013.04.016.

Bionda, D, U.P. Menti, and H Manz. 2014. "Kann Eine Gebaüdehülle Mit Steuerbarem U-Wert Zur Reduktion Des Kühlenenergiebedarfs Beitragen?" In Proceedings of BauSIM2014, the Fifth German-Austrian IBPSA Conference, 649–55.

Brahme, R., Z. O'Neill, W. Sisson, and K. Otto. 2009. "Using Existing Whole Building Energy Tools for Designing Net-Zero Energy Buildings – Challenges and Workarounds." In Proceedings of Building Simulation 2009, 9–16. Glasgow, Scotland.

Burdajewicz, F, A Korjenic, and T Bednar. 2011. "Bewertung Und Optimierung von Dynamischen Dämmsystemen Unter Berücksichtigung Des Wiener Klimas." Bauphysik 33 (1): 49–58.

Clarke, J.A. 2001. Energy Simulation in Building Design. Oxford: Butterworth-Heinemann.

Clarke, J.A., and J.L.M. Hensen. 2015. "Integrated Building Performance Simulation:Progress, Prospects and Requirements." Building and Environment, 1–13. doi:10.1016/j.buildenv.2015.04.002.

Claros-Marfil, L. J., Dentel, A., Padial, J. F., and B. Lauret. 2014. "Active and passive PCM walls simulation–a new TRNSYS PCM-Type." Proceedings of the 1st International Congress on research in Construction and Architectural Technologies.

Crawley, D, J Hand, M Kummert, and B Griffith. 2008. "Contrasting the Capabilities of Building Energy Performance Simulation Programs." Building and Environment 43 (4): 661–73. doi:10.1016/j.buildenv.2006.10.027.

Da, Y., O'Brien, W. ,Hong, T., Feng, X., Gunay, H.B., Tahmasebi, F. and A. Mahdavi. 2015. "Occupant behavior modeling for building performance simulation: current state and future challenges." Energy and Buildings 107: 264-278.

DeForest, N., A. Shehabi, G. Garcia, J. Greenblatt, E. Masanet, E.S. Lee, S. Selkowitz, and D.J. Milliron. 2013. "Regional Performance Targets for Transparent near-Infrared Switching Electrochromic Window Glazings." Building and Environment 61 (March): 160–68. doi:10.1016/j.buildenv.2012.12.004.

Delcroix, B, M Kummert, A Daoud, and M Hiller. 2012. "Conduction Transfer Functions in TRNSYS Multizone Building Model: Current Implementation, Limitations and Possible Improvements." In Proceedings of SimBuild 20102, the Fifth National Conference of IBPSA-USA, 219–26. Madison, WI.

Djedjig, R., Bozonnet, E. and R. Belarbi. 2015. "Analysis of Thermal Effects of Vegetated Envelopes: Integration of a Validated Model in a Building Energy Simulation Program." Energy and Buildings 86: 93–103. doi:10.1016/j.enbuild.2014.09.057.

Ellis, P. G., Torcellini, P.A. and D. B. Crawley. 2007. "Simulation of Energy Management Systems in EnergyPlus." In Proceedings of Building Simulation 2007, 1346–53.

Erickson, J. 2013. "Envelope as Climate Negotiator: Evaluating Adaptive Building Envelope's Capacity to Moderate Indoor Climate and Energy." PhD Thesis, Arizona State University.

Evans, M., and N. J. Kelly. 1996. Modelling Active Building Elements with Special Materials. ESRU Occasional Paper, University of Strathclyde, Glasgow.

Evins, R. 2013. "A Review of Computational Optimisation Methods Applied to Sustainable Building Design." Renewable and Sustainable Energy Reviews 22 (June): 230–45. doi:10.1016/j.rser.2013.02.004.

Fabi, V., Andersen, R. V., Corgnati, S., and B.W. Olesen. 2013. "Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models." Building and Environment 58: 188-198.

Favoino, F. 2015. "Assessing the Performance of an Advanced Integrated Facade by Means of Simulation: The ACTRESS Facade Case Study." Journal of Facade Design and Engineering, vol. Preprint, no. Preprint, pp. 1-23, 2015. DOI: 10.3233/FDE-150038

Favoino, F., Cascone, Y., Bianco, L., Goia, F., Zinzi, M., Overend, M., Serra, V. and M. Perino. 2015. "Simulating Switchable Glazing with EnergyPlus: An Empirical Validation and Calibration of a Thermotropic Glazing Model." In Proceedings of Building Simulation 2015. Hyderabad, India.

Favoino, F., Goia, F., Perino, M. and V. Serra. 2014. "Experimental Assessment of the Energy Performance of an Advanced Responsive Multifunctional Façade Module." Energy and Buildings 68 (January): 647–59. doi:10.1016/j.enbuild.2013.08.066.

Favoino, F., Jin, Q., and M. Overend. 2014. "Towards an Ideal Adaptive Glazed Façade for Office Buildings." In Proceedings of 6th International Conference on Sustainability in Energy and Buildings, 2014, Energy Procedia, Volume 62, 2014, Pages. Cardiff, Wales.

Favoino, F., and M. Overend. 2015. "A Simulation Framework for the Evaluation of next Generation Responsive Building Envelope Technologies." In Proceedings of 6th International Building Physics Conference, IBPC 2015,. Torino, Italy.

Favoino, F., Overend, M., and Q. Jin. 2015. “The Optimal Thermo-Optical Properties and Energy Saving Potential of Adaptive Glazing Technologies.” Applied Energy 156 (October 2015,): 1–15.

Freire, R. Z., Mazuroski, W., Abadie, M.O., and N. Mendes. 2011. “Capacitive Effect on the Heat Transfer through Building Glazing Systems.” Applied Energy 88 (12): 4310–19. doi:10.1016/j.apenergy.2011.04.006.

Goia, F., and Y. Cascone. 2014. “The Impact of an Ideal Dynamic Building Envelope on the Energy Performance of Low Energy Office Buildings.” Energy Procedia 58 (1876): 185–92. doi:10.1016/j.egypro.2014.10.427.

Goia, F., Perino,M. and M. Haase. 2012. “A Numerical Model to Evaluate the Thermal Behaviour of PCM Glazing System Configurations.” Energy and Buildings 54: 141–53. doi:10.1016/j.enbuild.2012.07.036.

González, J., and F. Fiorito. 2015. “Daylight Design of Office Buildings: Optimisation of External Solar Shadings by Using Combined Simulation Methods.” Buildings 5 (2): 560–80. doi:10.3390/buildings5020560.

Gunay, H. B., O'Brien, W. and I. Beausoleil-Morrison. 2013. "A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices." Building and Environment 70: 31-47.

Haldi, F., and D. Robinson. 2010. “On the Unification of Thermal Perception and Adaptive Actions.” Building and Environment 45 (11): 2440–57. doi:10.1016/j.buildenv.2010.05.010.

Hashemi, A., and S. Gage. 2012. “Technical Issues That Affect the Use of Retrofit Panel Thermal Shutters in Commercial Buildings.” Building Services Engineering Research and Technology 35 (1): 6–22. doi:10.1177/0143624412462906.

Heim, D, and J Clarke. 2004. “Numerical Modelling and Thermal Simulation of PCM–gypsum Composites with ESP-R.” Energy and Buildings 36 (8): 795–805. doi:10.1016/j.enbuild.2004.01.004.

Hensen, J.L.M., M Bartak, and F Drkal. 2002. “Modeling and Simulation of a Double-Skin Facade System.” ASHRAE Transactions 108 (2): 1251–59.

Hensen, J.L.M., Djunaedy, E., Trcka, M & Yahiaoui, A. (2004). Building performance simulation for better design: some issues and solutions. In Wit, M.H. de (Ed.), Proceedings of the 21st PLEA International conference on Passive and low energy architecture, 19-21 September, pp. 1185-1190(vol.2). Eindhoven: Technische Universiteit Eindhoven.

Hiller, M., and P. Schöttl. 2014. “Modellierung Komplexer Verglasungssysteme in Trnsys.” In Proceedings of BauSIM2014, the Fifth German-Austrian IBPSA Conference, 387–94.

Hoes, P, J.L.M. Hensen, M.G.L.C. Loomans, B De Vries, and D Bourgeois. 2009. “User Behavior in Whole Building Simulation.” Energy and Buildings 41 (3): 295–302. doi:10.1016/j.enbuild.2008.09.008.

Hoes, P., M. Trcka, J.L.M. Hensen, and B. Hoekstra Bonnema. 2011. “Investigating the Potential of a Novel Low-Energy House Concept with Hybrid Adaptable Thermal Storage.” Energy Conversion and Management 52 (6): 2442–47.

Hong, T., D’Oca, S., Turner, W.J.N., and S. C. Taylor-Lange. 2015. “An Ontology to Represent Energy-Related Occupant Behavior in Buildings. Part I: Introduction to the DNAs Framework.” Building and Environment 92: 764–77. doi:10.1016/j.buildenv.2015.02.019.

Hopfe, C. J., and J. L M Hensen. 2011. “Uncertainty Analysis in Building Performance Simulation for Design Support.” Energy and Buildings 43 (10): 2798–2805. doi:10.1016/j.enbuild.2011.06.034.

IEA. 2013. Technology Roadmap - Energy Efficient Building Envelopes. International Energy Agency.

Jin, Q., Favoino, F., and M. Overend. 2015. “Study in the Potential of Opaque Adaptive Façade for Office Building in a Temperate Climate.” In Proceedings of Building Simulation 2015. Hyderabad, India.

Joe, J., Choi, W., Kwon, H. and JH Huh. 2013. “Load Characteristics and Operation Strategies of Building Integrated with Multi-Story Double Skin Facade.” Energy and Buildings 60 (May): 185–98. doi:10.1016/j.enbuild.2013.01.015.

Kasinalis, C., R.C.G.M. Loonen, D. Cóstola, and J.L.M. Hensen. 2014. “Framework for Assessing the Performance Potential of Seasonally Adaptable Facades Using Multi-Objective Optimization.” Energy and Buildings 79 (August): 106–13. doi:10.1016/j.enbuild.2014.04.045.

Keilholz, W, Sette,P, and E. Soussi. 2009. "The W programming language User & Reference Manual". CSTB France.

Kendrick, C., and N. Walliman. 2007. “Removing Unwanted Heat in Lightweight Buildings Using Phase Change Materials in Building Components: Simulation Modelling for PCM Plasterboard.” Architectural Science Review 50 (3): 265–73. doi:10.3763/asre.2007.5032.

Kim, D. W., and C. S. Park. 2011. “Difficulties and Limitations in Performance Simulation of a Double Skin Façade with EnergyPlus.” Energy and Buildings 43 (12): 3635–45. doi:10.1016/j.enbuild.2011.09.038.

Kimber, M., W.W. Clark, and L. Schaefer. 2014. “Conceptual Analysis and Design of a Partitioned Multifunctional Smart Insulation.” Applied Energy 114 (February): 310–19.

Kośny, J. 2015. "Thermal and Energy Modeling of PCM-Enhanced Building Envelopes." PCM-Enhanced Building Components. Springer International Publishing. 167-234.

Kuhn, T. E., Herkel, S., Frontini, F., Strachan, P., and G. Kokogiannakis. 2011. “Solar Control: A General Method for Modelling of Solar Gains through Complex Facades in Building Simulation Programs.” Energy and Buildings 43 (1): 19–27. doi:10.1016/j.enbuild.2010.07.015.

Kuznik, F., David, D., Johannes, K. and J. J. Roux. 2011. “A Review on Phase Change Materials Integrated in Building Walls.” Renewable and Sustainable Energy Reviews 15 (1): 379–91. doi:10.1016/j.rser.2010.08.019.

Kuznik, F., Virgone, J., and K. Johannes. 2010. “Development and Validation of a New TRNSYS Type for the Simulation of External Building Walls Containing PCM.” Energy and Buildings 42 (7): 1004–9. doi:10.1016/j.enbuild.2010.01.012.

Liu, M., Wittchen, K.B., and P. K. Heiselberg. 2014. “Development of a Simplified Method for Intelligent Glazed Façade Design under Different Control Strategies and Verified by

Building Simulation Tool BSim." Building and Environment 74 (April): 31–38. doi:10.1016/j.buildenv.2014.01.003.

Llordés, A., Garcia, G., Gazquez, J., and D. J. Milliron. 2013. "Tunable near-Infrared and Visible-Light Transmittance in Nanocrystal-in-Glass Composites." Nature 500: 323–27. doi:10.1038/nature12398.

Lomanowski, B.A., and J.L. Wright. 2012. "The Complex Fenestration Construction: A Practical Approach for Modelling Windows with Shading Devices in ESP-R." Journal of Building Performance Simulation 5 (January): 185–98. doi:10.1080/19401493.2011.552735.

Loonen, R.C.G.M., and J.L.M. Hensen. 2013. "Dynamic Sensitivity Analysis for Performance-Based Building Desing and Operation." In Proceedings of Building Simulation 2013.

Loonen, R.C.G.M., P. Hoes, and J.L.M. Hensen. 2014. "Performance Prediction of Buildings with Responsive Building Envelopes - Some Challenges and Solutions." In Proceedings of Building Simulation and Optimization, IBPSA BSO14, 1–8. London, UK.

Loonen, R.C.G.M., S. Singaravel, M. Trčka, D. Cóstola, and J.L.M. Hensen. 2014. "Simulation-Based Support for Product Development of Innovative Building Envelope Components." Automation in Construction 45 (September): 86–95.

Loonen, R.C.G.M., M. Trčka, D. Cóstola, and J.L.M. Hensen. 2013. "Climate Adaptive Building Shells: State-of-the-Art and Future Challenges." Renewable and Sustainable Energy Reviews 25 (September): 483–93.

Loonen, R.C.G.M., M. Trčka, and J.L.M. Hensen. 2011. "Exploring the Potential of Climate Adaptive Building Shells." In Proceedings of Building Simulation 2011, 2148–55. Sydney, Australia.

Luible, A. 2015. "COST Action 1403." In Proceedings of Energy Forum 2015. Bern, Switzerland.

MacQueen, J. 1997. "The Modeling and Simulation of Energy Management Control Systems." PhD Thesis, University of Strathclyde, Glasgow.

Mateus, N. M., Pinto, A. and G Carrilho Da Graça. 2014. "Validation of EnergyPlus Thermal Simulation of a Double Skin Naturally and Mechanically Ventilated Test Cell." Energy and Buildings 75: 511–22. doi:10.1016/j.enbuild.2014.02.043.

McDowell, T.P., D.E. Bradley, J.W. Thornton, and M. Kummert. 2004. "Simulation Synergy: Expanding TRNSYS Capabilities and Usability." In Proceedings of SIMBUILD 2004, IBPSA-USA Conference on Building Sustainability and Performance Through Simulation, 1–6.

Moloney, J. 2011. Designing Kinetics for Architectural Facades: State Change. Routledge.

Nakhi, A.E. 1995. "Adaptive Construction Modelling within Whole Building Dynamic Simulation." PhD Thesis, University of Strathclyde, Glasgow.

Nielsen, M. V., Svendsen, S., and L. Bjerregaard Jensen. 2011. "Quantifying the Potential of Automated Dynamic Solar Shading in Office Buildings through Integrated Simulations of Energy and Daylight." Solar Energy 85 (5): 757–68. doi:10.1016/j.solener.2011.01.010.

Nouidui, T., Wetter, M., and W. Zuo. 2013. "Functional Mock-up Unit for Co-Simulation Import in EnergyPlus." Journal of Building Performance Simulation 7 (February): 192–202. doi:10.1080/19401493.2013.808265.

Oh, Sukjoon, and Jeff S. Haberl. 2015. “Origins of Analysis Methods Used to Design High-Performance Commercial Buildings: Whole-Building Energy Simulation.” Science and Technology for the Built Environment 4731 (October): 1–20. doi:10.1080/23744731.2015.1063958.

Pedersen, C O. 2007. “Advanced Zone Simulation in EnergyPlus: Incorporation of Variable Properties and Phase Change Material (PCM) Capability.” In Proceedings of Building Simulation 2007, 1341–45. Beijing, China.

Perino, M., ed. 2008. IEA ECBCS Annex 44. State of the Art Review. Volume 2A Responsive Building Elements.

Perino, M., and Serra, V. 2015. "Switching from static to adaptable and dynamic building envelopes: A paradigm shift for the energy efficiency in buildings. "Journal of Facade Design and Engineering, vol. Preprint, no. Preprint, pp. 1-21.

Plüss, I., P. Kräuchi, D. Bionda, M. Schröcker, S. Felsenstein, and G. Zweifel. 2014. “Modellbildung Eines Phasenwechsel-Fassadenelements in IDA ICE.” In Proceedings of BauSIM2014, the Fifth German-Austrian IBPSA Conference, 374–78.

Reinhart, C. F. 2004. "Lightswitch-2002: a model for manual and automated control of electric lighting and blinds." Solar Energy 77.1: 15-28.

Reynders, G., T. Nuytten, and D. Saelens. 2013. “Potential of Structural Thermal Mass for Demand-Side Management in Dwellings.” Building and Environment 64 (June): 187–99. doi:10.1016/j.buildenv.2013.03.010.

Ritter, V. 2014. “Challenges in the Development of the Adaptive Solar Thermal Facade System Fluidglass.” In Proceedings of Façade2014 – Conference on Building Envelopes. Luzern, Switzerland.

Rossi, D., Nagy, Z., and A. Schlueter. 2012. “Adaptive Distributed Robotics for Environmental Performance, Occupant Comfort and Architectural Expression.” International Journal of Architectural Computing 10 (2): 341–60.

Sahlin, P. 2004. “Whole-Building Simulation with Symbolic DAE Equations and General Purpose Solvers.” Building and Environment 39 (8): 949–58. doi:10.1016/j.buildenv.2004.01.019.

Sailor, D.J. 2008. “A Green Roof Model for Building Energy Simulation Programs.” Energy and Buildings 40 (8): 1466–78. doi:10.1016/j.enbuild.2008.02.001.

Sailor, D.J., and B. Bass. 2014. “Development and Features of the Green Roof Energy Calculator (GREC).” Journal of Living Architecture 1 (3): 36–58.

Sharaidin, K., Burry, J. and F. Salim. 2012. “Integration of Digital Simulation Tools With Parametric Designs to Evaluate Kinetic Façades for Daylight Performance.” In Physical Digitality: Proceedings of the 30th eCAADe Conference, 2:701–9.

Shi, X., and W. Yang. 2013. “Performance-Driven Architectural Design and Optimization Technique from a Perspective of Architects.” Automation in Construction 32: 125–35. doi:10.1016/j.autcon.2013.01.015.

Spitler, J.D. 2011. “Thermal Load and Energy Performance Prediction.” In Building Performance Simulation for Design and Operation, edited by J.L.M. Hensen and R. Lamberts, 84–142. Spon Press.

Tabares-Velasco, P.C., Christensen, C., and M. Bianchi. 2012. “Verification and Validation of EnergyPlus Phase Change Material Model for Opaque Wall Assemblies.” Building and Environment 54 (August): 186–96.

Tabares-Velasco, P. C., and B. Griffith. 2012. “Diagnostic Test Cases for Verifying Surface Heat Transfer Algorithms and Boundary Conditions in Building Energy Simulation Programs.” Journal of Building Performance Simulation 5 (5): 329–46. doi:10.1080/19401493.2011.595501.

Tian, W. 2013. “A Review of Sensitivity Analysis Methods in Building Energy Analysis.” Renewable and Sustainable Energy Reviews 20 (April): 411–19.

Trcka, M., J.L.M. Hensen, and M. Wetter. 2009. “Co-Simulation of Innovative Integrated HVAC Systems in Buildings.” Journal of Building Performance Simulation 2 (3): 209–30. doi:10.1080/19401490903051959.

US DOE. 2015a. “Application Guide for EMS Energy Management System - User Guide.” http://nrel.github.io/EnergyPlus/EMS_Application_Guide/EMS_Application_Guide/.

US DOE. 2015b. “Building Energy Software Tools Directory.” http://apps1.eere.energy.gov/buildings/tools_directory/.

Wetter, M. 2009. “Modelica-Based Modelling and Simulation to Support Research and Development in Building Energy and Control Systems.” Journal of Building Performance Simulation 2 (2): 143–61. doi:10.1080/19401490902818259.

Wetter, M. 2011a. “A View on Future Building System Modeling and Simulation.” In Building Performance Simulation for Design and Operation, edited by J.L.M. Hensen and R. Lamberts.

Wetter, M. 2011b. “Co-Simulation of Building Energy and Control Systems with the Building Controls Virtual Test Bed.” Journal of Building Performance Simulation 4 (3): 185–203. doi:10.1080/19401493.2010.518631.

Yan, D., O’Brien, W., Hong, T. ,Feng, X., Gunay, H. B., Tahmasebi, F. and A. Mahdavi. (2015). "Occupant behavior modeling for building performance simulation: current state and future challenges." Energy and Buildings 107: 264-278.

Zanghirella, F., Perino, M., and V. Serra. 2011. “A Numerical Model to Evaluate the Thermal Behaviour of Active Transparent Faades.” Energy and Buildings 43 (5): 1123–38. doi:10.1016/j.enbuild.2010.08.031.

Appendix A

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 analyzed. 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 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, EnergyPlus Runtime Language (ERL) was added to EnergyPlus (Ellis, Torcellini, and Crawley 2007) in order to replicate a building Energy Management System (EMS) in the simulation tool. The system is based, as in the real word, 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, characterised by different thermo-physical properties, to be used in sequence according to a user-defined control algorithm (Favoino, Overend, and Jin 2015). 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 (Favoino 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 literature. Moreover little evidence was found in 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 behavior 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 summarises 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 modeling dynamic behavior of windows; transparent multi-layer 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 modeling transparent facade systems. Both the complex fenestration constructions (CFC) (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 multi-layer 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 phase change materials. 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 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 modeling functionality. For example, the finite-difference multi-layer 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). Although 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 simulation of rule-based control of a building system and of the adaptive building envelopes available (shading devices, cavity ventilation, electro-chromic 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).

A.5 TRNSYS

The approach that TRNSYS takes towards managing complexity in the built environment is characterised 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 bi-directional 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 e.g., 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 behavior 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 behavior 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.