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Adaptive building envelope simulation in current design practice: findings from interviews with practitioners about their understanding of methods, tools and workarounds and implications for future tool developments

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Adaptive building envelope simulation in current design practice: findings from interviews with practitioners about their understanding of methods, tools and workarounds and implications for future tool developments

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ABSTRACT

Adaptive building envelopes can dynamically adapt to environmental changes to improve thermal building performance. To predict the performance of design proposals with adaptive building envelopes, Building Performance Simulation (BPS) tools can be employed. However, one shortcoming of existing tools is their limited extensibility, which implies that accurately predicting adaptive building envelope performance remains a challenge and requires *ad hoc* approaches. This challenge has made practitioners reticent in considering adaptive building envelopes, which in turn has led to a slow uptake of them in the built environment. This study seeks to advance the understanding of the limitations of adaptive building envelope simulation in current design practice and to suggest implications for future tool developments. To this aim, the study adopts a user-centred perspective through interviews with experts in the field. Findings suggest that current BPS tools hinder the reliable prediction of adaptive building envelope performance, as accurately representing the level of detail of the building envelope is challenging. The subsequent workarounds applied are either time- and cost-intensive or do not consider the dynamic building envelope components. More flexible modelling approaches that allow for rapid prototyping and easy integration are required to enable designers to take full advantage of adaptive building envelopes.

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1. Introduction

Previous studies have reported that energy-efficient, low-carbon technologies for buildings are central to meeting sustainability and carbon emission reduction targets globally. One approach to reducing greenhouse gas emissions in the building sector is the adoption of adaptive materials, components and systems (COST Action TU 1403 adaptive facade network 2018a), cumulatively referred to as adaptive building envelopes. Adaptive building envelopes improve the performance of buildings by dynamically adapting their behaviour over time to changing environmental conditions (Loonen et al. 2016). The main difference between adaptive and static building envelopes is that, in the latter case, the response to environmental changes happens only manually, i.e. through human intervention (Schnädelbach 2003). In contrast, adaptive building envelopes do not necessarily require user input to trigger a response from the building envelope. Rather,

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intelligent control strategies are used in operation to negotiate individual building envelope behaviours (Böke, Knaack, and Hemmerling 2019). Due to their adaptivity, these types of building envelopes can lead to reduced energy demand and improved interior comfort compared to static building envelopes (Matin and Eydgahi 2019).

To make use of adaptive building envelopes in the built environment, practitioners need to be able to predict the performance of building envelope proposals in the design decision-making process, but also need to use such tools to ensure compliance with building energy regulations. They can do this by employing Building Performance Simulation (BPS) tools that 'act as a virtual laboratory' (Loonen, de Klijn-Chevalerias, and Hensen 2019, 272) and assist, for example, in:

- effectively exploring design space parameters;
- quantifying aspects relevant to building design, control and operation parameters of building energy performance; and
- evaluating what-if scenarios in a virtual and hence comparatively low-cost way.

A significant part of building energy regulations concerns the thermal performance of buildings (Chartered Institution of Building Services Engineers (CIBSE) 2015), such as air temperature, occupant factors and controls (de Wilde 2018). This is why this paper focuses on BPS tools used to assess the thermal performance of adaptive building envelopes. While existing BPS tools, such as EnergyPlus (National Renewable Energy Laboratory (NREL) 2018), are capable of predicting the thermal performance of building design proposals, they are rather limited in their ability to provide insights into building-integration issues of adaptive building envelopes (COST Action TU 1403 adaptive facade network 2018a; Taveres-Cachat et al. 2017). One reason for this is the tight coupling of numerical solvers with the individual building component models, which imposes significant modelling constraints. Rules on input/output routines decide, for instance, where the internal data structure of the tool provides inputs to functions to compute building or control equipment (Wetter and van Treeck 2017). The unnatural coupling makes it particularly difficult for users to combine component models with e.g. control sequences; it also introduces barriers to developers in flexibly developing and deploying new tool functionalities. Loonen et al. (2016) note, however, that some models for adaptive building materials, components and systems have already been implemented in BPS tools. EnergyPlus, for example, allows the modelling of Electrochromic (EC) glazing and shading with slat angle control. Although these adaptive building envelope models are robust and relatively easy to use, their limited extensibility reduces flexibility in modelling new and not yet existing adaptive building envelopes. An example of a relatively new adaptive building envelope is electroactive polymer, which is deformable by electrostatic forces (Decker 2013). Current BPS tools consequently lack (i) relevant component models needed to predict the thermal performance of adaptive building envelopes and (ii) flexibility in modelling and testing adaptive building envelope concepts (e.g. control) beyond what is possible by simple scripting approaches. In design practice, this often creates a need for workarounds (Loonen, de Klijn-Chevalerias, and Hensen 2019) that quite often result in unintended and undesirable modelling artifacts.

The shortcomings described above have resulted over the past years in a significant number of publications related to the thermal building performance simulation of adaptive building envelopes. For instance, Attia (2019) conducted interviews with a wide range of experts in the field of building envelope engineering, from researchers to designers, to identify gaps and trends in the performance assessment of adaptive building envelopes. One of the interviewees reported that the lack of capabilities in BPS tools to simulate adaptive building envelopes is likely to hinder their adoption in practice. The work of Attia (2019) and others focused on developing a research roadmap but paid less attention to the needs of designers and the ways they use simulation as an exploratory tool helping design and tuning the operation of adaptive building envelopes. Designers have a significant role to play in making design decisions, and these are often based on the use of simulation tools (Donn, Selkowitz, and Bordass 2012). If such tools are not fit-for-purpose, conflicts arise that hinder the use of adaptive building envelopes and limit the realisation of the expected benefits. This limited consideration of end-user needs may be the reason why recent tool developments might not align with the end-user requirements, and workaround solutions are still widely used in practice. By taking the end-user perspective and understanding their needs and workarounds used, it may be possible to better understand functional and non-functional requirements for future tool developments that also meet end-user needs.

This study adopts the user-centred perspective above to complement existing research work. It aspires to advance the understanding of the limitations of current methods and tools that result in workaround solutions. More importantly, this work leads to suggestions for future tool developments that are able to better support the design practitioners to consider adaptive building envelopes. The work also gathers timely and specific information, which may not yet be widely available due to novelty, in this emergent area. The present study was designed to interview practitioners in thermal adaptive building envelope simulation on (i) current tool developments, (ii) challenges associated with the capabilities of tools, (iii) workaround solutions and (iv) future tool developments. The aim of this study was to:

- define the current status of adaptive building envelope simulation in design practice;
- gather information on challenges and workarounds the participants may have faced; and
- acquire feedback regarding practical improvements for future tool developments.

2. Background: current status of adaptive building envelopes

The term *adaptive* in the context of building envelopes is a term frequently used in the literature. To date, however, there is no consensus about a single definition for building envelope technologies that dynamically change and interact with the environment and the user. The term *adaptive* is often associated with a long list of similar terms, such as *intelligent*, *responsive* or *smart* (Romano et al. 2018). While all of the terms characterise differently focused concepts of adaptive building envelopes, one or more of the following technical characteristics is present in each of these concepts (Romano et al. 2018):

- high-performance, innovative materials and systems to absorb and store solar energy;
- devices to manage natural and mechanical ventilation systems;
- mobile screens to control solar radiation;
- technological solutions to enhance or control comfort in the building; and
- building management systems to manage plants and building envelope elements.

The past decades have seen a rapid development of adaptive building envelopes. Their development has largely been influenced by technological and environmental factors, which have their origin in revolutionary changes in technology and construction since the end of the nineteenth century (Matin and Eydgahi 2019). A recent report by the COST Action TU 1403 adaptive facade network (2018b) – a European Union (EU) initiative to harmonise and disseminate knowledge on adaptive building envelopes – presented one hundred sixty-five concepts of adaptive building envelopes. These building envelopes have been developed and tested in research laboratories, but only a few found application in real-world buildings. Hensen et al. (2015) suggest that most of the adaptive building envelopes applied to real-world buildings have been developed as bespoke solutions for individual building projects. For example, an algae-based bio-reactive façade system was developed for a pilot project for the International Building Exhibition (IBA) in Hamburg, Germany (Wurm 2013). Exceptions to the bespoke solutions are technologies that are widely commercially available, such as Phase Change Materials (PCMs), EC glazing and multi-functional shading systems (Attia et al. 2018; Loonen et al. 2013). Multi-functional shading systems in particular are used extensively, also in low-profile and low-budget building projects, as they represent a cost-effective solution that aligns well with current building practices (Loonen et al. 2016). An example of a multi-functional shading system is the perforated movable louvres designed by Colt International, a designer and supplier of solar shading, for a primary school at Neubiberg, Germany (Colt International 2012).

The fact that only few adaptive building envelopes have been applied to real-world buildings highlights the challenges of transition from research to practice (Attia et al. 2018). The slow rate of technology transfer can be attributed to a lack of case studies and associated tools that help quickly understand the implications of research-based innovations to commercial practice (Hensen et al. 2015). The reasons for the limited use of adaptive building envelopes to buildings in the design phase include a lack of real-world evidence of technology benefits, combined with a lack of benchmarks, standards and test procedures for performance evaluation of adaptive building envelopes. Table 1 presents further reasons for the slow rate of adoption during both the research and design phases of adaptive building envelopes.

To further support innovation processes of building envelopes, BPS tools can be employed. They provide an important opportunity to assist in informed decision-making from the early Research & Development (R&D) phases to marketing and sales support of adaptive building envelopes (Hensen et al. 2015). This may help to pave the way for future advancements in adaptive building envelope technologies. These advancements may be driven by (i) more powerful hard- and software to design and control even more complex systems, (ii) new internet technologies like wireless communication, cloud-based data storage and sensor network to integrate adaptive building envelopes with other building systems and (iii) the possibilities for occupants to control adaptive building envelopes with their smartphones (Matin and Eydgahi 2019).

3. Methodology

The interview study was part of a quantitatively driven mixed-methods research project, with the central question asked being: 'If and how could the dynamic behaviour of adaptive building envelopes be accurately and reliably predicted?' In establishing the state-of-the-art of adaptive building envelope simulation in design practice, the interview data were utilised to drive definition of requirements, thus guiding the research and informing the development of the potential solution for the prediction of adaptive building envelope behaviour.

3.1. Interview methodology: design, procedures and implementation

As part of a quantitatively driven mixed-methods research project, the present study adopted a semi-structured interview method. Semi-structured interviews are the most common qualitative method in quantitatively driven mixed-methods research designs as they produce the easiest data to be imported into the analysis in the results narrative (Morse 2015). An interview guide

Table 1. Reasons for limited use of adaptive building envelopes in buildings.

Reason		Explanation
R&D phase	Technology transfer	Difficulties of new technologies to bridge the gap between research-based innovations and their commercial application on the market.
	Real-world system operation	More real-world evidence may improve how stakeholders make decisions and expand the use of adaptive building envelopes in more buildings.
Design phase	Performance evaluation	A lack of benchmarks, standards and test procedures hinders the measurement and evaluation of adaptive building envelope performance.
	Costs	Indirect costs for maintenance and energy consumption that may be lower for adaptive than for static building envelopes are rarely considered by designers and clients.
	Design tools	Challenges in current design tools, such as trade-offs between model complexity and accuracy, make the design process more difficult.
	Delivery process	Spanning multiple engineering disciplines, the delivery process requires a high degree of cooperation among actors and often results in process-related challenges.

was developed to provide guidance to participants on what to talk about (Kallio et al. 2016) and to cover the topics under investigation completely (Taylor, Bogdan, and DeVault 2015). In an interview guide, topics are pre-specified, but the researcher may change the wording or the order of questions according to participants' feedback during the interview. The interview guide that was used during the interviews is presented in the appendix and covered four main themes:

1. *Current tool developments:* The aim of this theme was to determine current methods used to simulate adaptive building envelopes in design practice.
2. *Challenges associated with BPS tool capabilities:* This theme was designed to gain insights into the problems and limitations the participants experienced in simulating adaptive building envelopes.
3. *Workarounds:* This theme sought to learn about methods to overcome the challenges associated with BPS tool capabilities to simulate adaptive building envelopes.
4. *Future tool developments:* The aim of this theme was to inform future methods to simulate adaptive building envelopes.

To be able to maximise the applicability of findings in qualitative research to the broader context, samples must be representative of the population. This leads to the selection of information-rich samples to understand the phenomena that are of central importance to the purpose of the research (Patton 2002). In this study, the selection was achieved by following the key informant technique (DiCicco-Bloom and Crabtree 2006). Key informants provide the kind of information being sought by the researcher as a result of their personal knowledge and experience of the phenomenon under study, thereby enabling the researcher to provide a convincing explanation of the phenomenon. To ensure that participants fulfil the specific purpose relevant to the research objective, the key informant selection principles by Cleary, Horsfall, and Hayter (2014) propose to select participants purposefully and based on predetermined criteria. Selection criteria in the present study were:

- recent experience in thermal building performance simulation of adaptive building envelopes;
- deep understanding of strengths and weaknesses of BPS tools; and
- hands-on experience in the development of workaround solutions.

To justify adequate sample sizes in purposive samples, Hagaman and Wutich (2017) suggest the concept of theoretical saturation, which can be defined 'as the point at which no new insights, themes, or issues are identified' (25). In purposive samples, the minimum number of interviews needed to reach data saturation is between seven and twelve interviews (Hagaman and Wutich 2017). Because key informants needed to be highly specialised in their field, a theoretical population size of 22 was estimated based on a review of practitioners in the field of adaptive building envelope simulation in current European design practices. Potential participants were contacted by personal email or LinkedIn message, and 41% responded to the interview request. Two of them did not meet the selection criteria so that a total of seven participants were interviewed (Table 2).

To 'record' the human interaction, this study used both field notes and a recording device. While field notes are key in gathering information on the context and situational background, they cannot be replayed. Because this may result in a loss of information (Tessier 2012), the interviews were audio-recorded utilising a digital voice recorder. According to data protection and ethical practice, permission from each participant to audio-record the interview was sought during the interview setup phase.

Following the interviews, the audio recordings were directly coded to enable the researcher to repeatedly revisit the original data and maintain a greater sense of the interviewee's perspectives (Lapadat 2000). Quotations that were needed for publication and illustrative of the core aspects of the research were transcribed using pragmatic transcription, a verbatim transcription format with nonverbal information (Evers 2011). For the transcription of the nonverbal information,

Table 2. Information about interview participants.

Information	Proportion
Country of workplace	Denmark: 1, Sweden: 1, United Kingdom: 5
Experience of participant*	Entry level: 1, Mid-level: 2, Senior level: 4
Size of company†	Small: 1, Mid-sized: 1, Large: 5

* Entry level: 0–5 years, Mid-level: 6–10 years, Senior level: 11+ years.
† Small: 1–50 employees, Mid-sized: 51–250 employees, Large: 251+ employees.

the transcription keys by Jefferson (2004) were used, as presented in Table 3. To avoid disclosing interviewees' identities, individually-identifiable details were replaced with more generic phrases in [brackets].

3.2. Data analysis methodology

A qualitative content analysis method (Mayring 2000) was adopted for the interpretation of the interview data. The aim of a qualitative content analysis is to provide knowledge and understanding of the content of text data through the systematic process of coding and identification of themes or categories without necessarily requiring verbatim (i.e. word for word) transcripts (Vaismoradi, Turunen, and Bondas 2013). By identifying the relationships among codes and categories, the use of this method yields a set of themes that cover the data and allow for reframing the phenomenon under study (Cho and Lee 2014).

Compared to other qualitative analysis methods, such as grounded theory, a weakness of qualitative content analysis is its limitation in theory development. However, Hsieh and Shannon (2005) highlight that the results of qualitative content analysis are concept development or model building, which seemed sufficient for identifying important areas for further research.

In implementing the analysis strategy, Computer-Assisted Qualitative Data Analysis Software (CAQDAS) was adopted. CAQDAS allows for rapid and rigorous data analysis process, for instance, by enabling the researcher to identify relationships among codes and utilise these relationships in the analysis and to link them to text and codes and write memos (Weitzman 2000).

This study used the CAQDAS NVivo (QSR International 2018) to categorise simple codes into more encompassing categories. Instead of developing codes beforehand, categorisation was undertaken *ad hoc* based on the qualitative content analysis method by Hsieh and Shannon (2005). The coding process was simplified through the field notes with descriptions of the phenomena to be coded or categorised obtained through the interview process (Kvale 2004). As a result of the coding process, numerous themes and sub-themes emerged that corresponded with the major questions under study.

4. Findings and discussion

This section discusses the themes that emerged from the interviews with practitioners in the field of thermal building performance simulation of adaptive building envelopes in current design practice. When referring to specific interview participants, an interview code was applied, which was formed by the letter P (which stands for participant) and the number representative of the order in which the interview took place (e.g. P01 for the first interview).

Table 3. Transcription keys (Jefferson 2004).

Key	Use
(0.5)	Numbers in parentheses indicate elapsed time in seconds.
(.)	A dot in parentheses indicates a brief interval.
<u>word</u>	Underlining indicates vocal emphasis; the extent of underlining within individual words indicates the emphasised syllable(s).
word-	A dash indicates a cut-off.
()	Empty parentheses indicate that the transcriber was unable to get what was said.

4.1. Feedback from participants on BPS tools used

To examine BPS tools used for thermal building performance simulation of adaptive building envelopes in current design practice, participants were asked to give feedback on the types of BPS tools they adopt to predict the performance of projects with adaptive building envelopes. The present study found that:

- six out of seven participants use IES Virtual Environment (IES VE) (Integrated Environmental Solutions 2019), a proprietary BPS tool with integrated suites of applications linked by a common Graphical User Interface (GUI);
- three out of seven participants use EnergyPlus, an open-source BPS tool designed to be used through a text-based interface; and
- one out of seven participants uses IDA Indoor Climate and Energy (IDA ICE) (EQUA Simulation 2018), a BPS tool that describes physical systems with symbolic equations in a general modelling language (Sahlin et al. 2004).

While there are many other BPS tools that can be used for the thermal building performance simulation of adaptive building envelopes (see Loonen et al. (2016) for further details), the experience of the practitioners interviewed in this study was limited to IES VE, EnergyPlus and IDA ICE. These three tools are, however, representative of the BPS tools used in current design practice. A recent survey conducted informally with 6,000 followers of the Performance Network, a webinar provider, found that DesignBuilder (DesignBuilder Software 2019), a GUI for the EnergyPlus simulation engine, IES VE and IDA ICE accounted for nearly half of the votes in response to the question 'What is your favourite energy modelling interface?' (Bakshi 2016). It is important to bear in mind that Bakshi (2016) did not include simulation engines like EnergyPlus in the survey.

In the interview data, themes related to the reliability of BPS tools were particularly prominent. The majority of participants indicated that it is key for them to know that the predictions of BPS tools are reliable throughout the design process of adaptive building envelopes. When they believe that tool capabilities are not sufficient to reliably predict the behaviour of the building envelope, participants tend to use more elaborate tools. For instance, participants often use EnergyPlus as an alternative to IES VE to facilitate control of the modelling, workflow integration or parametric analysis to answer particular design questions (P02, P03, P05). In reference to this issue, an interviewee said:

> I always ask my team (.) to think about, you know, what's the purpose of the analysis, (0.3) you know, why we're doing it and often that will (.) help us understand what tool we want to use. (P02)

The participants' responses suggest that the tool selection highly depends on the tool's capabilities to complete project work reliably. Further perspectives concerning the performance of BPS tools were that most interviewees are satisfied with the overall usefulness of the BPS tools they are utilising (P01, P04, P05, P06, P07). This satisfaction is mainly due to the suitability of the tools for the purposes of the user's analyses. It was noted, however, that the usefulness of tools is strongly linked to the user's modelling skills and ability to ask appropriate questions (P01, P02, P04). As one interviewee put it: 'The predictions, (0.3) if you use them right, (.) are good. But if you use them wrong, it creates (.) odd results or wrong results' (P01). Despite this, participants believe that the transparency and openness of BPS tools determine their accuracy and reliability. Participants tend to trust pure calculation engines, like EnergyPlus or Radiance (Lawrence Berkeley National Laboratory (LBNL) 2018), a suite of tools for the analysis and visualisation of lighting, more than other software. This preference is due to the interviewees' perception that pure calculation engines have more transparent calculation procedures (P02, P04, P05), as illustrated by the quotes in Table 4. In contrast to EnergyPlus, the majority of participants perceive IES VE as 'a bit of a black box' (P05) preventing users from understanding the inner algorithms and procedures it performs and obligating users to rely on its predictions (P02, P04, P05, P06). Nevertheless, participants perceive IES VE as trustworthy. Some consider their trust as legitimate because IES VE is an industry standard.

4.2. Challenges associated with BPS tool capabilities

Initial observations suggest that the participants have differing perceptions of the capabilities of BPS tools to simulate the thermal performance of buildings with adaptive building envelopes. For example, one interviewee stated that 'adaptive building envelopes are (.), of course (0.3), already been implemented into our thermal building simulations to some extent' (P01). And another commented: 'I mean, it is limiting, but what isn't? And no software is perfect' (P07). Rating the degree of the capabilities of BPS tools on a scale of one to ten, where one means full capability and ten hardly any capability to simulate adaptive building envelopes, responses ranged from three to six with an average of 4.3 (Table 5). Four participants rated IES VE, two IES VE and EnergyPlus and one IDA ICE. Interviewees rating IES VE rated it without considering the recently launched Python Application Programming Interface (API) in IES VE (Integrated Environmental Solutions 2018) because they do not have personal experience with it. Nevertheless, one individual rated the capabilities of IES VE as three saying that 'the technologies, which are (.) part of adaptive building envelopes, are not completely implemented into the thermal building simulations' (P01). By contrast, another participant rated the capabilities of IES VE as seven and those of EnergyPlus as three because of the Energy Management System (EMS) scripting feature (Ellis, Torcellini, and Crawley 2007). The EMS scripting feature is a simple programming language in EnergyPlus to specify control logics. According to the participant, it opens up the capabilities of EnergyPlus, especially for custom control algorithms. Because IDA ICE is highly programmable, its capabilities were rated as three, similar to EnergyPlus.

The participants identified several challenges that can be associated with the capabilities of BPS tools to predict the thermal performance of adaptive building envelopes. The challenges mentioned most often by interviewees were an accurate representation of building envelope systems, materials and controllers. The challenges they reported were compared with the BPS tool capabilities found by Loonen et al. (2016), who studied current capabilities and limitations of BPS tools for adaptive building envelope simulation. This was done to cross-check the responses of the interviewees with the literature, and the comparison in Table 6 is revealing in several ways. First, participants do not seem to be fully aware of the existing capabilities of BPS tools to model adaptive building envelopes. This is, for example, evident in the case in Double Skin Façades (DSFs). Two participants reported a lack of capabilities to model DSFs in IES VE, although it is generally possible to simulate them in IES VE as well as in EnergyPlus and IDA ICE (Loonen et al. 2016). Second, Loonen et al. (2016)

Table 4. Transparency and accuracy of BPS tools used by participants.

Tool	Quote
IES VE	'IES is a bit different, 'cause it is a bit more of a black box. (.) It hides a lot of things from the user, (0.4) and I think that's- that can be risky.' (P02)
EnergyPlus	'The use of (a) pure calculation engine, like Radiance or EnergyPlus, I tend to trust them a lot because they are quite transparent.' (P05)
IDA ICE	'At any point you can do (reliability) checks. (.) So, even if you stretch the software way (0.4) beyond the possibilities or the validation itself that it was carried out (.) by extracting any value that you want, you see whether it makes sense () or not.' (P04)

Table 5. Participant's rating of the capabilities of BPS tools.

Participant	P01*	P02†	P03†	P04‡	P05*	P06*	P07*	Min	Max	Mean
Rating	3.0	5.0	6.0	3.0	-	5.0	4.0	3.0	6.0	4.3

BPS tool rated by participant: * IES VE, † IES VE and EnergyPlus, ‡ IDA ICE.

Table 6. Challenges associated with BPS tool capabilities reported by participants.

Type	Reported challenge	Tool capabilities found by Loonen et al. (2016)		
		IES VE	EnergyPlus	IDA ICE
System	DSF (P02, P06)	Yes	Yes	Yes
	Curvy façade element (P06, P07)*	No	No	No
Material	PCM (P01, P03, P05)	No	Yes	Yes
	Dynamic insulation (P01)	No	Yes	Yes
	Material motions by changes in e.g. volume or shape (P05)*	No	No	No
	Photochromic glazing (P07)	Yes	Yes	Yes
Controller	Custom control logic (P01, P02, P05)			
	Sensor	Limited	Any output	Any output
	Actuator	Limited	Limited	Limited
	Control logic based on weather conditions (P03, P06)			
	Air temperature	No	Limited	Limited
	Solar radiation	Limited	Limited	Limited
	Windspeed	No	Limited	Limited
	Shading with slat angle control (P06)	No	Yes	Yes

* Based on information in user manuals and forums.

highlight that BPS tools differ in the models they have implemented for the prediction of adaptive building envelope behaviour. Therefore, it is recommended that practitioners select tools depending on the modelling capabilities needed. This recommendation is in line with the finding that three of the seven participants reported that they already select BPS tool depending on the use case (P02, P03, P04). However, the fact that four of seven interviewees use one BPS tool for whatever use case suggests that practitioners may need to learn more BPS tools to apply the tool that is the most suitable one for the particular use case.

A recurrent theme in the interviews was a sense amongst participants that the lack of capabilities of BPS tools would hinder practitioners in considering adaptive building envelopes' benefits in the design process. This obstacle, in turn, would take any argument from practitioners as to why adaptive building envelopes should be part of the future building sector (P01, P06). As one interviewee argued:

> Materials, such as PCM in glass, is a technology, which is not used within the [local] building sector at present. But since it's not being implemented in the calculation software, we can't officially prove the (.) benefits of PCM in glass and, therefore, we don't have any argumentation of why should PCM in glass be a (.) future building component within the [local] building sector. (P01)

It is certainly true that further research on the development and integration of numerical models of PCM in glass in BPS tools is needed (Vigna et al. 2018). However, the response above contrasts with a considerable amount of literature that has demonstrated that models for some adaptive building envelopes exist in current BPS tools (e.g. COST Action TU 1403 adaptive facade network 2018a; Loonen et al. 2016). It seems, therefore, possible that there is a lack of knowledge about these models and how to use them in current design practice. Nevertheless, it is important to bear in mind that there are many adaptive building envelopes at prototype or product stage that could currently not be modelled in BPS tools (Loonen et al. 2016). This, together with the reasoning by P01, suggests that it is likely that BPS tools tend to lag behind commercially available adaptive building envelope technologies cutting off the transition of adaptive building envelopes from lab to market. It thus seems plausible that the lack of capabilities of current BPS tools hinders the adoption of market-ready adaptive building envelopes in buildings besides potentially substantial contributions towards improved energy efficiency.

The effect of the lack of capabilities on the predictions of BPS tools was evaluated differently by the interviewees (Table 7). On average, participants rated the impact as 5.7 on a scale of one to ten, where one means no effect and ten large effect, ranging between four and eight. Some interviewees argued that the lack of capabilities is not decisive for the simulation outcome because there are also many other aspects in a model affecting the predictions. Other participants believed 'if you would

Table 7. Participants' rating of the effect of the BPS tool capabilities on the predictions.

Participant	P01*	P02†	P03†	P04‡	P05*	P06*	P07*	Min	Max	Mean
Rating	5.0	4.5	4.5	7.0	7.0	8.0	4.0	4.0	8.0	5.7

BPS tool rated by participant: * IES VE, † IES VE and EnergyPlus, ‡ IDA ICE.

model a CCF, and you cannot, a Closed Cavity Façade, and you cannot do it, the impact is tragic' (P04). This is why the use of workarounds becomes necessary.

4.3. Workarounds to overcome the lack of BPS tool capabilities

To overcome the lack of capabilities of BPS tools to simulate the thermal performance of adaptive building envelopes in design practice, participants apply different workarounds. Interviewees used the term workaround to refer to a method, sometimes used temporarily, for resolving an issue occurring with a BPS tool when a functionality offered by a BPS tool is not working properly. Workarounds are applied when capabilities of BPS tools are not sufficient for a particular project despite correct input parameters. The decision to use a workaround usually follows a thorough checking of inputs and outputs, as can be seen from Figure 1. The two most widely used workarounds for adaptive building envelope simulation are scripting and post-processing, both of which are used by four of the seven participants.

Scripting methods are applied by four participants (P02, P03, P04, P05), and one interviewee reported:

> But then we also (.) write our own (.) software if we find that something of the shelf isn't quite doing what we need. So, we've got some coders in-house. (.) They can work with things like Python and MATLAB and (0.3) different scripting interfaces. (P02)

Python (Python Software Foundation 2018) and MATLAB (MathWorks 2018) are high-level programming languages that can be integrated into the simulation workflow (Miller, Hersberger, and Jones 2013). However, the interview data suggest that the most widely used scripting method employed by participants is not Python or MATLAB but Grasshopper (Robert McNeel & Associates 2014), a visual programming language. Grasshopper has been used in previous studies, for example, to set the geometric parameters of an origami-inspired shading device (Pesenti et al. 2015). Another widely used scripting method employed by participants is the EMS scripting feature of EnergyPlus, which offers flexibility to customise control logics in EnergyPlus models. Although it can be daunting if users have not the skills to run e.g. IF-statements, it seems likely that scripting becomes more and more standard practice, as suggested by one participant:

> Normally what happens is that (0.4) more and more in team there are people, who are able to, even if they are () architects or engineers, who are very keen in doing- coding and scripting, essentially to create your own workaround. (P03)

By contrast with scripting, a workaround that may introduce human error and be less repeatable (P02) but can also be conducted in IES VE is, as most participants called it, post-processing. As shown in Figure 2, post-processing describes a process of predicting all modes of an adaptive building envelope independently from each other and of manually interpolating the predictions e.g. in an Excel spreadsheet. This workaround is adopted by four of seven interviewees (P01, P02, P05, P07) and is perceived as standard practice by these participants when the predictions of a BPS tool are not as expected. However, a major drawback of this approach is that it takes no account of the dynamic behaviour of the envelope. It consequently provides no understanding of the actual workings of the adaptive building envelope and the correct implementation into the building (P06).

A workaround that has not been reported by participants is co-simulation. Co-simulation describes the joint simulation of coupled systems that share common variables. This method has been widely investigated in recent years (e.g. Borkowski et al. 2019; Loonen et al. 2016) and

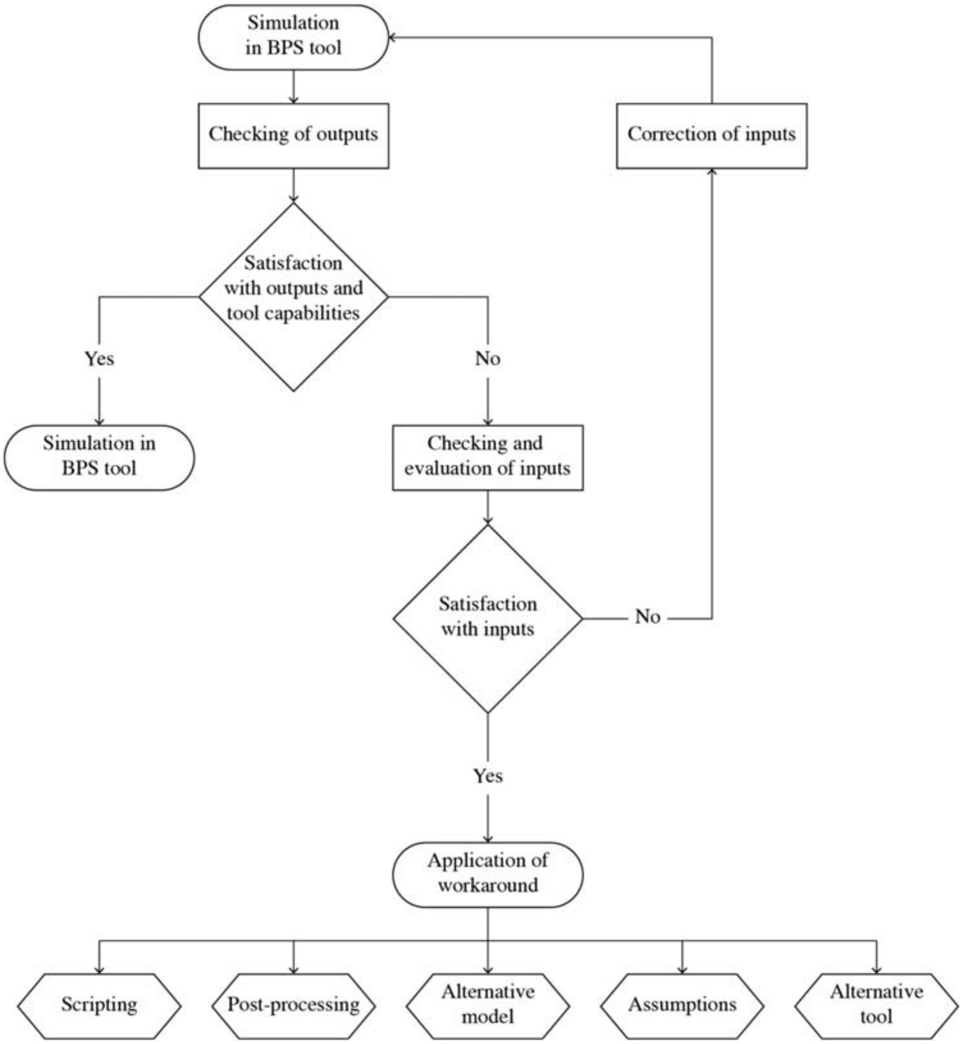

Figure 1. Typical process until decision to use a workaround is reached.

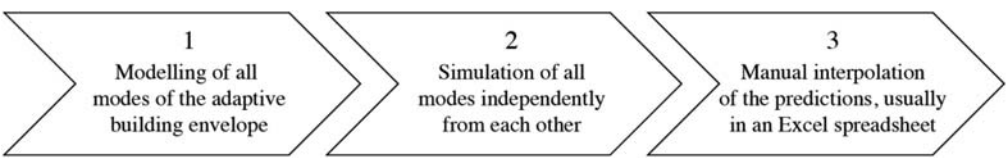

Figure 2. Steps of post-processing as workaround.

seems as a promising solution to overcome the challenges associated with the capabilities of BPS tools to predict the behaviour of adaptive building envelopes.

In general, participants find the workarounds applied so far useful since they solve questions that BPS tools cannot answer (P01, P02, P03). As one interviewee said:

> Ultimately, I think, (.) it's- it is quite successful in (0.3) the way that we deliver these workarounds or these, you know, alternative (.) approaches. It kind of has to be. Otherwise, we're not able to (.) produce the analysis outputs that we need to for the purpose of the project. (P02)

A recurrent theme in the interviews was a sense amongst interviewees that the predictions of workarounds are less accurate and reliable than the ones of BPS tools. A consequence of this is that the application of workarounds is more difficult in everyday project work. Approaches reported by participants to test the accuracy and reliability of workarounds are (i) comparative testing, (ii) four-eyes principle, which means that at least two people must approve a workaround, (iii) knowledge and experience by the user and (iv) quality assurance of input and output data.

Together, these results provide important insights into the use of workaround solutions to overcome the lack of tool capabilities for thermal adaptive building envelope simulation. The fact that six of the seven participants adopt workarounds suggests that there is currently a mismatch between need and availability of information obtainable from BPS tools concerning adaptive building envelope simulation in design practice. Therefore, the evidence presented thus far agrees with earlier observations in the literature and clearly demonstrates that the lack of tool capabilities has the potential to:

- hinder practitioners in considering adaptive building envelopes' benefits in the design process taking any argument from them as to why they should be part of the future building sector; and
- complicate informed decision-making in the R&D phase and hinder the successful commercialisation of adaptive building envelopes.

Moreover, the present study extends the knowledge of how practitioners currently deal with the challenges that can be associated with the limited capabilities of BPS tools to predict the behaviour of adaptive building envelopes. The study has demonstrated that there may be a lack of knowledge about the availability and use of adaptive building envelope models already implemented in BPS tools in current design practice. Also, this study has documented the workaround solutions that are currently used in the industry. Although each of the workarounds has its pros and cons, it has been pointed out that post-processing, in contrast to scripting, does not consider the dynamic behaviour of adaptive building envelopes. Given that the performance of adaptive building envelopes fully depends on the consideration of the dynamic components of the building envelope, it seems that post-processing is not the most suitable workaround.

4.4. Resulting needs and gaps

To assist R&D processes for a successful commercialisation of adaptive building envelopes, the capabilities of BPS tools – i.e. the modelling of materials, systems and controllers – need to be improved. Talking about future tool developments, however, participants most frequently reported improved tool capabilities for the modelling of controllers (P01, P02, P05, P06, P07) while the modelling of materials and systems was of secondary importance. A possible reason for this may be that adaptive building envelope performance fully depends on the control logic for building envelope adaptation during operation (P06) (Böke, Knaack, and Hemmerling 2019).

What might help in the process of improving tool capabilities for controller modelling is the current trend of graphical plug-and-play modelling (Nouidui, McNeil, and Lee 2011). For example, co-simulation allows to plug and play different simulators to identify optimised controller parameters for an adaptive building envelope (Borkowski et al. 2019). Graphical plug-and-play modelling is also promoted by tools like Modelica (Modelica Association 2017), an object-oriented, equation-based modelling language, which allows tool coupling. This type of modelling might shape how specific building systems will be simulated in the future, provide freedom to plug-and-play different systems, sensors and actuators and reuse existing models (P02). This may result in controllers that will be more flexible and more applicable to more façade and building elements with varying levels of details, abstraction and processes enabling practitioners to make the most out of the design (P02, P05, P06). Discussing the use of plug-and-play modelling in the future, one interviewee said:

> Your closed cavity façade, if we stick to this example, has a number of sensors that are plugged together and are prioritised, and you can sense how warm the space is inside, how warm the cavity () of the glass is, what the outside conditions are, and then it can actuate the rotation or the deployment or, you know, the drop of the shades. (0.4) And maybe it could be plugged together with a- (.) an electrochromic or dynamic glass so that one of the services in the CCF build up is dynamic. (P02)

This finding, while preliminary, suggests that more flexible modelling approaches like graphical plug-and-play modelling that allows for rapid and easy integration of models and tools are needed. Besides flexibility, further implications for future tool developments, which emerged in the analysis and were most frequently reported, were:

- *Integrated approach:* Integration of different data and models, preferably from different design stages, into tools (P01, P05, P06, P07).
- *Tool capabilities:* Implementation of parametric modelling and optimisation to enable users to understand model parameters (P01, P05).
- *User support:* Accessible training and detailed documentation to facilitate understanding of tool capabilities (P02, P04).
- *Transparency:* Tracking of parameters the tools use in modelling and simulation processes to enable users to understand codes and algorithms (P01, P04).
- *Modelling and computing time:* A short model setup and simulation run time to allow for quick results and decision-making (P02).

4.5. Implications of findings for future research and practice

The present study set out to acquire feedback regarding practical improvements for future tool developments in the field of thermal building performance simulation of adaptive building envelopes in current design practice. As discussed in the previous section, a major finding to emerge from this study is that future tool developments need to be capable of better predicting the dynamic components of adaptive building envelopes. To group the improvements for future tool developments, this study used the concept of software requirements typically used in software development to improve software quality and to meet end-user's needs (Umar and Khan 2011). Requirements can be categorised into Functional Requirements (FRs) and Non-Functional Requirements (NFRs):

- *FRs:* The specific functions a tool must perform at any level of abstraction to transform inputs to outputs.
- *NFRs:* The quality attributes of a tool, such as usability, reliability, performance, supportability, scalability and maintainability.

Figure 3 reveals that there are mainly NFRs that future tool developments should take into account. In their analysis of NFRs for software development, however, Umar and Khan (2011) point out that developers rarely focus on NFRs. This is because they are difficult to address as they often interact in synergistic or competing ways. Nonetheless, the present study has demonstrated that future tool developments should concentrate on NFRs, and research addressing these requirements has already been undertaken in recent years. This is exemplified in the work undertaken by IBPSA Project 1, which set out under the umbrella of the International Building Performance Simulation Association (IBPSA) to develop computational tools for buildings and district energy systems (Wetter and van Treeck 2017). The outcomes of IBPSA Project 1 represent an excellent opportunity to be used in research on adaptive building envelope simulation (e.g. Borkowski

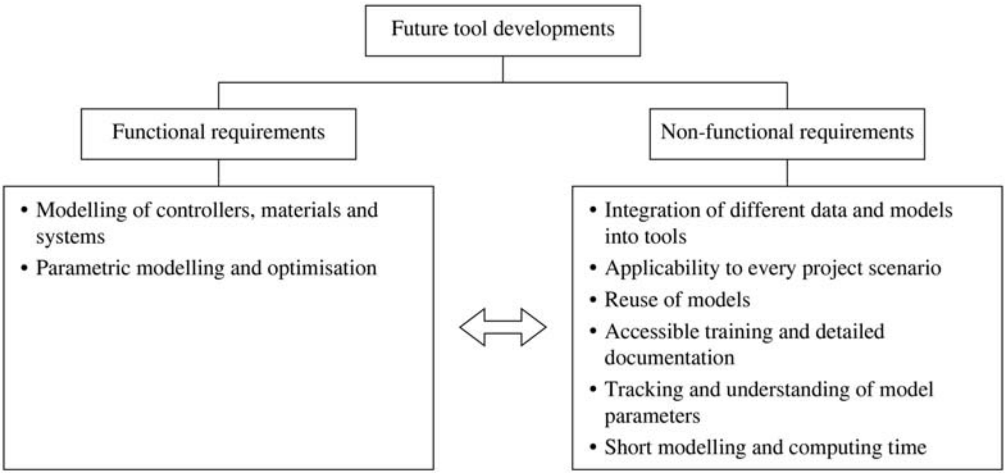

Figure 3. Implications for future tool developments.

et al. 2019). What is now needed is to make the research outcomes accessible and understandable to practitioners, potentially without specialised knowledge, to enable them to reliably and accurately predict adaptive building envelope behaviour in the future.

Despite the previous research on the requirements for future tool developments, the findings of the present study have the following important implications:

- *More flexible modelling approaches:* BPS tools used in design practice lag behind commercially available adaptive building envelope technologies. To foster their innovation and product development, practitioners promptly require more flexible modelling approaches that allow for rapid and easy integration of bespoke models and tools.
- *Collaborations and development share:* Industry-university collaborations would be worthwhile to transfer knowledge and technology between research and design practice effectively. Development share among software developers, design firms and other organisations would be of great help to allow for reuse of solutions and avoidance of redundant efforts.
- *Continuing professional development for practitioners:* It has been shown that practitioners lack knowledge about the capabilities of existing BPS tools in terms of availability and use of adaptive building envelope models. Also, practitioners know and work only with a limited number of BPS tools which might not always be the most suitable one for a particular use case. This finding suggests that there is a need to educate practitioners about available models and tools and to train practitioners to apply them.

What seems more and more common in design practice is that practitioners use more elaborate analysis, such as optimisation and parametric analysis (P01, P05), as an expansion of traditional building performance analysis. This development has been in part driven by plug-ins, such as Ladybug (Roudsari and Pak 2013), a plug-in for Grasshopper to carry out parametric analyses, which enable practitioners to build generative algorithms to link building performance models with e.g. daylight and 3D models, and by BPS tools, such as DesignBuilder, which integrate optimisation and parametric analysis tools (Ordoñez, Cito, and Rovira 2018). As found in this study, such plug-ins and tools are already adopted in the design of adaptive building envelopes. This sets out the need for future research to concentrate on examining how building performance analyses need to be expanded to take account of the design opportunities that the introduction of adaptive building envelopes entails. Further research should also be done to investigate methods, tools and workarounds used in current design practice to predict other performance aspects of adaptive building envelopes and their components, such as mixed-mode strategies with combined natural and mechanical ventilation and cooling components (Center for the Built Environment (CBE) 2013).

5. Conclusions

This study adopted a user-centred perspective to advance the understanding of the limitations of current methods, tools and workarounds used to predict the thermal performance of adaptive building envelopes. Based on this, it suggested requirements for future tool developments that also meet end-user needs. The interview data showed that practitioners need BPS tools primarily to complete their everyday project work. However, the BPS tools available on the market keep practitioners from reliably and accurately predicting the behaviour of adaptive building envelopes, especially new and not yet existing ones, consequently:

- complicating informed decision-making in the process of designing adaptive building envelopes;
- limiting the argument as to why they should play a role in the future building sector; and
- hindering the introduction of adaptive building envelopes on the market.

Data for this study were collected interviewing seven practitioners, who were selected because of their personal knowledge and experience of thermal adaptive building envelope simulation in current design practice. Although the study has successfully demonstrated methods, tools and workarounds used to predict the behaviour of adaptive building envelopes in current design practice, it has two important limitations that need to be considered. First, the sample size was determined by the small theoretical population size of 22. While the population was representative of the population and the interviews achieved a point at which no new insights, themes and challenges were identified, a larger sample size might have captured some subtle or conceptual challenges. Second, the interviews could have been limited by self-selection bias of interviewees (Robinson 2014), favouring those more interested in the topic than the general sample universe. This self-selection bias was, however, taken into account by e.g. fact-checking challenges associated with the thermal building performance simulation of adaptive building envelopes reported by participants with the literature.

Notwithstanding these limitations, the study's findings make two noteworthy contributions to the current body of knowledge. For the first time, this study has explored in detail methods, tools and workarounds used in current design practice to predict the thermal performance of projects with adaptive building envelopes by taking the end-user perspective into account. It thus provides additional evidence with respect to real-world challenges of the practical application of BPS tools and to the requirements for future tool developments tailored to the needs of the end-users. Findings of the study show, for example, that BPS tools available on the market lack relevant component models and algorithms to integrate innovative building envelope technologies in tools and that practitioners lack knowledge about the availability and use of adaptive building envelope models already implemented in BPS tools. Secondly, the gathered information on workarounds and challenges associated with the capabilities of current BPS tools and feedback regarding practical improvements for future tool developments helped to establish a greater degree of understanding of major research needs and gaps, which might not yet fully exist due to novelty, in the key emergent area on adaptive building envelope simulation. The findings of this study can therefore be used in research and design practice to assist in creating a building sector that allows practitioners to use innovative building envelope technologies to meet sustainability and carbon emission reduction targets across the world. Finally, the research project, which included the present study, used the findings of the interviews to inform the development of a potential solution for the prediction of adaptive building envelope behaviour.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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